Template/Pro forma for Submission

NMHS-Himalayan Institutional Project Grant

NMHS-FINAL TECHNICAL REPORT (FTR)

Demand-Driven Action Research and Demonstrations

NMHS Reference No.:	**GBPNI/NMHS-2017-18/SG10**

Date of Submission:	3	0	0	3	2	0	2	2
	d	**d**	**m**	**m**	**y**	**y**	**y**	**y**

IDENTIFICATION OF HYDROPOWER SITES AND CRITICAL GLACIAL LAKES FOR SUSTAINABLE WATER RESOURCE MANAGEMENT IN HIMACHAL PRADESH.

Project Duration: *from* (**01.04.2018**) *to* (**31.12.2021**).

***Submitted to*:**
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GENERAL INSTRUCTIONS:

1. The Final Technical Report (FTR) has to commence from the date of start of the Project (as per the Sanction Order issued at the start of the project) 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 details contents of training programme technical details and techniques involved) or any such display material related to project activities along with slides, charts, photographs should be brought at the venue of the Annual Monitoring & Evaluation (M&E) Workshop and 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 proponent and verified by the Head of the Lead Implementing Organization/ Institution/ University.
5. Five (5) bound hard copies of the Project Final Technical Report (FTR) and a soft copy should be submitted to the **Nodal Officer, NMHS-PMU, GBP NIHE HQs, Kosi-Katarmal, Almora, Uttarakhand**.

The FTR is to be submitted into following two parts:

Part A – Project Summary Report

Part B – Project Detailed Report

Following Financial and other necessary documents/certificates need to be submitted 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 Assets Certificate** showing the cost of the equipment in Foreign and Indian currency, Date of Purchase, etc. (with break-up as per the NMHS Sanction Order and year wise).
Annexure IV	**List of all the equipment, assets and peripherals** purchased through the NMHS grant with current status of use including location of deployment.
Annexure V	Letter of Head of Institution/Department confirming Transfer of Equipment Purchased under the Project to the Institution/Department
Annexure VI	**Details, Declaration and Refund of any Unspent Balance transferred through Real-Time Gross System (RTGS) in favor of NMHS GIA General**

DSL: Date of Sanction Letter

0	1	0	4	**2**	**0**	**1**	**8**
d	d	m	m	y	y	y	y

DPC: Date of Project Completion

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

Part A: Project Summary Report

1. Project Description

i.	Project Reference No.	**GBPNI/NMHS-2017-18/SG10**					
ii.	Type of Project	Small Grant	X	Medium Grant		Large Grant	
iii.	Project Title	Identification hydropower sites and critical glacial lakes for sustainable water resource management in Himachal Pradesh.					
iv.	State under which Project is Sanctioned	Himachal Pradesh					
v.	Project Sites (IHR States covered) (Maps to be attached)	Himachal Pradesh					
vi.	Scale of Project Operation	Local		Regional	X	Pan-Himalayan	
vii.	Total Budget/ Outlay of the Project	0.46 (in Cr)					
viii.	Lead Agency	Indian Institute of Technology Indore					
	Principal Investigator (PI)	Dr. Nitin Joshi					
	Co-Principal Investigator (Co-PI)	Dr. Manish Kumar Goyal					
ix.	Project Implementing Partners	Indian Institute of Technology Jammu					

	Key Persons / Point of Contacts with Contact Details, Ph. No, E-mail	Dr. Manish Kumar Goyal, mkgoyal@iiti.ac.in, +91-9435880989 Dr. Nitin joshi, nitin.joshi@iitjammu.ac.in, +91-9479446050

2. Project Outcomes

2.1. Abstract (not more than 500 words) [it should include background of the study, aim, objectives, methodology, approach, results, conclusion and recommendations).

Background: Quantification of renewable natural resources on a global scale suggested about the presence of enormous resources in the Himalayas, these resources are mostly dominated by the presence of geopotential elevation and presence of high amount of precipitation. A combination of factors (elevation and precipitation) which when utilized with caution can help us generate a large amount of energy but can also trigger hazards such as landslides, avalanche and Glacial Lake Outburst Flood (GLOF).

Objectives/ Aim: Following are the objectives of the study

1 Using geospatial techniques and hydrological models to access hydropower potential zones for establishing small hydropower projects (SHPs)

2 Hotspot analysis of glacial lakes and estimate the water hazard associated with GLOF (which includes Steep lake front area determination, lake classification, lake expansion, potential downstream impact assessments etc).

3 To map water use patterns and livelihood linkages and adaptation strategies

Methodology: The present study developed a novel algorithm to assess the suitability of site for run-off river hydropower generation based on GIS analysis, hydrological models and multicriteria decision-making analysis. Furthermore, the study also developed a framework to assess the susceptibility of glacial lakes to outburst. The criteria for identifying the lake dangerous includes susceptibility to avalanche and landslides, potential flood volume, distance to glaciers, elevation, stability of slopes and potential downstream impact. A remote sensing-based hazard and risk assessment was performed on these lakes. The potential number of buildings, bridges, and hydropower systems that could be inundated by GLOF in each lake were quantified.

Conclusion: Remote sensing can be utilized to assess the suitability of remotely located sites for hydropower generation and can also be used to assess critical glacial lakes. The study identified 11 sites for potential hydropower generation in the Beas river basin. The study identified 329 glacial lakes of size greater than 0.05 km2 in the Indian Himalayas. Lake size distribution of these lakes revealed that 129 (39%) lakes were smaller than 0.1 km^2, 178 (54%) had size ranging between 0.1 km^2 to 0.5 km^2 and only 22 (7%) were found to be greater than 0.5 km^2 In 1993, the area covered by these lakes was 56.8 ± 15.69 km^2 which increased to 65.80 ± 4.37 km^2 by 2018, i.e., a 15.84 % increase in lake area over 25 years. Analysis for entire India suggested a total of 23 lakes were identified as very high risk lakes and 50 as high-risk lake. Jammu and Kashmir and Ladakh consist of the highest number of very high downstream impact lakes, followed by Sikkim, Uttarakhand, Himachal Pradesh and lastly Arunachal Pradesh, which has no lake that shows very high downstream impact. Livelihood survey suggested that the major source of income in the hilly regions defines the adaptation and mitigation capabilities of the population.

Recommendations*:* Field assessments are recommended before implementing any procedures (such as dam construction or lake lowering)

2.2. Objective-wise Major Achievements

S. No.	Objectives	Major achievements (in bullets points)
1.	Using geospatial techniques and hydrological models to access hydropower potential zones for establishing small hydropower projects (SHPs);	Developed novel algorithm to assess the suitability of site for run-off river hydropower generation. The study identified 11 sites for potential hydropower generation in the Beas river basin using hydrological model and multi-criterion descision making tools.
2.	Hotspot analysis of glacial lakes and estimate the water hazard associated with GLOF	Developed framework to assess the susceptibility of glacial lakes to outburst. A remote sensing-based hazard and risk assessment was performed on these lakes The potential number of buildings, bridges, and hydropower systems that could be inundated by GLOF in each lake were quantified Created google earth based inventory of glacial lake and identified 329 glacial lakes of size greater than 0.05 km2 in the Indian Himalayas In 1993, the area covered by these lakes was 56.8 ± 15.69 km2 which increased to 65.80 ± 4.37 km2 by 2018, i.e., a 15.84 % increase in lake area over 25 years Analysis for entire India suggested a total of 23 lakes were identified as very high risk lakes and 50 as high-risk lake
3.	To map water use pattern and livelihood linkages and adaptation strategies.	To carry out livelihood survey in 2 villages of Himachal Pradesh Conducted workshop to increae awareness towards increasing the water use efficiency.

2.3. Outputs in terms of Quantifiable Deliverables*

S. No.	Quantifiable Deliverables*	Monitoring Indicators*	Quantified Output/ Outcome achieved	Deviations made, if any, & Reason thereof:
1.	Digital maps of specific locations of the SHPs and	No. of New Database/ Datasets/ Maps/	Identified 11 sites for potential hydropower	No

	hydropower potential zones in the Beas river basin	Templates generated on the identified dynamics (No.) viz., Geospatial techniques; Hydrological Models; Water use patterns; etc.;	generation. Digital maps ere generated.	
2	Quantitative maps of critical glacial lakes and the water hazard associated with GLOF		Identified 329 glacial lakes of size greater than 0.05 km2 in the Indian Himalayas GIS/Google earth based inventory of the glacial lakes were created. Analysis for entire India suggested a total of 23 lakes were identified as very high risk lakes and 50 as high-risk lake	Entire Himalayan region was covered to make study more comprehensive.
3	Livelihood survey assessment	Field survey in remote villages	Assessment report on livelihood for Himachal Pradesh	No

(*) 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/ Attachment
1.	New Methodology developed	GIS based hydropower location identification	
2.	New Models/ Process/ Strategy developed	Framework to identify critical glacial lake	
3.	New Species identified	Nil	-
4.	New Database established	Google earth based glacial lake inventory of Himalayan region	https://agupubs.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1029%2F2019WR026533&file=wrcr24558-sup-0003-2019WR026533-ds01.kmz

S. No.	Particulars	Number/ Brief Details	Remarks/ Attachment
5.	New Patent, if any		-
	I. Filed (Indian/ International)	Nil	
	II. Granted (Indian/ International)	Nil	
	III. Technology Transfer (if any)	Nil	
6.	Others (if any)	-	-

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	Nil	
2.	Diffusion of High-end Technology in the region	Nil	
3.	Induction of New Technology in the region	Nil	
4.	Publication of Technological / Process Manuals	4 publications	
	Others (if any)		

4. New Data Generated over the Baseline Data

S. No.	New Data Details	Status of Existing Baseline	Additionality and Utilisation New data
1	Glacial lake inventory of Himachal Pradesh	Glacial lake inventory developed for Himachal Pradesh for the year 1993, 2000, 2010 and 2018	Various glaciological studies
2	Identification of potential hydropower sited for SHP in Beas river basin	Identified 11 sites for potential hydropower generation. Digital maps ere generated.	

5. Demonstrative Skill Development and Capacity Building/ Manpower Trained

S. No.	Type of Activities	Details with number	Activity Intended for	Participants/Trained			
				SC	**ST**	**Woman**	**Total**

1.	Workshops	2	1) Address the hydropower potential of Himachal Pradesh and demonstrate the risk associated with glacial lakes 2) Water management in hilly areas for sustainable development 3) Sustainable water resources management in the himalayan region				
2.	On Field Trainings	-	-				
3.	Skill Development	-	-				
4.	Academic Supports	1	Funding contribution for the PhD of Mr. Saket Dubey				
	Others (if any)	-	-				

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

S. No.	Linkages /collaborations	Details	No. of Publications/ Events Held	Beneficiaries
1.	**Sustainable Development Goal (SDG)**	Identified 11 sites for potential small hydropower generation.		
2.	**Climate Change/INDC targets**	Identified risks associate with GLOF and changes in glacial lake over indian Himalayas		
3.	International Commitments	Nil		
4.	Bilateral engagements	Nil		
5.	National Policies	Nil		
6.	Others collaborations	Nil		

7. Project Stakeholders/ Beneficiaries and Impacts

S. No.	Stakeholders	Support Activities	Impacts
1.	Gram Panchayats	Nil	
2.	Govt Departments (Agriculture/ Forest)	Workshops	

3.	Villagers	Nil	
4.	SC Community	Nil	
5.	ST Community	Nil	
6.	Women Group	Nil	
	Others (if any)	Nil	

8. Financial Summary (Cumulative)

S. No.	Financial Position/Budget Head	Funds Received	Expenditure/ Utilized	% of Total cost
I.	Salaries/Manpower cost	936000	1208401	25.8
II.	Travel	400000	195668	4.2
III.	Expendables &Consumables	350000	74745	1.6
IV.	Contingencies	165000	71315	1.5
V.	Activities & Other Project cost	400000	41000	0.9
VI.	Institutional Charges	0	0	0.0
VII.	Equipments	1450000	1338244	28.5
	Total	3701000	2929373	62.4
	Interest earned	9963		
	Grand Total	3710963		

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

9. Major Equipment/ Peripherals Procured under the Project** (if any)

S. No.	Name of Equipments	Cost (INR)	Utilisation of the Equipment after project
1.	Mike Flood 1D	327994	With IIT Jammu for research work
2.	Mike Flood 2D	871440	
3.			
4.			
5.			

Details should be provided in details **(*ref* Annexure III &IV).

10. Quantification of Overall Project Progress

S. No.	Parameters	Total (Numeric)	Remarks/ Attachments/ Soft copies of documents
1.	IHR States Covered	1	Himachal Pradesh
2.	Project Site/ Field Stations Developed	-	-
3.	New Methods/ Modeling Developed	2	
4.	No. of Trainings arranged	-	-
5.	No of beneficiaries attended trainings	-	-
6.	Scientific Manpower Developed (Phd/M.Sc./JRF/SRF/ RA):	1	PhD of Mr. Saket Dubey at IIT Indore
7.	SC stakeholders benefited	-	-
8.	ST stakeholders benefited	-	-
9.	Women Empowered	-	-
10.	No of Workshops Arranged along with level of participation	3	
11.	On field Demonstration Models initiated	.... (attach maps about location & photos)	
12.	Livelihood Options promoted	2	Capacity building in 2 remote villages
13.	Technical/ Training Manuals prepared	-	-
14.	Processing Units established	.... (attach photos)	-
15.	No of Species Collected	-	-
16.	New Species identified	-	-
17.	New Database generated (Types):	1	Glacial lake inventory
	Others (if any)		

11. Knowledge Products and Publications:

S. No.	Publication/ Knowledge Products	*Number*		*Total Impact Factor*	*Remarks/* Enclosures
		National	International		
1.	Journal Research Articles/ Special Issue:	1	3	12.46	
2.	Book Chapter(s)/ Books:	-	-	-	-
3.	Technical Reports	1	-	-	-
4.	Training Manual (Skill Development/ Capacity Building)	-	-	-	-
5.	Papers presented in Conferences/Seminars	1	1	-	-
6.	Policy Drafts/Papers	-	-	-	-

S. No.	Publication/ Knowledge Products	*Number*		*Total Impact Factor*	*Remarks/* Enclosures
		National	International		
7.	Others:	-	-	-	-

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

12. Recommendation on Utility of Project Findings, Replicability and Exit Strategy

Particulars	Recommendations
Utility of the Project Findings	1) Identified hydropower locations can be used to generate hydropower. This would be used to generate better livelihood oppotrutnies and development of the region. 2) Developed the glacial lake inventory for Indian Himalayan region. 3) Identified critical glacial lake and a remote sensing-based hazard and risk assessment was performed on these lakes 4) The potential number of buildings, bridges, and hydropower systems that could be inundated by GLOF in each lake were quantified. The risk associated proper monitoring could help in minimizing the associated risk of GLOF
Replicability of Project	Developed method and framework can be applied to other IHR states The google earth based glacial lake inventory is made available and it can be used for regular monitoring the critical lakes.
Exit Strategy	The GIS datasets generated in theis study is made available freely. Thease datasets can be used to monitor critical glacial lakes and minimize the downstream impacts associated with the possible GLOF events.

Dr. Nitin Joshi
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(**PROJECT PROPONENT/ COORDINATOR**)

(**HEAD OF THE INSTITUTION**)

(Signed and Stamped)

Place: Jammu
Date: 8./12/2022

PART B: PROJECT DETAILED REPORT

The Detailed report should include an Executive Summary and it should have separate chapters on (i) Introduction (ii) Methodologies, Strategy, and Approach (iii) Key Findings and Results (iv) Overall Achievements (v) Project's Impacts on IHR (vi) Exit Strategy and Sustainability (vii) References and (viii) Acknowledgement (It should have a mention of **a** 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 project, Manual of Standard Operating Procedures (SOPs) developed, Technology developed/Transferred etc should be enclosed as Appendix.

1 EXECUTIVE SUMMARY

In India, energy demand has increased considerably during last few decades. In order to meet this increasing energy demand sustainably, there is a need to move towards low-carbon energy sources. Himalayan water towers have a huge potential for generating clean and renewable energy. Small-scale hydropower projects (SHP) could provide clean and renewable energy and have a minimal impact on ecology and biodiversity. Therefore the present study uses hydrological model and geospatial techniques to identify hydropower potential zones for establishing small hydropower projects. A generalized methodology was assessed to determine hydropower potential zones in hilly catchments using hydrological model (SWAT) to measure the stream flow at different segments in the watershed. This methodology aims to determine the potential sites in the watershed having a capacity to develop at least 4MW of hydropower even at 90% dependable flow in the stream considering 50% efficiency of the system. Five parameters (Restriction for national parks, evapotranspiration, Euclidean distance from roads, LULC, and soil) were considered to obtain the priority value for the feasibility of potential sites for hydropower generation. a multi-criteria decision-making tool namely Analytical hierarchy process (AHP) was utilized to identify the sites. In this process relative importance of each parameter is assessed with respect to every other parameter and then priority matrices are prepared to determine the weightage of each parameter

The watershed of the Beas River, Himachal Pradesh, has high potential for the development of small hydropower plants with a total of 11 sites found satisfying the above criteria. The watershed was calibrated for daily discharge using SUFI-2 algorithm and the performance evaluation parameters showed satisfactory results. An attempt to consider feasibility of construction, operation and maintenance of hydropower structures was applied using Analytic Hierarchy Process (AHP) to assign weights to different parameters based on their significance in the Beas River watershed. The weighted overlay analysis method classified the watershed into 4 zones describing them from most suitable for hydropower site to least suitable.

Global warming has resulted in glacier retreating and snowmelt which further results in the formation of glacial lakes. This glacial lakes when breach could result in glacial lake outburst flood (GLOF) causing flash flood downstream. GLOF hazard has become a prominent concern for harnessing hydropower potential of the Himalayan regions. Therefore it is important to identify the hotspot, monitor the health of these lakes and estimate the potential risk associated with GLOF. To assess the spatiotemporal change of lake dimensions, a glacial lake inventory for the years 1993, 2000, 2013, and 2018 was prepared using LANDSAT multispectral images. In this study, we first identified 329 glacial lakes of size greater than 0.05 km^2 in the Indian Himalayas, and then a remote sensing-based hazard and risk assessment were performed on these lakes. A new combination of parameters was applied to identify critical lakes which incorporates the determination of moraine's stability using the concept of Potential flood volume (PFV); i.e., the maximum volume of water that could be released if the lake surface is lowered to a level where it eradicates steep lakefront area (SLA). Critical glacial lakes were then assessed for dynamic failures such as inflow of an avalanche, rockfall or upstream GLOF, and potential downstream impact by stochastic simulations using monte-carlo least cost path (MC-LCP) method. Further, a stochastic inundation model was applied to quantify the potential number of buildings, bridges, and hydropower systems that could be inundated by GLOF in each lake. Finally, the hazard parameters and downstream impact were collectively considered to determine the risk linked with each lake. Lastly, a livelihood survey in two remote villages of Himachal Pradesh was carried out to understand the water use pattern and assess their adaptation skills in case of disasters.

Lake size distribution of these lakes revealed that 129 (39%) lakes were smaller than 0.1 km^2, 178 (54%) had size ranging between 0.1 km^2 to 0.5 km^2 and only 22 (7%) were found to be greater than 0.5 km^2 In 1993, the area covered by these lakes was 56.8 ± 15.69 km^2 which increased to 65.80 ± 4.37 km^2 by 2018, i.e., a 15.84 % increase in lake area over 25 years. Analysis of the entire India suggested a total of 23 lakes were identified as very high-risk lakes and 50 as high-risk lakes. Jammu and Kashmir and Ladakh consist of the highest number of very high downstream impact lakes, followed by Sikkim, Uttarakhand, Himachal Pradesh, and lastly Arunachal Pradesh, which has no lake that shows very high downstream impact. Elevation dependence of lakes revealed that all the very high-hazard lakes were lying above the elevation range of 4000 m. Most of the lakes with very high downstream impact were located below the elevation of 5000 m except for 3 lakes in Uttarakhand and 1 lake in Sikkim. The lakes present above the elevation of 5000 m.a.s.l were predominantly ice-dammed and moraine-dammed. There was no apparent trend between risk and elevation of lakes. The potential flood volumes associated with various triggering mechanisms were also measured and were used to identify the lakes with the most considerable risk, such as Shakho Cho and Khangchung Tso.

Modeling of dynamic failure revealed that out of 329 lakes, 36 (11%) are susceptible to an avalanche entering the lake, 52 (16%) are susceptible to a rockfall, and 37 (11%) are susceptible to an upstream GLOF. It was also observed that only 8 (22%) out of 36 avalanches and 15 (29%) out of 52 rockfalls were entering the lake with a direct hit which implied that most of the mass entering the lake was along its minor axis. Concerning moraine stability, 247 (75%) lakes have an unstable moraine (average SLA angle >10°), and 80 (24) have ice cores present in their damming structure. Assessment of lake expansion revealed that from 1993 to 2018, 64 (19.5%) lakes significantly expanded and 6 (2%) lakes significantly drained. Modeled hazards were used to classify the lakes into various hazard categories; that is, 28 lakes were categorized as very high hazard, 50 as high hazard, 198 as moderate hazard, and 53 as low hazard. Sikkim has the maximum number (20) of very high-hazard lakes followed by the union territories of Ladakh, and Jammu and Kashmir (4). The state of Himachal Pradesh and Arunachal Pradesh contains two very high-hazard lakes each, whereas Uttarakhand has no very high-hazard lake.

There are 217 lakes that inundated at least 20 buildings while 138 inundated at least 100 buildings; nine lakes were identified to inundate more than 1000 buildings. Six lakes inundating more than 1000 buildings were located in the union territories of Jammu and Kashmir and Ladakh whereas three lakes were located in Uttarakhand. The number of buildings inundated varied from 0 to 2010, with a median number of 54. The number of lakes that inundated at least one hydropower system was 67 whereas the number of lakes that inundated two hydropower systems was 15. The number of bridges inundated ranged from 0 to 17 with a median value of 4. This study is anticipated to support stakeholders and decision-makers in identifying critical glacial lakes and make well-informed decisions related to future modeling efforts, field studies, and risk mitigation measures. The livelihood survey suggested that the major source of income in the hilly regions defines the adaptation and mitigation capabilities of the population.

2 INTRODUCTION

2.1 Background of the Project (max. 500 words)

Climate Change undoubtedly emerged as an eminent phenomenon in the recent past owing to its striking response. Burning of fossil fuels (Ghosh and Mujumdar 2009) for energy production releases heat-trapping pollutants which in turn influence the major drivers of regional precipitation and variability in the heat distribution. To account for this, researchers around the world are intrigued to understand it and come up with the best possible alternative source of energy production which is a sustainable, comparatively less harmful, and renewable resource. Glacier retreat is a well-known outcome caused majorly due to global climate warming. It creates a great level of threat to the environment (Bajracharya et al. 2008;

Kaser et al. 2004; Worni et al. 2013). The warming of the Tibetan plateau and the eastern Himalayas has a high influence on the retreat of Himalayan glaciers. However, the retreat of the individual glacier is a characteristic of its own location and climatic condition. Thinning and retreating of large glaciers such as Bara Shigri, Chadra and Chota Shigri is evident from Previous studies (Berthier et al. 2007; Kulkarni et al. 2005; Wagnon et al. 2007), these retreating glaciers expose over deepenings leading to the formation and expansion of glacial lakes. Glacial lake outburst flood (GLOF) is an event where a rapid discharge of a significant amount of water along with debris occurs because of either breach or overtopping of the damming structure. Development and enlargement of glacial lakes increase the chances of a GLOF event. In addition to this, the majority of these lakes are dammed by unstable and loosely consolidated end-moraines which can generate a breach even with a small instability in the system (Fujita et al. 2013). The downstream impact worsens when the flow path is steep and erodible as in the case of the Kedarnath GLOF event which took place on 16th June 2013, leading to destructive debris flows causing the death of about 4000 people (Allen et al. 2016; Breien et al. 2008; Cui et al. 2011). Many other such events have occurred in the past such as the ice avalanche induced GLOF in lake Palcacocha (Chisolm and McKinney 2018) on 13th December 1941 which destroyed the town Huarez killing around 1800 people, the Dig Cho lake outburst in Nepal in 1985, and so on (Gurung et al. 2017; Rafiq et al. 2019; Somos-Valenzuela et al. 2015). Hence, it is evident that these glacial lakes are potentially dangerous and there is a need to monitor and develop a warning system to plan and adopt mitigation measures.

2.2 Overview of the Major Issues to be Addressed (max. 1000 words)

Hydropower emerges as one solution and if optimally used it can be rendered as a huge potential for providing sufficient energy. However, they come at a heavy expense requiring a huge area for its construction, high head drop, appropriate discharge, and environmental and ecological feedback (World, Greed, and Elgar 2004). Fulfillment of these essential requirements can hamper the design of an economical hydropower plant and the lack of knowledge and resources will reduce the feasibility of the structure as well. To utilize the available resources optimally, the knowledge of potential zone for hydropower assessment is vital which pertains to sufficient water availability, appropriate water head, presence of geologically stable strata, recoverable sediment accumulation, and ease of accessing materials required for the construction of the suitable site. To assess the suitable site location lot of studies have been carried but none of them showed a generalized picture for site suitability analysis, rather, these analyses depicted that the criteria of site selection may differ from one region to another based on the requirements of beneficiaries, availability of resources, cultural influence and sustainable amount of environmental impact. Earlier assessments of potential sites were based on onsite surveys and manual techniques. These methods were time-consuming and tedious. Recent advancements in remote sensing and the proliferation of satellite images enable us to extract potential information regarding the optimal location of hydropower sites.

Additionally, alpine regions are also susceptible to flood events related to outbursts in glacial lakes and most of these glacial lakes are situated in remote locations, it is challenging, unmanageable, and time-consuming to analyse each of these lakes through field studies. Accessibility of chronologically ordered multispectral satellite data enables us to assess the current hazard potential of these glacial lakes, although a clear framework to study these glacial lakes remotely has not been developed.

2.3 Baseline Data and Project Scope (max. 1000 words)

With the recent development in technology, there has been an upsurge in finding efficient ways of optimizing hydropower energy such as identifying the most suitable sites and developing more efficient ways of extraction. The main drivers for this upsurge include increased electricity demand, environmental concerns, and climatic impacts (Majumder et al. 2013). Hydropower is associated with a clean, environmentally less harmful, and secure energy source (World Energy Resources 2015). On one hand, it provides a low-cost energy supply and on the other hand, it acts as an asset in controlling the river flow leading to reductions in upsetting extreme events such as floods and droughts. These multiple benefits have strengthened policy maker's interest in hydropower and have changed the perception of its utility.

The current method of identifying potential hydropower sites relies basically on morphological and metrological information available from government agencies and remote sensing satellites. The elevation information of the Beas River basin was obtained SRTM Digital Elevation Model (30 m spatial resolution). The precipitation and temperature data for running the hydrological model was obtained from Indian Metrological Department (IMD) whereas the data on relative humidity and solar radiation was obtained from Climate Forecast System Reanalysis (CFSR). The data on soil properties were obtained from Food and Agricultural Organization (FAO), USA. The landcover map for the study area was developed using supervised classification on Landsat imageries. Discharge data for calibration and validation of the hydrological model was obtained from Nadaun discharge gauging station, Himachal Pradesh (provided by Bhakra Beas Management board).

Himachal Pradesh, India, is present within North-Western Himalayas and is drained by rivers such as Satluj, Beas, Ravi, Indus, and Chennab. It covers an area of 55627 km^2. The elevation profile of the study area ranges from ~195 to 6558 meters above sea level (m.a.s.l). It is home to 2100 glaciers, covering approximately an area of 3800 km^2 which is ~6.8 % of the state. Recent studies incorporating past imageries have suggested about the increased rate of retreating glaciers in Himachal Pradesh, and as a feedback large number of glacial lakes are formed due to the melting of ice. However, the knowledge of glacial change in Himachal Pradesh is limited in terms of its dimensions (Jha and Khare 2017).

The study on the identification of critical glacial lakes relies on a relatively higher resolution Digital Elevation Model (ALOS PALSAR) to determine the steep lakefront area (SLA) which will be further aided in estimating the potential lowering of the moraine dam in case of a breach. This potential lowering in conjunction with other morphometric characteristics were used to assess the outburst susceptibility of GLOF event for each lake. Hydrodynamic modeling of the most hazardous lakes was based on cross-section and elevation information from high-resolution ALOS Palsar DEM. Digital interpretation for lake delineation was carried out using the Normalised Difference Water Index (NDWI) and plotting NDWI contour plots at an interval of 0.025. The visual interpretation was used in picking the contour values representing the glacial lake boundary. These selected contours were then used to prepare the lake map. Randolph Glacier Inventory 5.0 (RGI version 5) was used as glacier boundaries.

2.4 Project Objectives and Target Deliverables (as per the NMHS Sanction Order)

The project objective based on NMHS sanction order is

Project Objectives	**Quantifiable Deliverables**
• Using geospatial techniques and hydrological models to access hydropower potential zones for establishing small hydropower projects (SHPs); • Hotspot analysis of glacial lakes and estimate the water hazard associated with GLOF; • To map water use patterns and livelihood linkages and adaptation strategies.	• Digital maps of specific locations of the SHPs and hydropower potential zones in the Beas river basin; • Quantitative maps of critical glacial lakes and the water hazard associated with GLOF; • Generating awareness towards increasing the water use efficiency and capacity building of village-level institutions in 2 districts.

3 METHODOLOGIES, STRATEGY, AND APPROACH

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

(1) Methodology for identification of potential hydropower sites

Determination of streamflow

DEM of the study area obtained from satellite-based products was further used to delineate the watershed using the automatic delineation toolbar in the ArcSWAT extension of ArcGIS. Further, the hydrological response units were generated by overlaying DEM, land cover classes, soil map, and slope classes in the HRU definition toolbar of ArcSWAT.

Meteorological data obtained from various IMD grid point stations as well as CFSR data for relative humidity and solar radiation were used as an input to SWAT for the creation of the hydrological model. A flow chart of overall methodology is described in Figure 1. Simulation of the hydrological model was carried out for a period of 31 years from 1983 to 2013, with 4 years for NYSKP (Number of years skipped) which acts as the warm-up period for the model.

Calibration and validation of the SWAT model were carried out using SWAT-CUP. Firstly, sensitivity analysis was applied to find out the sensitive parameters to water balance. Calibration is an adjustment of model parameters based on observation to ensure a similar response over time. In this study, a semi-automated method of finding the solution, the SUFI-2 (Sequential Uncertainty Fitting) algorithm, in SWAT-CUP has been used for calibration and validation purposes. According to SUFI-2, Calibration can be done in two ways: The first approach is the deterministic approach in which the trial and error method is applied for parameter values to get a response similar to observed results. Whereas for the study, the second approach which is the stochastic approach, is applied where an algorithm based on Latin hypercube sampling is used to assess the best set of parameters for the study area. Calibrated watershed model is then used to assess the streamflow in each stream. Flow duration curves are plotted for each stream and 50%, 75%, and 90% dependable flows (available for at least 50%, 75%, and 90% time of the year) are assessed for hydropower potential estimation.

Head drop along the stream is determined using focal statistics. This is a tool in ArcGIS that calculates the statistics around a specified region for each cell of a raster. Streamline is determined for the study area using DEM. Streamline feature is converted into raster using polyline to raster tool. Each cell of the river raster is given a value 1 whereas other cells are marked as no data. The elevation value is multiplied to each river cell using the raster calculator. Focal statistics (Minimize) is applied along the river raster searching within 5 cells for minimum value. Head drop is calculated by subtracting DEM values by minimized raster.

Determination of hydropower potential sites

All the locations where at least 4MW capacity is available at 90% dependable flow in the stream are chosen as hydropower potential sites. The steps involved include:

- Calculation of flow duration curve for each stream in the watershed.
- Determination of 50%, 75%, and 90% dependable flow in each stream
- Above determined flow values are multiplied with head drop along the stream.
- The hydropower potential at a specified location can be assessed using the equation.

  $p = \rho g Q h$

  Where p represents power, g represents acceleration due to Gravity Q is flow and h is head drop along the stream. Please note that it was assumed that the system is 50 % efficient.

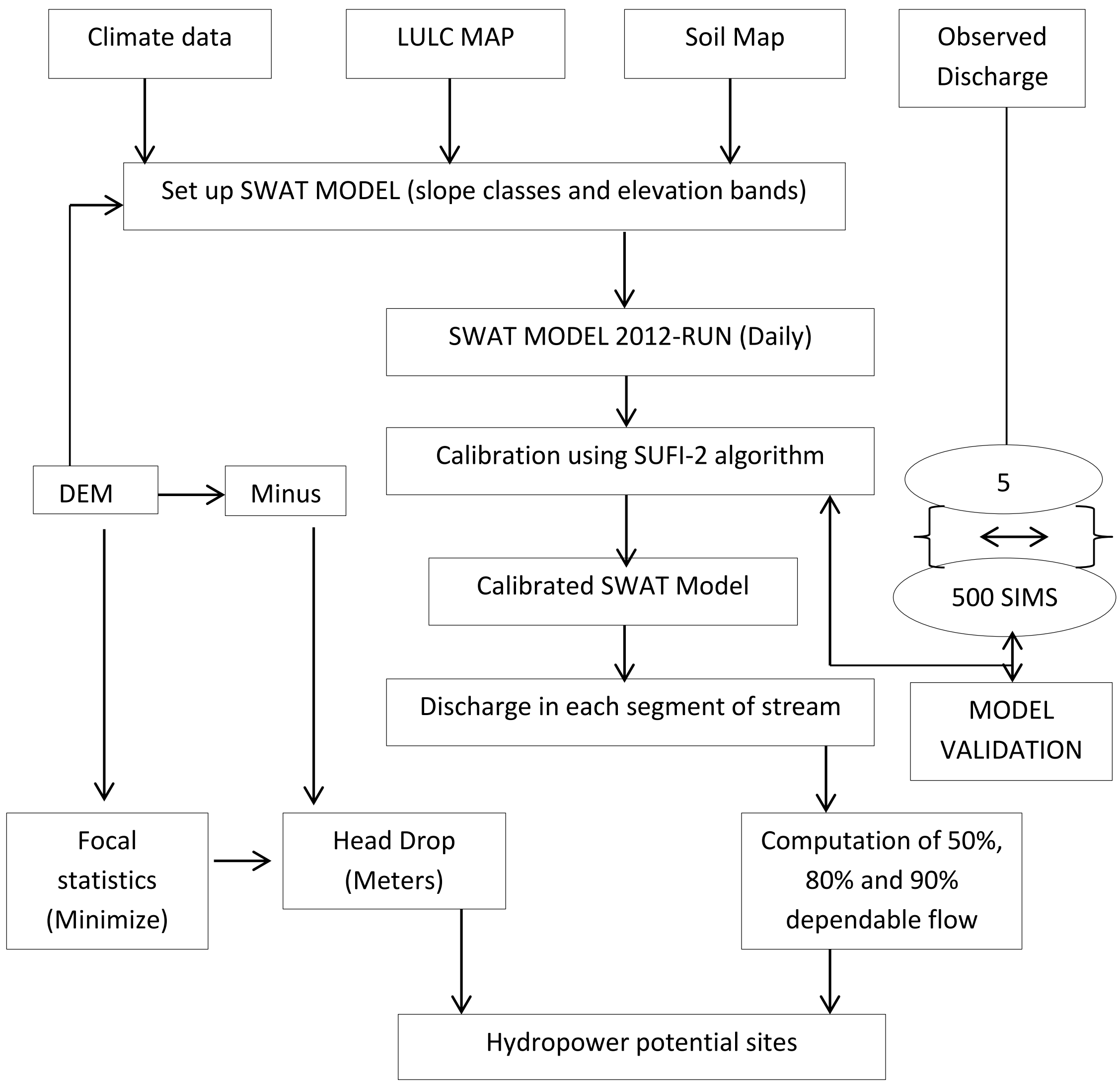

Figure 1. The methodology applied for the determination of hydropower potential sites.

Later identified points with sufficient hydropower potential were prioritized based on the weighted overlay analysis, weights were assigned to various parameters. In the study, Analytic hierarchy process (AHP) is used to determine the weight of each parameter. AHP gives the relative weight of different parameters and break down a problem into a hierarchy and then solve by AHP steps (Saaty, 1971). This method also checks on the consistency of the judgments. Further details on various parameters and weights for prioritizing the hydropower potential site is available in section 3.5.

(2) Methodology for identification of critical glacial lakes

The overall method for the identification of critical glacial lakes is shown in Figure 2.

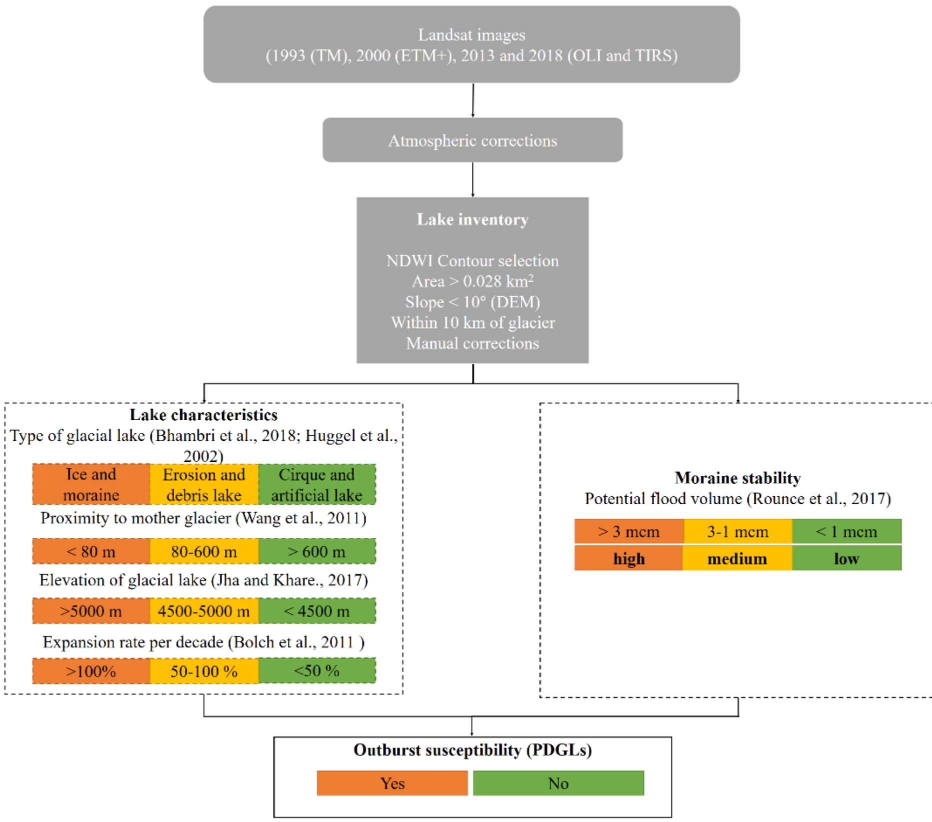

Figure 2. The workflow of the proposed methodology for the identification of potentially dangerous glacial lakes.

Uncertainty estimation

The coarse (~30 m) spatial resolution of Landsat images introduces uncertainties in the lake delineation. This uncertainty was estimated based on the method used in previous studies (Byers et al. 2019; Jha and Khare 2017; Rounce et al. 2017; Xin et al. 2012). These studies assume that the coastline of glacial lakes passes mid-way between pixels.

The uncertainty values obtained from this method ranged from 8.75 % for larger lakes to 51.58 % for smaller lakes. This overestimation for smaller lakes arose because a large number of pixels were considered as boundary pixels. To overcome this, we applied manual corrections to make sure that mapped boundaries exactly overlap the exact boundaries, specifically for smaller lakes, and hence to interpret the uncertainty meaningfully the lakes having size > 0.1 km^2 were only considered for uncertainty estimation. The average uncertainty for these lakes was calculated as 13.574%, which was slightly on the higher side but was comparable with previous studies (Fujita et al. 2013; Shuklaet al. 2018; Wang et al. 2013).

Estimation of moraine's stability

To determine the moraine's stability, a method suggested in Fujita et al., 2013 was utilized which is based on the concept of eradication of the steep lakefront area (Figure 3). It estimates the PFV based on potential lowering (H_p) of the dam which can be calculated by evaluating the steepest depression angle from the lake surface to any area within 1 kilometer of the lake surface, with a threshold angle of 10°. The potential flood volume was then calculated by multiplying H_p by the lake area considering cylindrical bathymetry for the lake. For some lakes, the potential lowering was observed to be greater than the mean depth of the lake for such cases the potential flood volume was calculated by multiplying the area by min of H_p or D_m, where D_m represents mean lake depth which was computed based on the equation given by $55 \times (\text{lake area } (km^2))^{0.25}$. This assumption was applied as lake bathymetry cannot be calculated using remote sensing.

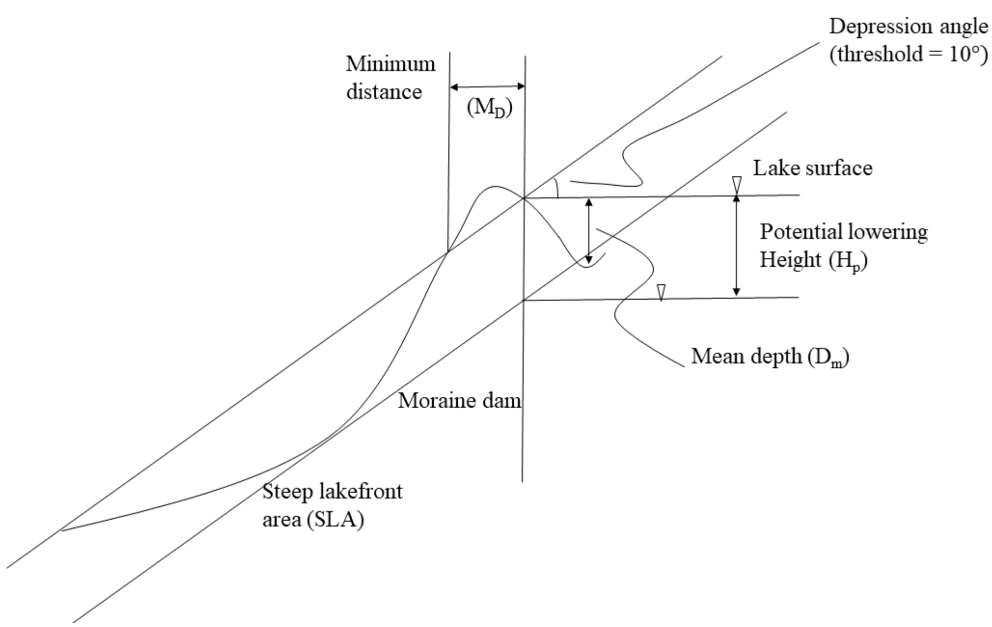

Figure 3. Steep lakefront area (SLA) concept, mean depth (D_m), Potential lowering height (H_p), and minimum distance (M_D). Threshold angle 10° defined from (Fujita et al. 2013; Rounceet al. 2017). Figure reconstructed (Fujita et al. 2013).

Identification of potentially dangerous glacial lakes (PDGLs)

With the current state of art remote sensing technology, it is still not feasible to assess the prediction of specific occurrences of a GLOF event. Although many studies (Byers et al. 2019; Huggel et al. 2002; Rounce et al. 2017; Somos-Valenzuela et al. 2015; Westoby et al. 2014; Worni et al. 2014) have tried identifying potentially dangerous lakes using different criteria, the selection of most important criteria varies for individual lake condition, which induces subjectivity into marking a lake potentially dangerous. Field base assessment may still be the best way to assess a glacial lake condition but taking into consideration lakes' remote location and harsh weather conditions, a field study of each lake may be cumbersome and infeasible. Parameters assessed in the present study to mark a lake as potentially dangerous are basic lake characteristics in conjunction with moraine's stability parameter using the concept of SLA as it estimates the flood volume in case of a breach, irrespective of its triggering mechanism.

Lake Characteristics

1. Type of glacial lake - glacial lakes are classified as moraine-dammed lake, ice-dammed lake, glacier erosion lake, cirque lake, debris-dammed lake and artificial lake. Moraine-dammed lakes and ice-dammed lakes are usually the most dangerous and unstable structures considering the unpacked damming structure. Past studies also signify that these lakes have shown the highest number of GLOF events (Clague 2002), followed by the glacier erosion lake and the debris dammed lakes. Cirque lakes are considered the least dangerous as they have closely packed damming structures with marginal variation over time.
2. Proximity to parent glacier – ice calving and avalanches have caused a large number of GLOF events due to the formation of the tsunami-like wave which overtops or breaches the damming structures. The probability of ice calving and avalanche increases with the increase in
3. the proximity of the lake to its parent glacier.
4. Elevation of the glacial lake – the presence of glacial lake at higher elevation provides higher potential to flooding water which eventually leads to higher runout length and a larger amount of debris flow along its path (Khanal et al. 2015).
5. Expansion rate – most of the glacial lakes that have undergone a GLOF event have shown a significant enlargement over time. Additionally, expansion of the glacial lake changes the damming condition by shifting the damming structure from the pre-consolidated dam to the unconsolidated loosely packed damming structure (Ageta et al. 2000; Fujita et al. 2009; Rounce et al. 2017).

Moraine's stability

6. Potential Flood volume – downstream impact of a GLOF event is closely related to potential flood volume as it significantly influences the amount of debris flow, runout length, and inundation area

Dynamic failure and downstream impact

Lakes identified as PDGLs were assessed for dynamic failure using avalanche, rockfall, and upstream lake GLOF trajectories. Avalanche and rockfall trajectories were defined using the approach in Rounce et al. (2016) where the avalanche and rockfall prone areas were defined as any glaciated region with slope between 45°- 60° and non-glaciated regions with slopes greater than 30°, respectively. These avalanches and rockfall prone areas were then used to estimate the maximum avalanche and rockfall prone areas using a variable kernel filter with 100% threshold, i.e., a 1×1 pixel is checked if it is prone, which is then extended to a 2×2 grid, the process is continued until the grid fails to meet the 100% threshold. Later, due to limited availability of the data on avalanche and rockfall depths. An avalanche thickness of 50 m and a rockfall thickness of 4 m were assumed to determine the maximum avalanche and rockfall volumes. These volumes were then used to determine the trajectories of dynamic flow using the equation given by Huggel et al. (2004), i.e., Equation 1.

$$\tan(\alpha) = 1.11 - 0.118\log(V) \qquad (1)$$

Where V denotes the maximum volume of inflow and α denotes the average slope trajectory. These slope trajectories were then used with a flow direction algorithm to determine the end point of avalanche and rockfall volume flow. The minimum average slope trajectory for avalanche and rockfall were assumed to be 17° and 20°, respectively (Rounce et al. 2016). Hydrodynamic modeling of Chandratal lake was carried out using the Mike model. Various breach scenarios were considered to assess the uncertainties associated with potential downstream impact.

3.2 Preparatory Actions and Agencies Involved (max. 1000 words)

Data obtained from various government agencies and remote sensing satellites were gap filled and bias-corrected. Various tools in ArcGIS were used to preprocess the data for hydrological modeling and application of the AHP process. Datasets available at different spatial resolutions were resampled to match the grid size of the study. Google-earth was used to assess the potential downstream impact of flood events. IMD provided the metrological data related to precipitation and temperature. Bhakra Beas Management Board provided the data on discharge for Nadaun gauging station in Himachal Pradesh.

USGS, VERTEX, and CFSR provided satellite and reanalysis products. To decimate the findings of the study a workshop on “Identification of hydropower sites and critical glacial for water resource management in Himachal Pradesh” on 22 Feb 21 in Shimla.

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

(1) Details of scientific data collected for the determination of potential hydropower sites

The Digital Elevation Model (DEM) of any area is comprised of longitude, latitude, and elevation data in a gridded format at a specific resolution which can be used to delineate the watershed based on topography.

Soil Map at 10 km spatial resolution at a scale of 1:5,000,000 was obtained from Food and Agriculture Organization (FAO) of United Nations. The acquired data contains detailed soil information which includes bulk density, organic carbon content, particle size distribution as well as available water capacity. The study area is mainly comprised of loamy soil. For this study area, more detailed and broadly classified soil maps were available but because of the high level of details required about the soil type and their properties by SWAT, a relatively coarser soil map obtained from FAO was used which classifies Beas River watershed into 5 broad classes namely Dystric Cambisol, Eutric Cambisol, Eutric Regosol, lithosol, orthic luvisol along with the glacier.

Land use and land cover is an important aspects of a watershed. It shows the type of cover that is present over the land such as forest, wetland, water body, impervious surface etc. These are usually obtained by applying complex classification methodologies over satellite imageries. LULC map is created by classifying the satellite data which can be accomplished using supervised as well as unsupervised classification techniques. In the first technique, operators classify an area or group of pixels that belong to one or more categories of specific land use/land cover. The other is the unsupervised classification method in which the operator determines how many different classes are described and classifies all data into the statistically created classes using a sophisticated set of algorithms.

For this study supervised classification of satellite imageries was applied to develop a well-defined LULC map of the study area. The land use and land cover map was prepared using 7 bands obtained from cloud-free LANSAT 8 imageries. https://glovis.usgs.gov/. Using supervised classification, the study area was classified into 10 different LULC classes.

The slope class is also required to be defined in SWAT for the creation of HRUs and for the study; Beas watershed was divided into 5 slope classes i.e. 0-10, 10-20, 20-30, 30-40, and 40-9999.

Land use, soil classes, and slope classes are overlaid on each other to generate hydrological response units (HRU). HRU is a unique combination of land use, soil, and slope which gives a homogeneous response to hydrology. A total 86 number of sub-watershed are created and these sub-watersheds are further divided into 601 numbers of HRUs. Runoff and other objective functions are calculated at HRU level and then routed towards the sub-basin outlet.

SWAT requires the weather database to be formatted in a particular format. In this study, precipitation data was acquired from the Indian Meteorological Department which was prepared using interpolation at a spatial resolution of 0.25° and temperature data from IMD at the resolution of 0.5° whereas other datasets (relative humidity, solar radiation, and wind) required by the SWAT were taken from Climate Forecast System Reanalysis (CFSR).

Average annual rainfall in the state of Himachal Pradesh is about 850 mm out of which more than 80% occurs during the southwest monsoon (Hp 2015) which usually sets up around second week of June and continues till second week of October. Beas River is dependent upon rainfall and snowmelt for its stream flow. In this study, rainfall data is collected for a period of 31 years from 1983-2013. For the calibration and validation of the model, the discharge gauging station (G&D) located at Nadaun is used.

(2) Details of scientific data collected for the identification of critical glacial lakes

The dataset includes Landsat satellite imageries and digital elevation models. Landsat series data provides a long and continuous record of satellite-based observations at a medium spatial resolution, which makes it an important tool for monitoring global change (Deo et al. 2017; Wulder et al. 2016). This no-cost publically available multispectral dataset can be obtained from https://glovis.usgs.gov/ and for the present study, the data was retrieved for the year 1993, 2000, 2013, and 2018. The data for the year 1993 and 2000 was chosen considering the first cloud-free images for Himachal Pradesh from Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+) sensors, respectively during the period of least snow cover (September, October, and November for the Himalayas). The data for the year 2013 and 2018 were retrieved from Landsat 8 Operational land imager (OLI) sensors.

High resolution (spatial resolution= 12.5 m) radiometrically terrain corrected digital elevation model (DEM) available from Alaska satellite facility collected by ALOS Phased Array type L-band Synthetic Aperture Radar (Kimura and Ito 2000) was retrieved from https://vertex.daac.asf.alaska.edu/#. A total of 24 tiles covered Himachal Pradesh which was then merged together to obtain information such as elevation (figure 4), slope, SLA, inundation map etc.

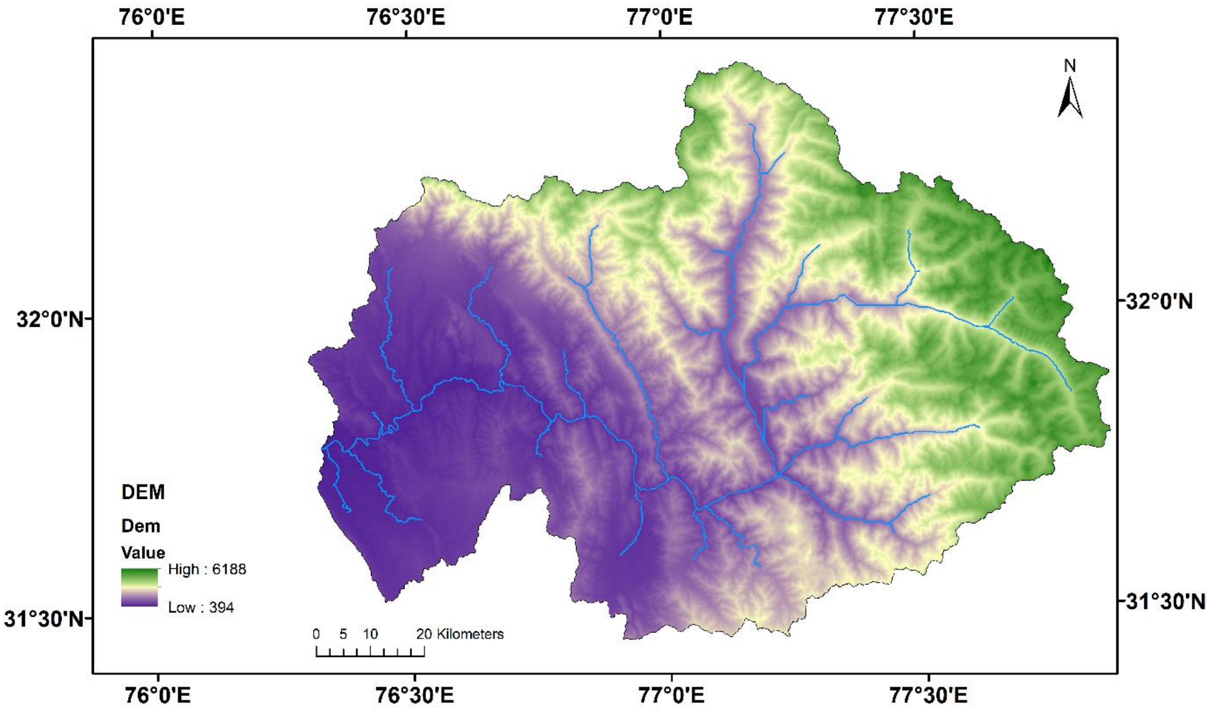

Figure 4. Digital elevation model of Beas River watershed.

3.4 Details of Field Survey arranged (max 500 words)

Field surveys were carried out in two remote villages of Himachal Pradesh. The questionnaire for the survey is as follows

<u>Livelihood Survey Questionnaire</u>

1. Name:
2. Occupation:
3. Household size (HS)
4. Age (AG)
5. Education (ED)
6. Farming years (FY)
7. Labor input (LI)
8. Training (TR)
9. Number of land blocks (NL)
10. Cultivated land area (LA)
11. Land quality (LQ)
12. Housing Type (HT)
13. Homestead area (HA)
14. Housing years (HY)

15. Current value of the house (CV)
16. Distance to markets (DM)
17. Distance to agriculture fair (DF)
18. Agricultural income (AI)
19. Nonagricultural income (NI)
20. Number of telephone contacts (TN)
21. Number of relatives (NB)
22. Village cadres (VC)
23. Time to the furthest household in a village (TF)
24. Sources of water supply:
25. Quality of water supply:
26. Duration of water supply:
27. Number of trips to collect water:
28. Time taken for trips:
29. Awareness about rain water harvesting:
30. Awareness of climate change:
31. Awareness of GLOF:
32. Water demand and supply gap:

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

Using geospatial techniques and hydrological models to access hydropower potential zones for establishing small hydropower projects (SHPs);

The identification of hydropower sites was based on a physically based hydrological model coupled with topographical information. The potential sites were then classified based on AHP analysis. Since there is some sort of subjectiveness inherent in AHP method, the information on various selected parameters are provided here

Weighted overlay analysis of thematic layers

Weighted overlay analysis is carried out to assess the feasibility of the hydropower site at the specified location. This study also tries to priorities the practicability of each specified location with respect to other sites.

1. In the study, 5 parameters are considered for the identification of suitable sites (LULC, soil, evapotranspiration, restriction to national parks, and Euclidean distance from road). These parameters have been selected based on their influence on the selection of hydropower potential sites. The overall methodology describing weighted overlay analysis is shown in Figure 5. The procedure adopted for the preparation of these layers are as follows-
    - **Soil:**. HSG classification for different soil groups is described in Table 1
    - **LULC:** Described in previous section.
    - **Euclidean distance from road:** Road map containing major roads of Himachal Pradesh was obtained from https://mapcruzin.com/free-india-country-city-place-gis-shapefiles.htm which was then used with Euclidean distance tool to determine the distance of various potential sites from roads.
    - **Restriction to national parks:** Map of national parks in the study area was obtained from https://mapcruzin.com/free-india-country-city-place-gis-shapefiles.htm. The areas included in the national parks were given less priority as government restricts any type of constructions in the reserved forest.
    - **Evapotranspiration:** Prepared from the results obtained from calibrated watershed model. In this study, it is assumed that the regions with minimum evapotranspiration will be best suitable for SHP site location.

Table 1 Soils and their HSG classification

Hydrologic Soil Group	Soil Order	Infiltration Rate
A	Sand, loamy sand or sandy loam	High
B	Silt loam or loam soils	Moderate
C	Sandy clay loam soils	Low
D	Clay loam, silty clay loam, sandy clay, silty clay or clay soils	Very Low

2. After preparing these 5 layers, all layers were converted into raster.
3. All raster layers were reclassified to the same scale for overlay analysis.
4. All reclassified layers were assigned appropriate weights, which were calculated using AHP. Weights signify the priorities of layers as per their significance in hydropower generation.
5. After assigning weights, all layers were integrated using the weighted overlay analysis tool.
6. Overlay analysis gives site suitability zones for SHPs.

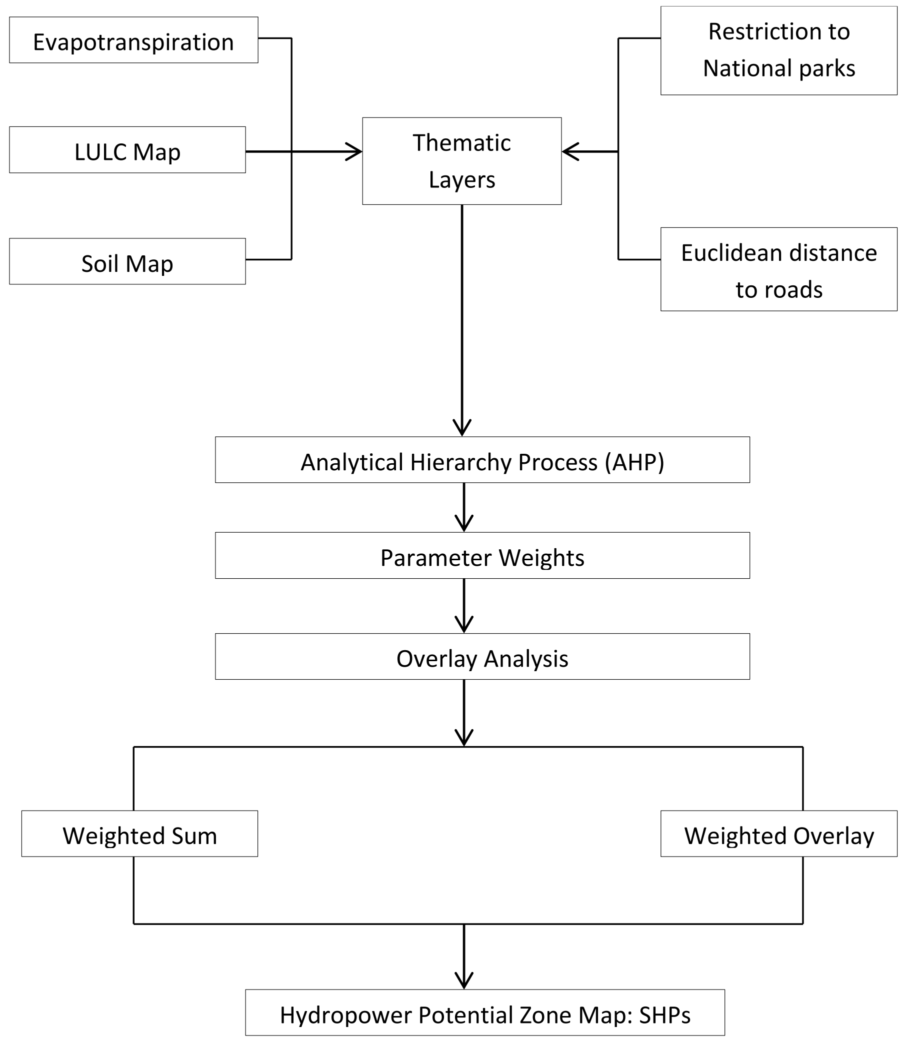

Figure 5. Site suitability methodology based on AHP.

Hotspot analysis of glacial lakes and estimate the water hazard associated with GLOF

This starts with the preparation of glacial lakes (that are greater than 0.05 km^2) inventory for the Indian Himalayas (Figure 5). The 0.05 km^2 threshold was applied to maximize the number of glacial lakes which is also consistent with past catastrophic GLOF events (Nie et al., 2018). Glacial lakes were delineated for the fall of 2018 using Sentinel-2 Multispectral Instrument (MSI) imageries, and to assess the temporal change in lake dimensions the glacial lakes were delineated for the year 1993 using Landsat 5 Thematic Mapper Plus (TM) imageries. The presence of clouds hinders the visibility of imageries. Therefore, for the cloud masked lakes, the imageries of 2017 were used to assist the lake delineation of 2018 whereas imageries of 1992 were used to assist the lake delineation of 1993. The initial period for the lake delineation was considered to be 1992 as this year represents the initial stage of Landsat 5 data availability during the months of least snow cover for the Indian Himalayas. Glacial lake boundaries were manually delineated, and the presence of glacial lake was identified using the Normalized Difference Water Index (NDWI; McFeeters, 1996). Uncertainty in lake delineation was presumed to be the lake perimeter multiplied by half the pixel size (Rounce et al., 2017; Shukla et al., 2018). Glacial lakes were categorized as moraine-dammed lake, ice-dammed lake, bedrock-dammed lake and other glacial lakes (Maharjan et al., 2018). Glacier outlines were obtained from Randolph Glacier Inventory Version 5.0 (RGI; Arendt et al., 2012), which is based on satellite imageries acquired between 1999 and 2003. The uncertainty associated with RGI inventory has been estimated to be ~15% (Nuimura et al., 2014).

Hazard assessment implies the determination of susceptibility to various triggers such as avalanche, rockfall, upstream GLOF, lake expansion, presence of ice cores, and instability of damming moraine. The study aimed at modeling self-destructive failures using hydrostatic pressure, the presence of ice core in damming moraine, and significant expansion over time. Whereas, dynamic failure (mass inflowing into the lake) using ice avalanche trajectories, landslide/rockfall, and upstream GLOFs. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 acquired between 2000 and 2010 with spatial resolution of 30 m and absolute vertical accuracy of ~17 m (Tachikawa et al., 2011), hereon referred as DEM in conjunction with RGI, was used to determine the areas that are prone to an avalanche, that is, any glaciated region with slope ranging between 45° and 60° (Alean, 1985; Osti et al., 2011). Avalanche-prone areas were then cumulated into maximum avalanche-prone areas using a variable kernel filter with 100% threshold. Here, a 1 × 1 grid was checked, and if all the pixels were prone to an avalanche, it was expanded to a 2 × 2 pixel grid. This expansion of the grid was continued until it fails to meet the threshold of 100%. Furthermore, three scenarios were assumed considering the avalanche thicknesses of 10, 30, and 50 m, respectively; these thicknesses are consistent with their relationship between slope and shear stress and are of the same order as observed in Switzerland, Austria, and Alaska (Alean, 1985). These thicknesses were combined with the maximum avalanche-prone area to determine the avalanche volume. A minimum threshold of 0.1 × 106 m^3 was applied on lake volume as defined by Richardson and Reynolds (2000), a volume large enough to destroy a village.

Any GLOF event in upstream of glacial lake having the ability to cascade a series of GLOF events was modeled using the Monte Carlo least cost path method (MC-LCP; Watson et al., 2015); MC-LCP uses the Monte Carlo loop to model DEM uncertainty and implements an iterative least cost path analysis to produce inundation probabilities for each DEM cell. This method is computationally inexpensive and relies merely on the geometry of the downstream channel acquired from the DEM. It generates the flow path without differentiating between flash floods and debris flows. The MC-LCP model implemented with both Shuttle Radar Topography Mission (SRTM) DEM v.4 and Aster GDEM v.2 generated reasonable flood extent when compared against the flood extent generated by Sattar et al. (2019) except for few places, where the model does not capture the simulated flood extent. This could be highly problematic for downstream impact assessment if these areas were populated. A more detailed analysis on the comparison of the flood extent from both the DEMs revealed that GDEM v2.0 tracked the main channel better. Therefore, MC-LCP along with Aster GDEM v2 was used to model potential GLOF from each lake.

Each lake was assessed for its downstream impact using the MC-LCP model with a cutoff distance of 50 km to facilitate a standardized comparison between different lakes; the 50 km threshold was consistent with GLOF event at Dig Tsho in 1985 (Watson et al., 2015), Chilleon Valley in 2015 (Wilson et al., 2019), Chorabari in 2013 (Rafiq et al., 2019), and so forth. Although some of the GLOF events have shown runout length up to 200 km (Richardson and Reynolds, 2000), considering such outliers may lead to overestimation of downstream impact. Generated flood extents were used to assess the downstream impact of GLOF for each lake by quantifying the number of bridges, hydropower systems, and buildings that could be affected. The number of hydropower systems that could be affected was primarily assessed using the database available from 43rd report on hydropower by the Ministry of India, but it was later acknowledged that the available location of various hydropower systems was representative of the system but not essentially the location of a particular part of system such as dam. To resolve this discrepancy, hydropower systems were manually marked using Google Earth and Google Maps. The locations of the buildings were retrieved from OpenStreetMap (https://www.openstreetmap.org) and were confirmed and updated using Google Earth. For the Indian Himalayas, the buildings were majorly underrepresented; more than 10,000 buildings were updated for the local inventory. Bridges were identified using OpenStreetMap as any road crossing the watercourse.

3.6 Activity wise Time frame followed [using Gantt/ PERT Chart (max. 1000 words)]

S.No.	Activities	0-6	6-12	12-18	18-24	24-30	30-36	36-42
1.1	Recruitment of project staff and procurement							
1.2	Geospatial data such as Land use pattern, soil map, DEM etc.							
1.3	Daily data set of all hydro-meteorological variables							
2	Hydrological model parameterization and calibration/validation							

3	Weighted sum overlay analysis for site suitability and hydropower assessment							
3.1	Weighted sum overlay analysis by integrating geospatial and hydrological data							
	Identifying optimum SHP potential zones and their mapping							
4	Glacial lake inventory and identifying critical glacial lakes (hotspots							
4.1	Preparing detailed inventory of glacial lakes							
5	Identifying critical glacial lakes and analyzing the vulnerability of glacial lakes							
5.1	Obtaining PFV, lateral inflows, discharge-water level (Q-h) relationship							
5.2	Risk Hazard and downstream impact assessment using flood inundation model							
6	Survey of the selected villages to identify linkage between water use and livelihood							
6.1	Selection of village and identification and training of resource person							
6.2	Preparation of questionnaire for survey							

6.3.5	Traditional knowledge/information available about the area or sources							
6.5	Awareness generation and capacity building							

4 KEY FINDINGS AND RESULTS

4.1 Major Research Findings (max. 1000 words)

Using geospatial techniques and hydrological models to access hydropower potential zones for establishing small hydropower projects (SHPs);

The model was run with 601 HRUs with observed precipitation and temperature data obtained from IMD and relative humidity and solar radiation data obtained from CFSR. The model was run for a period of 31 years (1983–2013) years with a warm-up period of 4 years (1983-1986).

The calibration and validation of the model were carried out using SWAT-CUP software fitted with the SUFI-2 algorithm. Before carrying out the main calibration and validation processes, uncertainty analysis was performed for the model to check the sensitivity of various parameters. Since the watershed is affected by snow, firstly one set of calibration with 2000 iterations is carried out with snow parameters to correlate the snow melt runoff well. After the first set of calibrations, initially, calibrated values of snow parameters are fed into SWAT for further simulation and the swat model is calibrated again with management, soil, and groundwater parameters. We were able to generate a better performing watershed model of the basin with 2 step calibrations rather than using a single set. The need for fine-tuning the snow parameters in calibration suggested the significant role of snowmelt contribution in the Beas River watershed. Sequential Uncertainties Fitting Ver-2 (SUFI-2) Algorithm has been used for the sensitivity analysis of parameters. A total of eight numbers of snow parameters are tested for their sensitivity to the watershed. The ranking has been given according to the global Uncertainty-Analysis, Figure 6 shows the t statistics and p-value of different parameters

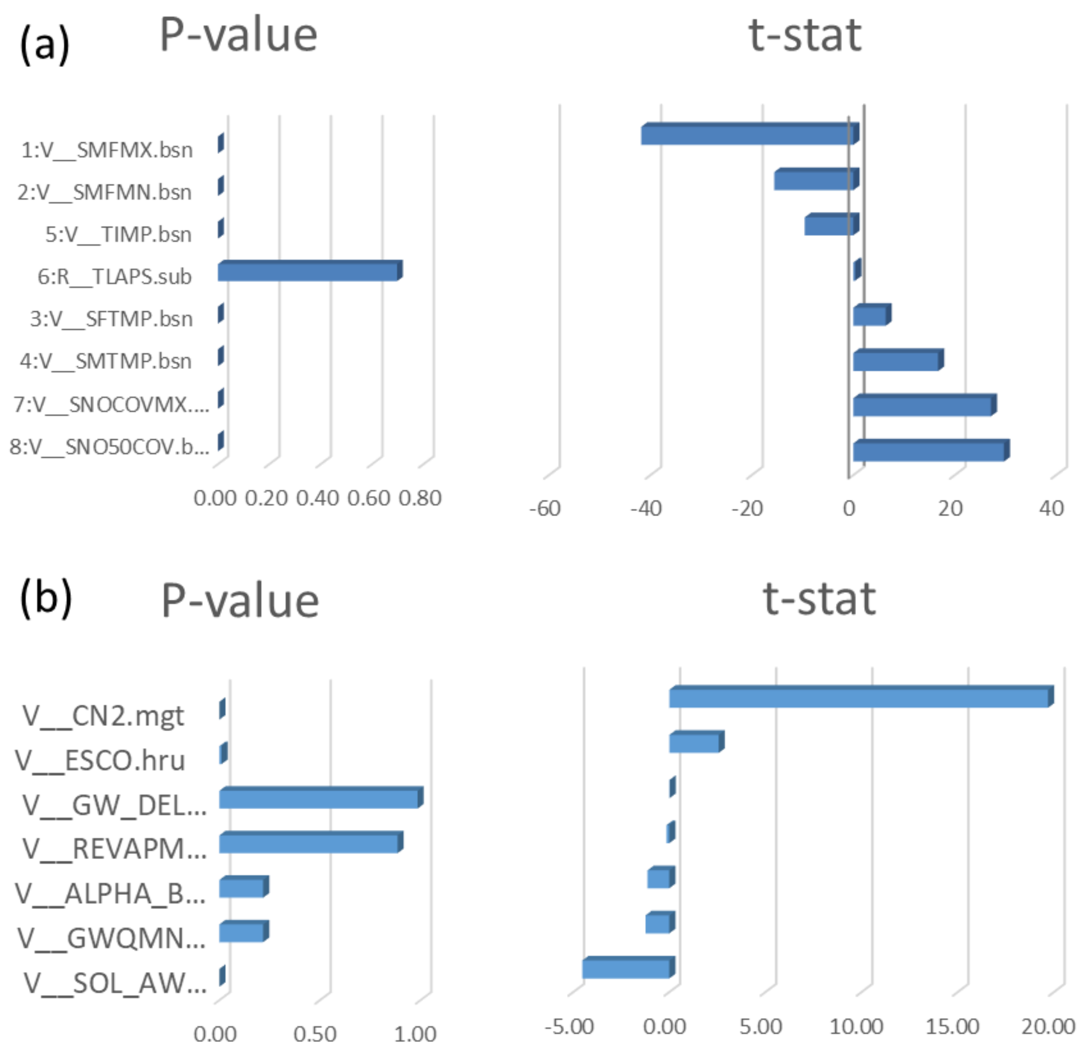

Figure 6. Global sensitivity with (a) snow parameters (b) management, soil, and groundwater parameters

Khalid et al. (2016) has described that in SUFI-2, the assessment of sensitive parameters is measured using the t-stat values, where the parameters are more sensitive for larger t-stat values. P-values are used to determine the significance of the sensitivity where the parameter becomes significant if the P-values is close to zero.

It was observed that among the snow parameters, the melt factor for snow on SMFMX.bsn is the most sensitive parameter with the smallest p-value followed by SNO50COV whereas among the management parameters curve number and soil evaporation compensation factor (ESCO) were found to be sensitive. Since the model was calibrated twice considering only snow parameters first, a comparison to see if management parameters are more sensitive than snow parameters was not possible.

Discharge data from the Nadaun gauge station was collected and was further split into two sets, 5 years (2001 to 2005) for calibration and 1 years (2009) for validation. Discharge data from the year 2009 is used for validation considering the latest set of available data with minimum number of missing days. Table 2 shows statistical parameter results for stream flow

Table 2 Statistical parameter results for stream flow

Station	**Mean Stream Flow (Cumecs)**		**RSR**	**R^2**	**NSE**	**PBIAS**
	Observed	Simulated				
Calibration	188.33	176.35	0.68	0.55	0.54	6.4
Validation	148.07	99.56	0.69	0.57	0.53	32.8

The behavioral plot of stream flow for calibration and validation period are shown in figure 7 (a) and figure 7 (b) respectively.

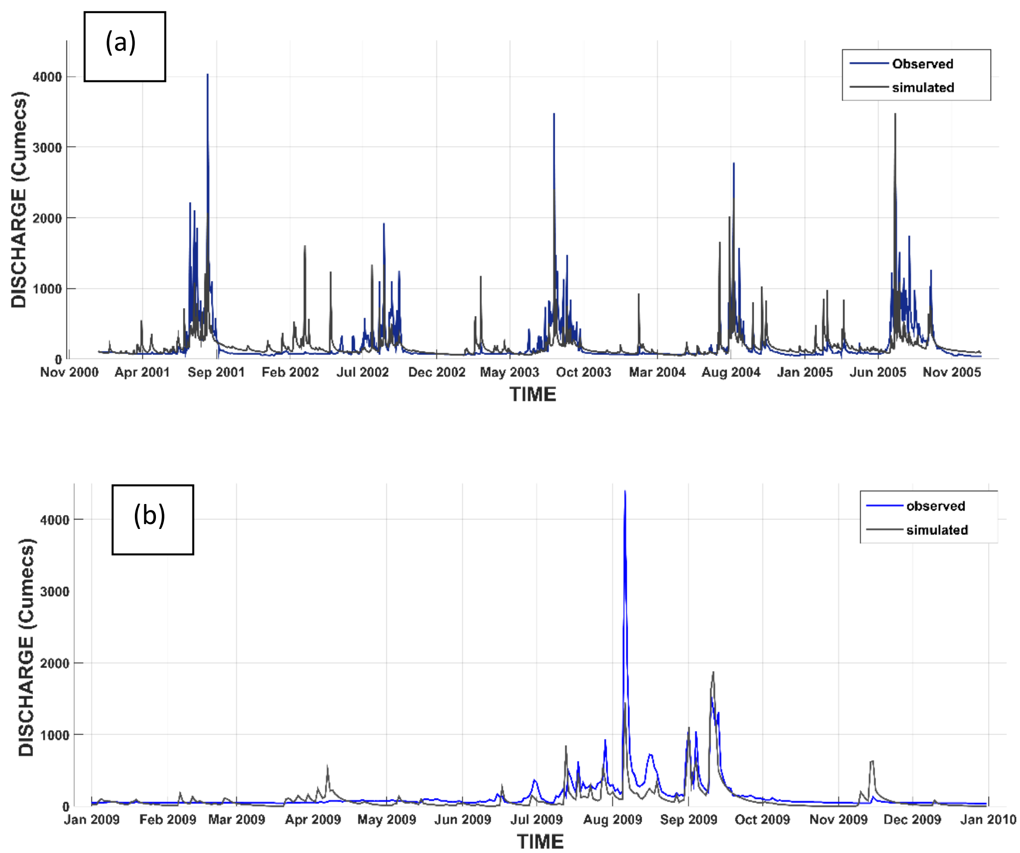

Figure 7. Annual cycle of streamflow with both simulated and observed data for (a) calibration period (2001-2005); (b) validation period (2009)

Hydrological Components through SWAT simulation are shown in Table 3

Table 3 Water distribution in the Beas river watershed

S.No.	Different Hydrological Components	Water Depth (mm)
1.	Evapotranspiration	658.8
2.	Surface Runoff	114.77
3.	Percolation to Shallow Aquifer	303.7
4.	Lateral Flow	215.75
Total Precipitation	1291.4	

Weighted overlay analysis

Five parameters (Restriction for national parks, evapotranspiration, Euclidean distance from roads, LULC, and soil; Figure 8) were considered to obtain the priority value for the feasibility of potential sites for hydropower generation. Evapotranspiration map was prepared using IDW applied on SWAT's output. A land use map was prepared using 7 bands obtained from Landsat 8 imageries (https://glovis.usgs.gov/) and it was then classified using supervised classification. The soil Map was obtained from FAO and was reclassified based on HSG classification (based on infiltration capacity).

To assign weights to different parameters multi-criteria decision-making was applied using AHP in which the importance is given based on specialists opinions and foregoing studies (Ahmad and Verma 2017; Symposium, Publ, and Politecnico 1989; Tarigan et al. 2018). The weights given to different parameters were consistent with a consistency value of 7%. Raster maps for different layers were prepared and overlaid to determine the feasibility of potential sites for hydropower generation using SHPs. A grid size of 25m was used for the production of thematic raster layers using IDW.

4.3.1 RESTRICTION FOR NATIONAL PARKS

As per the guidelines of the Government of India, construction activities in the eco-sensitive zones of national parks are prohibited without prior permission and the Government tries to maintain a threshold on the areas to be urbanized. To keep this into account less priority is given to the areas lying in such regions. However, there is also a possibility of government approval in cases where there is a high potential to harvest hydropower energy (Figure 8(b)).

4.3.2 EVAPOTRANSPIRATION

This map was prepared by applying inverse distance weighting (IDW) on the results obtained from calibrated SWAT model and it was perceived that a high amount of water was lost through evapotranspiration. A site is considered to be suitable when the evapotranspiration in the area is least; the map was reclassified giving the highest priority to the area with minimum evapotranspiration (Figure 8(d)). The weight assigned to evapotranspiration in site suitability is taken to be 8% owing to the fact that the influence is relatively less in comparison to dominant parameters such as relative distance from the roads and effects on the ecosystem by restricting the natural flow of the stream.

4.3.3 EUCLIDEAN DISTANCE FROM THE ROAD

Construction, maintenance, and operation of any structure in a remote area having less road connectivity is problematic not just because of lack of resources but also due to economic factors and the risk of failure. A large part of area lying within the hilly regions lacks proper road connectivity (Figure 8(c)). AHP analysis suggested that Euclidean distance from road plays a major role in prioritizing the hydropower location and thereby a weight of 24% is associated with this factor.

4.3.4 SOIL MAP

The soil map was obtained from the FAO waterbase. This data is readily prepared to be used in SWAT and can be obtained from https://swat.tamu.edu/. This map was reclassified based on HSG soil classification owing to the fact that this classification is mostly based on the soil's infiltration capacity. The soil is classified as A, B, C, and D where A represents most permeable soil and D represents least permeable soil. For the classification, it is assumed that the soil having least permeability is best suited for development of hydropower site (Ahmad and Verma 2017). Total 5 types of soils are present in the area along with glaciers (Figure 8(e)). Most of the soil present in the Beas basin has loamy texture and are under category B of HSG soil classification. Glacier has been given least priority because of the difficulty in establishing a hydropower in remote location with varying depth of ice underneath. 14% weightage is provided to the soil classification in determining suitable site for SHPs.

4.3.5 LAND USE AND LAND COVER MAP

LULC map was prepared using LANSAT 8 imageries and was classified into 10 distinct classes with maximum area under forest. A relatively lower priority is given to Urban, Forest and wetlands (representing glacier) owing to the difficulty in establishing SHPs and higher priority is given to water, agriculture, grassland, barren land, etc (Figure 8(a)). Establishing SHPs near areas of settlement may be complex due to difficulties linked with rehabilitation of inhabitants and land acquisition.

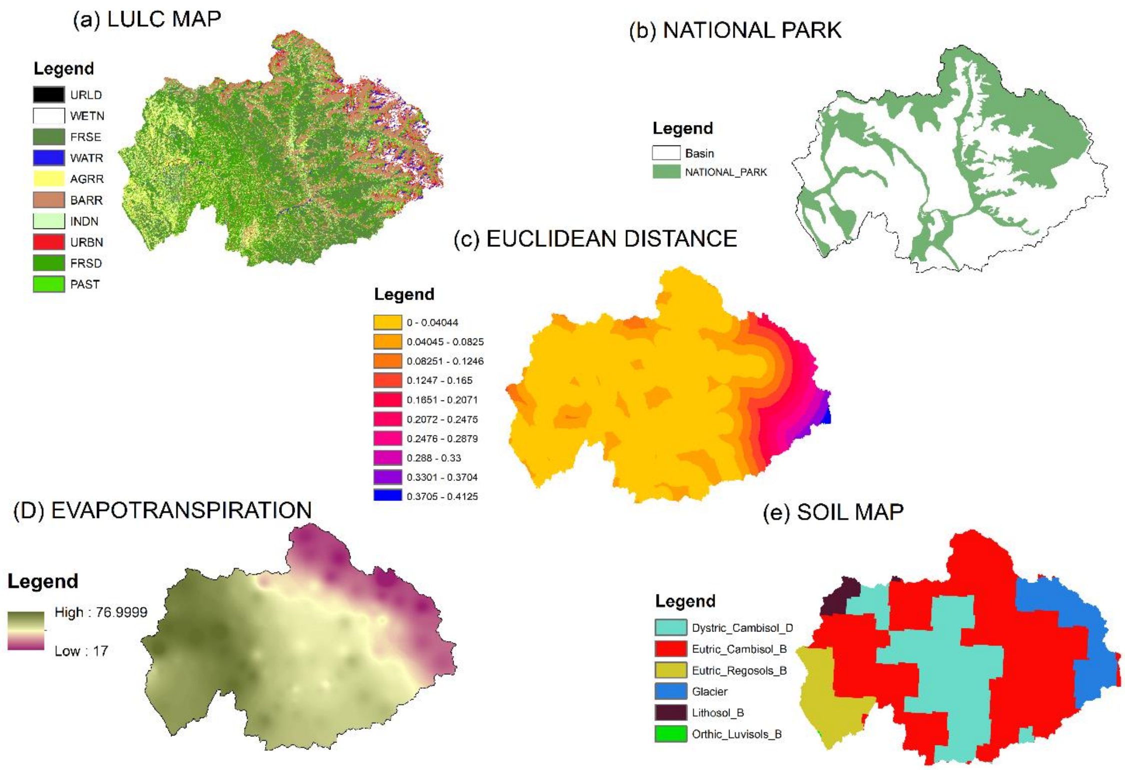

Figure 8 Thematic layers prepared for site suitability analysis

Analytical hierarchy process (AHP)

The analytical hierarchy process (AHP) is a multi-criteria decision-making approach that has the potential to solve complex problems requiring human inputs in deciding weights to the variable influencing the objective function. The consistency in the importance table is assessed and when it is found less than 10%, the weights are assumed to be consistent. Importance table for different parameters are shown in Table 4.

Table 4 Ranking assigned to each parameter in AHP

PARAMETERS	NATIONAL PARK (Restriction)	EUCLIDEAN DISTANCE	LULC	EVAPOTRANSPIRATION	SOIL
NATIONAL PARK (Restriction)	1	2	3	4	3
EUCLIDEAN DISTANCE	0.5	1	2	3	2
LULC	0.33	0.5	1	2	1

EVAPOTRANSPIRATION	0.25	0.33	0.5	1	0.5
SOIL	0.33	0.5	1	2	1
WEIGHTS (%)	**40**	**24**	**14**	**8**	**14**
CONSISTENCY	7.36				

These weights are then assigned to different reclassified parameters to determine suitable zones for hydropower generation. Different thematic layers prepared for weighted overlay analysis are shown in Figure 9.

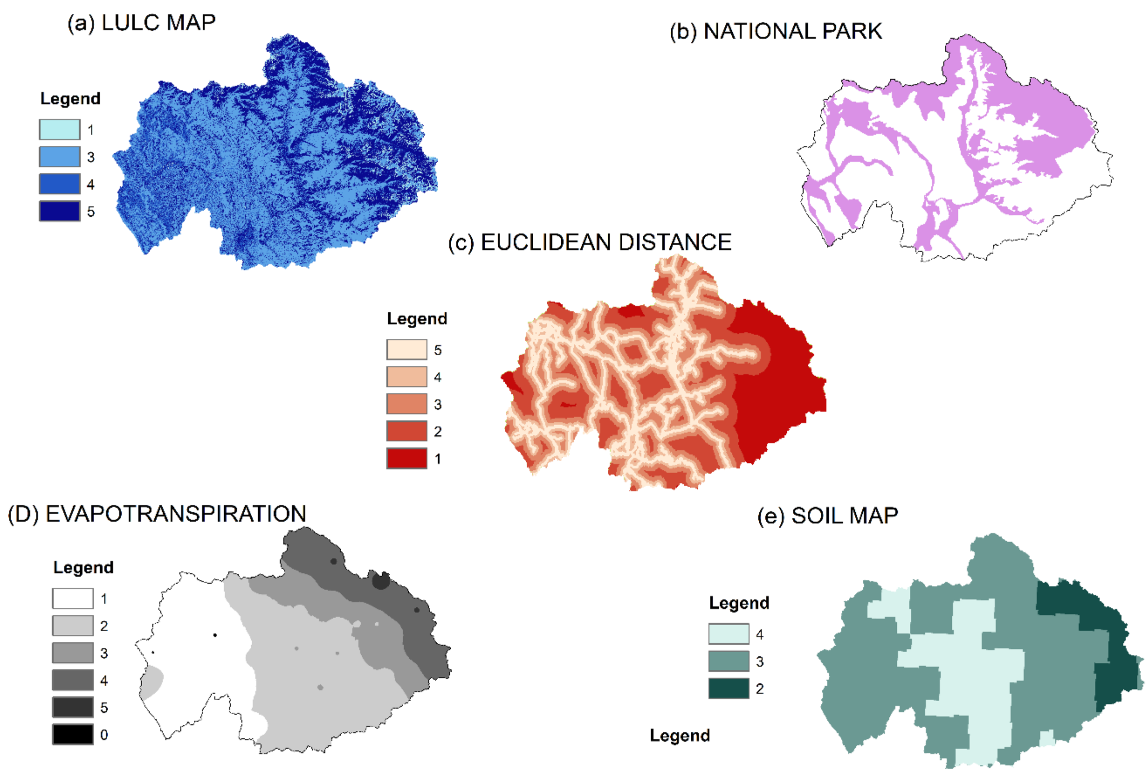

Figure 9. Reclassified thematic layers

Site suitability map

All the sites within the study area having a capacity to develop at least 4 MW of hydropower energy pertaining to 90% dependable flow are considered to be hydropower potential sites. Some of the available sites also had enough potential to develop large-scale hydropower plants. Within the study area, 11 sites were found to have a hydropower potential of at least 4 MW at 90% dependable flow (Figure 10). Most of the potential sites are found on higher order streams owing to high discharge contributed by lower order streams. It is not possible to extract 100% potential of any hydropower potential location because of the losses associated with the turbines, water storage, and its transport, therefore efficiency of 50% is considered while calculating the hydropower extraction capacity. The site suitability map is prepared considering various parameters taking into account the environmental and economic factors can be used to assess the feasibility of construction at different potential sites. Table 5 shows the capacity of selected sites at 50%, 75% and 90% dependable flows considering 50% power plant efficiency.

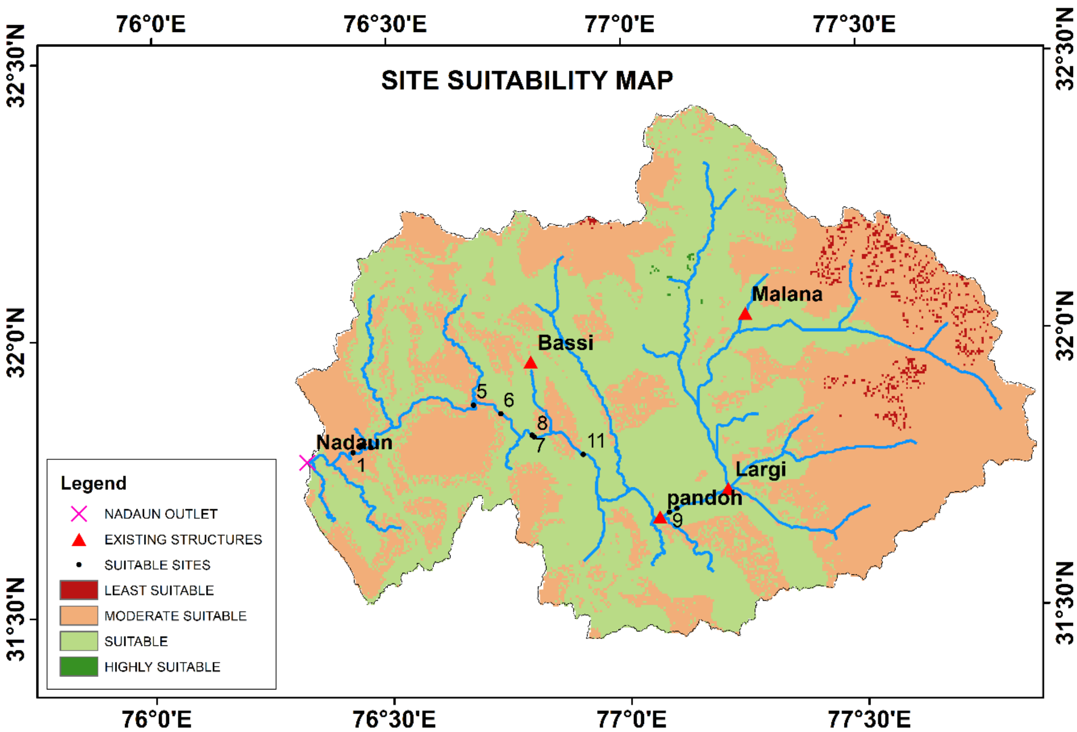

Figure 10. Site suitability map

Table 5. The capacity of selected sites at 50%, 75%, and 90% dependable flows considering 50% power plant efficiency

Site Id	Power (MW) (50% dependable flow)	Power (MW) (75% dependable flow)	Power (MW) (90% dependable flow)
1	25	10	4
2	43	17	8
3	22	9	4
4	24	10	4
5	27	12	4
6	52	22	7
7	31	13	4
8	31	13	4
9	41	16	4
10	41	16	4
11	40	16	4

Results: Hotspot analysis of glacial lakes and Estimate the water hazard associated with GLOF

This study first identified 329 glacial lakes of size greater than 0.05 km^2 in the Indian Himalayas, and then a remote sensing-based hazard and risk assessment were performed on these lakes. Different factors such as avalanche, rockfall, upstream GLOF, lake expansion, identification of the presence of ice cores, and assessment of the stability of moraine were considered for the hazard modeling. Further, the astochastic inundation model was applied to quantify the potential number of buildings, bridges, and hydropower systems that could be inundated by GLOF in each lake. Finally, the hazard parameters and downstream impact were collectively considered to determine the risk linked with each lake. A total of 23 lakes were identified as very high-risk lakes and 50 as high-risk lakes. The potential flood volumes associated with various triggering mechanisms were also measured and were used to identify the lakes with the most considerable risk, such as Shakho Cho and Khangchung Tso.

In the Indian Himalayas, 329 glacial lakes (>0.05 km2) were inventoried for the year 2018 as shown in Figure 11. These lakes were scattered in four states (Himachal Pradesh, Uttarakhand, Sikkim, and Arunachal Pradesh) and two union territories (Ladakh, and Jammu and Kashmir) of India. State-wise distribution of these lakes reveals that the union territories encompass 98 (30%) glacial lakes. Himachal Pradesh comprises 36 (11%) glacial lakes, Uttarakhand comprises 22 (7%) glacial lakes, Sikkim comprises 88 (27%) glacial lakes, and Arunachal Pradesh comprises 85 (26%) glacial lakes (Figure 12a).

Major river basin-wise distribution reveals that the Indus basin contains 134 (41%) glacial lakes, the Ganga basin contains 22 (7%) glacial lakes, and the Brahmaputra basin contains 173 (52%) glacial lakes (Figure 12c). These lakes covered an area of 65.80 ± 4.37 km^2 in 2018. Lake size distribution of these lakes revealed that 129 (39%) lakes were smaller than 0.1 km^2, 178 (54%) had size ranging between 0.1 and 0.5 km^2, and only 22 (7%) were found to be greater than 0.5 km^2. Distribution of lakes according to their type revealed that moraine-dammed lakes account for 154 (47%) lakes, followed by 57 ice-dammed lakes (17%), 31 bedrock-dammed lakes (9%), and 87 other lakes such as erosional and debris-dammed lakes (26%) (Figures 12b and 12d). Elevation profile of the lakes revealed that the lakes ranged from 3,000 (meters above sea level) m.a.s.l to 5,661 m.a.s.l with the mean elevation value of 4,484 m.a.s.l. The lakes present above the elevation of 5,000 m.a.s.l were predominantly ice-dammed and moraine-dammed. Almost all bedrock-dammed lakes were present below 5,000 m.a.s.l, whereas other lakes were uniformly distributed among all the elevation zones (Figure 12e). It was observed in the Indus and Ganga basins, large-sized lakes were present below 4,400 m.a.s.l, whereas for the Brahmaputra basin all the large-sized lakes were located above the elevation 4,900 m.a.s.l (Figure 12f). All the lakes of the union territories and Himachal Pradesh were located within the Indus basin, the lakes of Uttarakhand were located within the Ganga basin, whereas all the lakes of Sikkim and Arunachal Pradesh were located within the Brahmaputra basin. In 1993, the area covered by these lakes was 56.8 ± 15.69 km2 which increased to 65.80 ± 4.37 km2 by 2018, that is, a 15.84% increase in lake area over 25 years. A similar increase in lake area has been observed in Tibetan Plateau (Zhang et al., 2014), Nepal (Nie et al., 2013), Bhutan (Komori, 2008), Tien Shan (Narama et al., 2010), Central Andes (Wilson et al., 2018), and *Western Greenland (Carrivick & Quincey, 2014).* Figures 13, 14, 15, 16, and 17 show the summary of the distribution of hazard parameters, impact, and risk in various Indian Himalayas, along with major river basins and states.

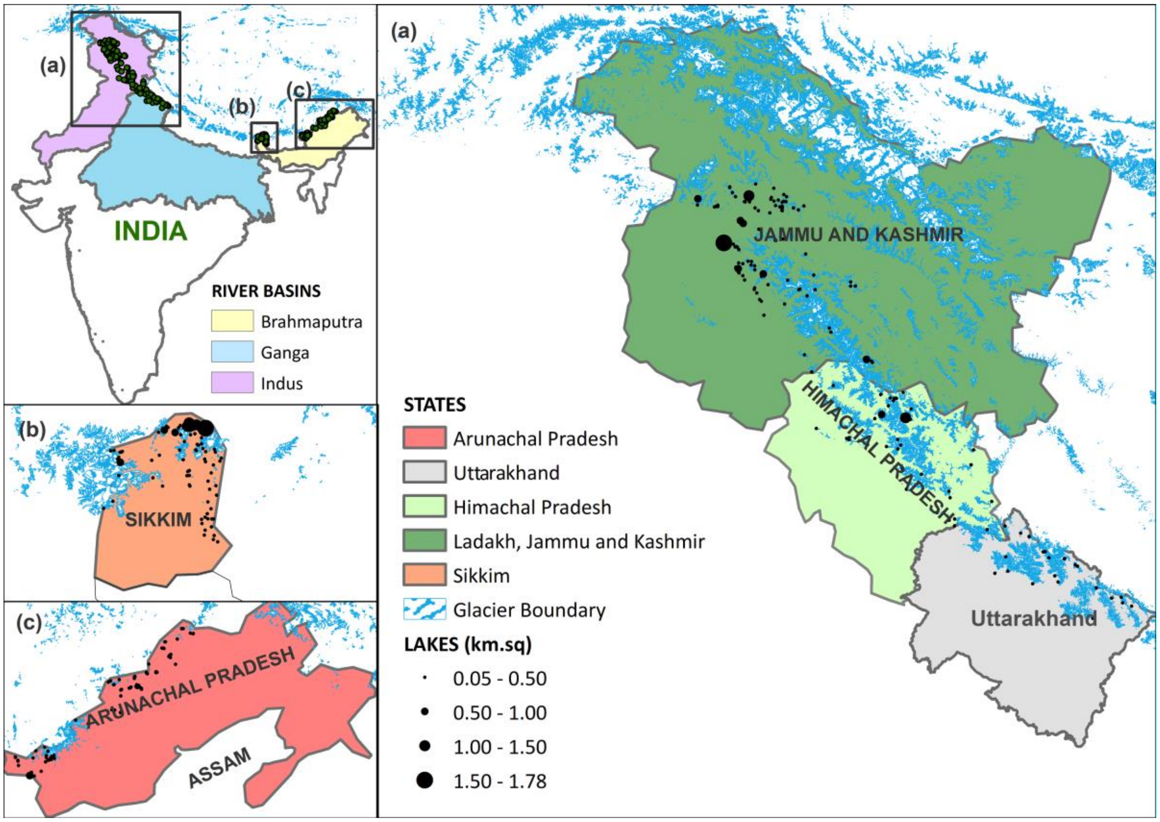

Figure 11. Glacial lakes in Indian Himalayas, along with major river basins and states. Jammu Kashmir shown in the figure has been recently divided into 2 union territories (Jammu and Kashmir, Ladakh).

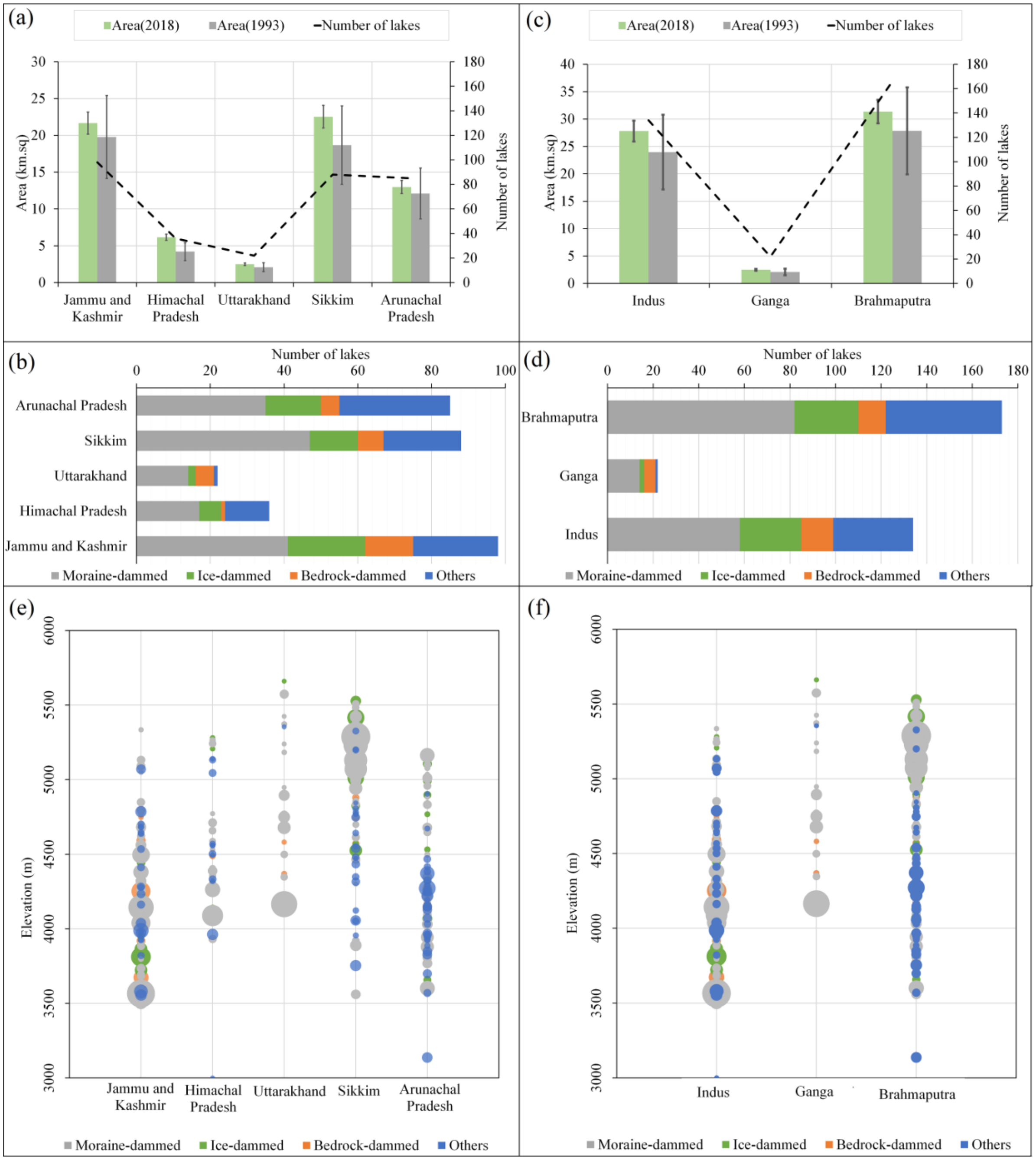

Figure 12. Areal distribution of lakes in various states (a) and basins (c). The dotted line is plotted in correspondence with the secondary axis to represent the number of lakes. Distribution of various lake types in states (b) and basins (d). Figures (e) and (f) represent glacial lakes in various elevation zones, the colour of the circles represent various lake types, whereas the size of the circles represents the size of the lake.

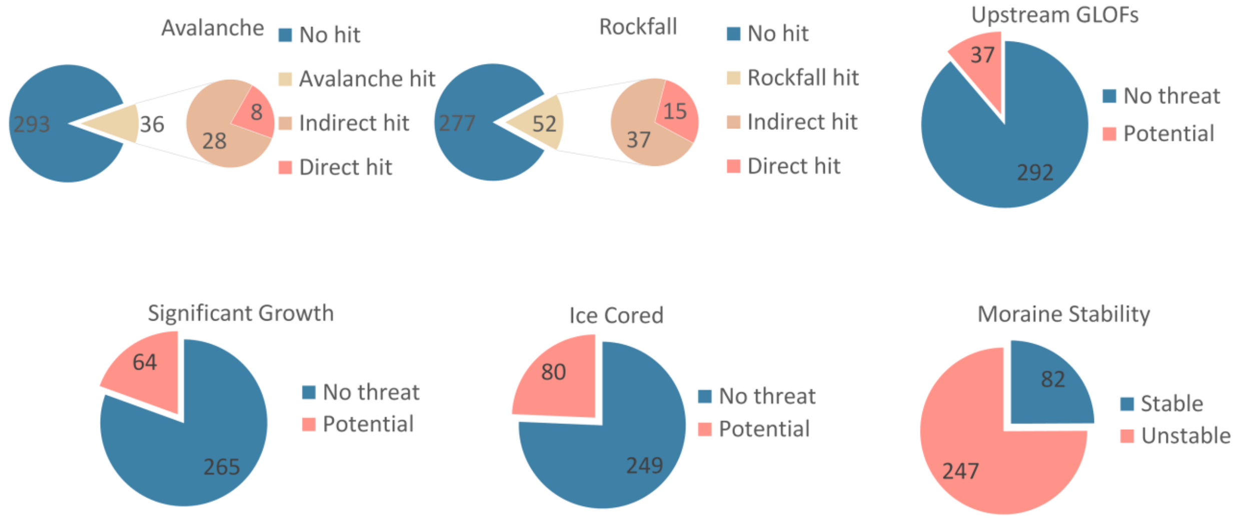

Figure 13. Summary of hazard parameters.

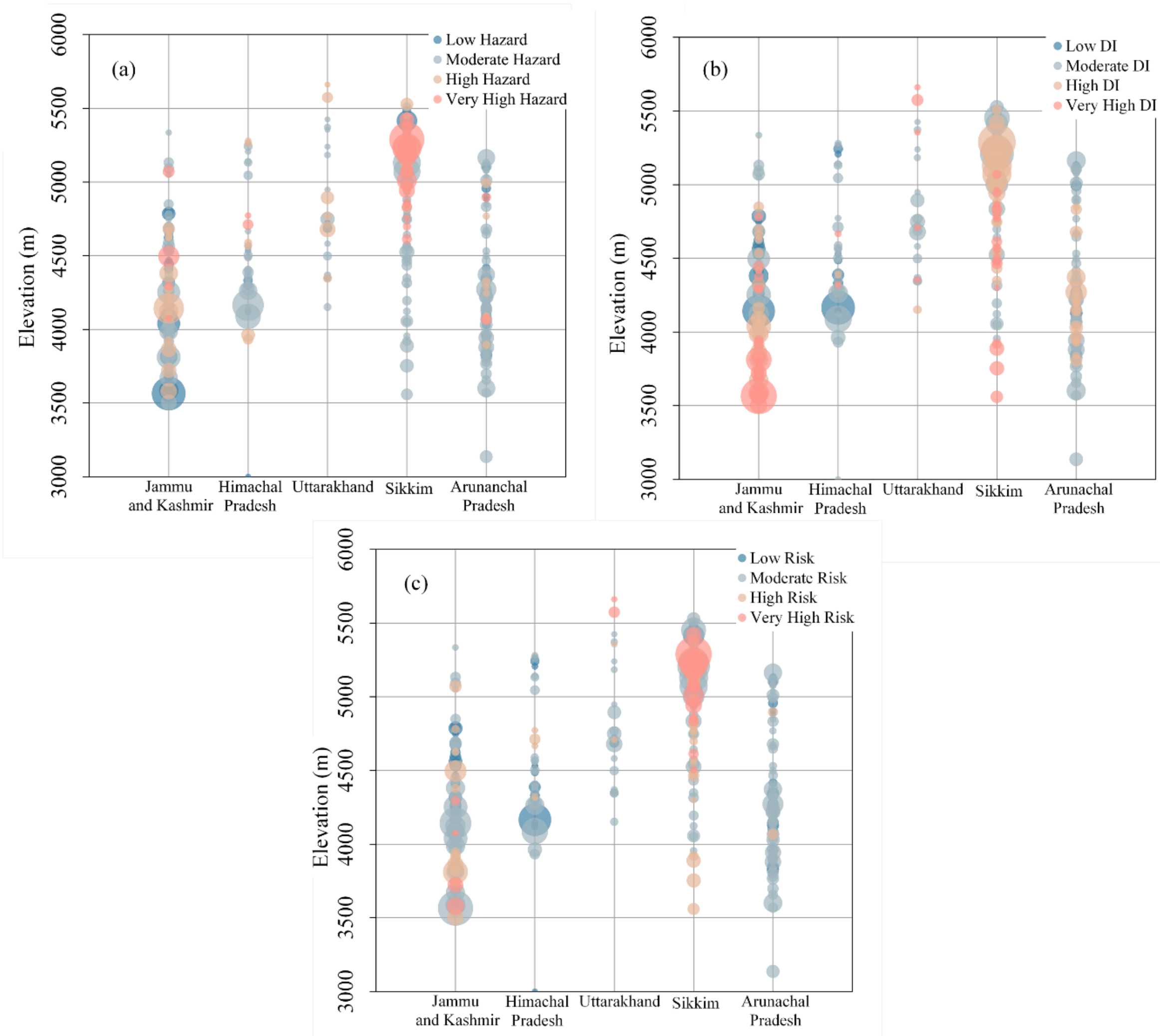

Figure 14. Distribution of (a) hazard, (b) downstream impact (DI) and (c) risk in various elevation zones. Colour of the circle represents very high, high, moderate, and low rankings of risk, hazard, and downstream impact. The size of the circle represents the size of the lake.

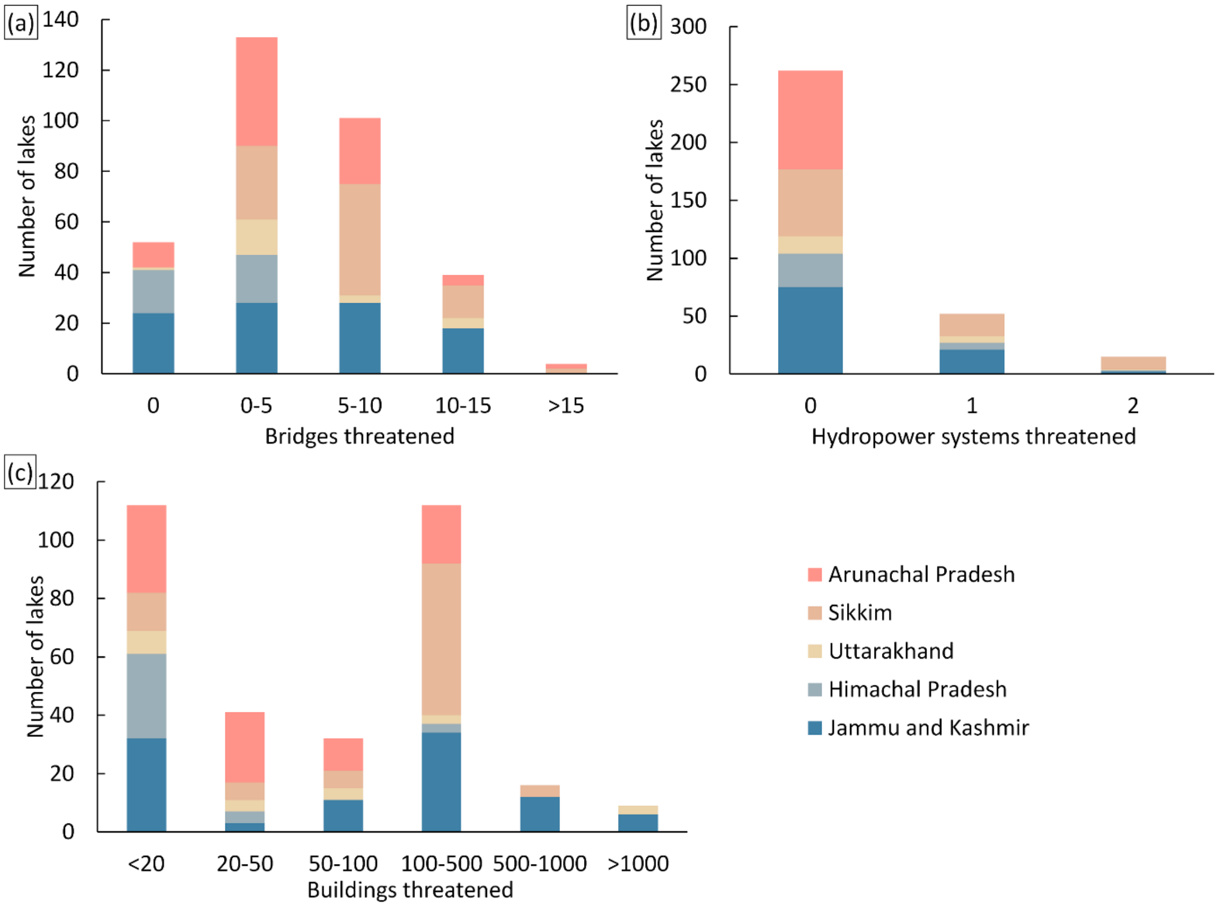

Figure 15. Downstream impact summary representing the potential number of (a) bridges, (b) hydropower systems, and (c) buildings threatened by GLOFs

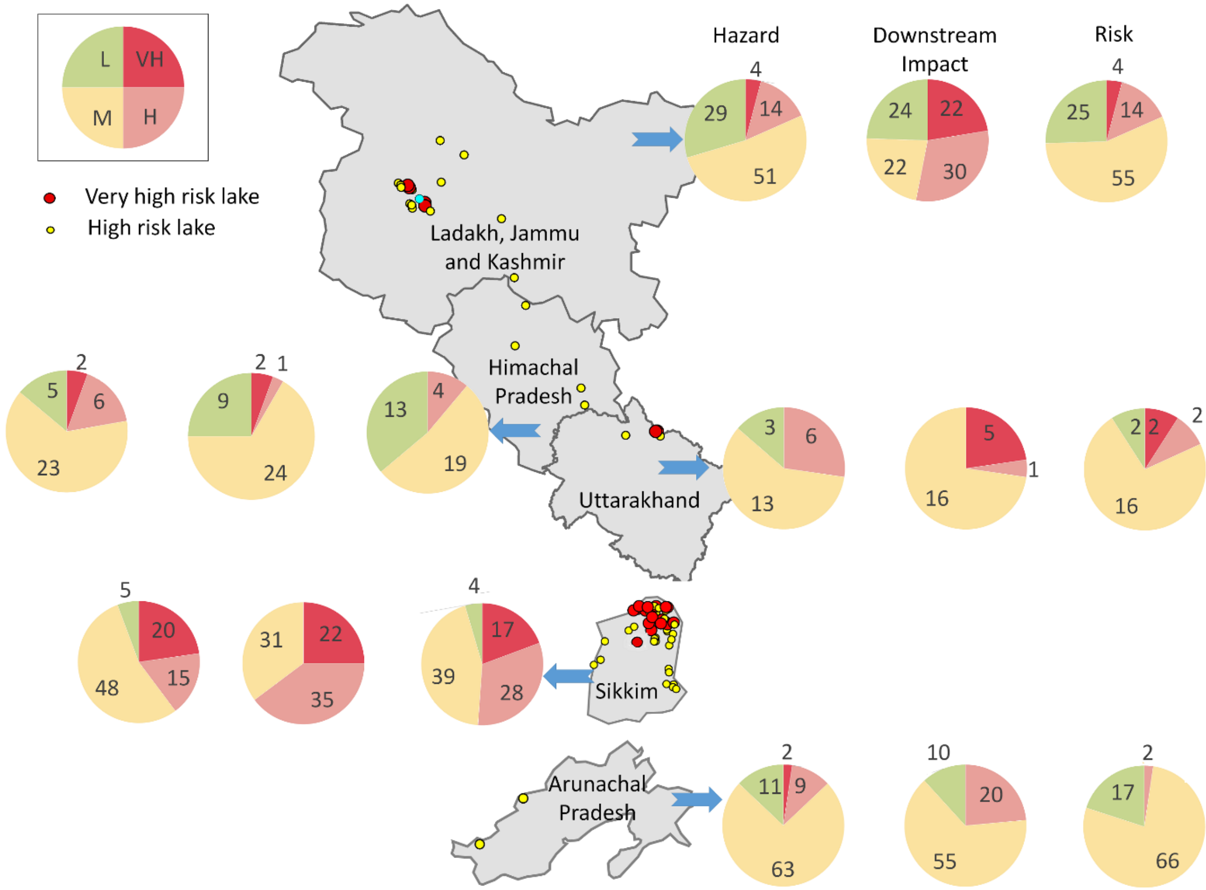

Figure 16. Distribution of hazard, downstream impact, and risk classification (pie charts) for various states.

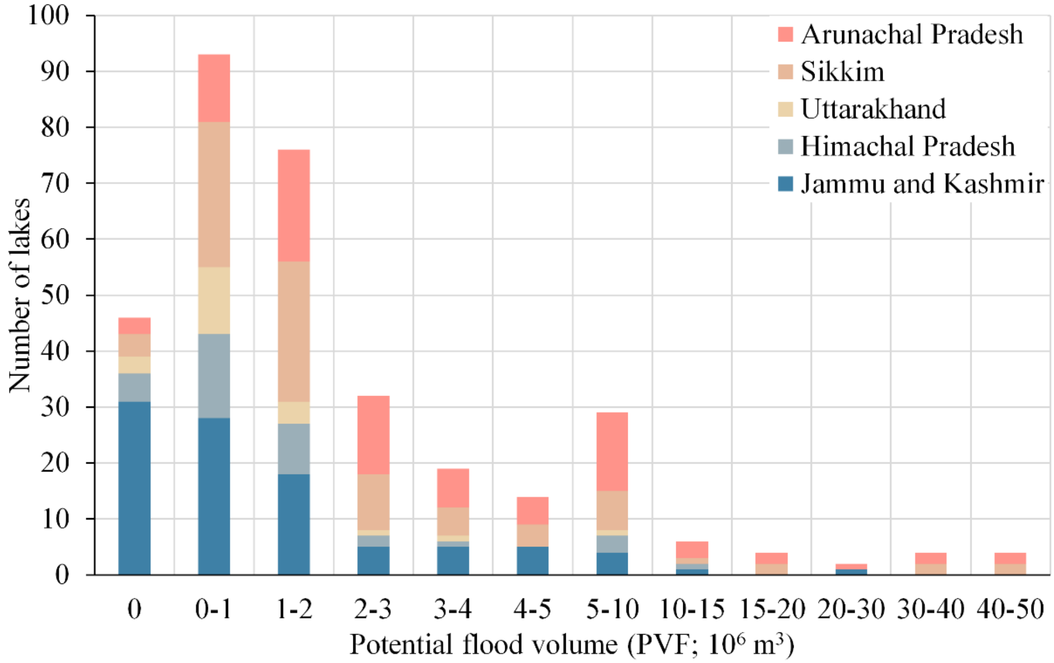

Figure 17. Distribution of PFV for the lakes in the Indian Himalayas.

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

Identification of hydropower sites

- Snowmelt contribution plays a major role in the discharge pattern of Himalayan River basins, especially Beas River watershed and thereby it is crucial to incorporate it as an important factor while designing hydropower systems.
- Maps prepared in the project are useful in the identification of suitable sites for hydropower structures, for future water management planning.
- Parameters such as Restriction for national parks, evapotranspiration, Euclidean distance from roads, LULC, and soil are crucial factors while prioritizing the location of run-off river hydropower systems.
- AHP is powerful multi-criteria decision-making approach capable of optimizing various potential sites of hydropower extraction.
- Within the study area, 11 sites were found to have a hydropower potential of at least 4 MW at 90% dependable flow.
- Most of the potential sites are found on higher order streams owing to high discharge contributed by lower order streams.
- Various thematic maps prepared for present study will also serve as raw data for various analysis and studies.
- It is not recommended to decide the potential sites for hydropower generation without a manual survey because the results from computer simulations are bound to uncertainties that may lead to misleading results.
- This study will sort the locations to be manually surveyed and give an idea about the location's feasibility as a potential hydropower site considering various aspects including economic and environmental factors.
- This methodology demonstrated a modeling-based approach to identify zones suitable for hydropower generation but will require a manual survey considering social impacts on the lives of

inhabitants living near the Beas River basin. The overlaid map is classified into 4 categories ranging from highly suitable to least suitable.

Identification of critical glacial lakes

- The results indicated that glacial lakes expanded by 15.84% between 1993 and 2018, where 64 lakes significantly expanded and 6 lakes significantly drained; 36 lakes are susceptible to an avalanche where most of the hit is expected along the minor axis.
- Application of stochastic flood model reveals that 67 glacial lakes contain at least one hydropower system along their flow path.
- The risk assessment indicates that there are 23 very high risk lakes and 50 high-risk lakes in the Indian Himalayas
- Some of the notable lakes with very high PFV include Gurudongmar Lake, Tso Lhamo Lake, and J R B Lake, whereas some of the lakes with high PFV and very high risk include Khangchung Tso and Shakho Cho.
- However, with the current state-of-the-art knowledge of GLOF triggers and available datasets, the inherent subjectiveness of the methodology is inevitable in these first-pass assessments.
- The presented results will help in prioritizing the lakes for further field and modeling studies. We recommend that these results should be discussed with stakeholders such that decisions in ranking the lakes in distributing available resources can be made in line with the scientific facts.
- We suggest the use of the Potential flood volume associated with the breach of each lake as an important indicator for identifying PDGLs as a sizeable flood volume, high hazard possibility, and large downstream impact can be expected.
- A Survey of villages suggested that the major source of income in the hilly regions defines the adaptation and mitigation capabilities of the population.
- People living at higher altitudes are aware of GLOFs and are more aware of the possible consequences of the events.

4.3 Conclusion of the study (maximum 500 words in bullets)

- The development of small hydropower plants is an environmentally friendly, efficient, replenishable way to supply electricity even to remote areas of the country.

- Beas River has a high potential for SHP development as the river has a sufficient amount of water throughout the year and the area is characterized by hilly terrain which acts as a driver for hydropower generation.
- The benefits from the project can be in terms of smaller area for the establishment, smaller investment, shorter period for planning and construction, cheaper generation cost, and use of local labor and resources.
- This study was carried out to study the glacial lakes in Himachal Pradesh with the objective of assessing their evolution and outburst hazard susceptibility.
- Through the multi-temporal satellite data, GLOF prospect of glacial lakes was studied. The study concluded that over the period of 26 years, i.e., from 1993 to 2018, the glacial lakes in Indian Himalayas expanded by 15.84%, where 64 lakes significantly expanded and 6 lakes significantly drained; 36 lakes are susceptible to an avalanche where most of the hit is expected along the minor axis.
- We conducted a comprehensive assessment of the risk and hazard with a total of 23 lakes were identified as very high risk lakes and 50 as high-risk lakes, these lakes were in close proximity to critical areas such as tourist base camps and hydropower systems.
- Hydrodynamic modelling is capable of determining critical sections in the flood path of glacial lakes that need further attention.
- Livelihood survey suggested that the major source of income in the hilly regions defines the adaptation and mitigation capabilities of the population.
- Fortunately, people living in higher susceptible areas to GLOFs are more aware of the possible consequences of the events.

5 OVERALL ACHIEVEMENTS

5.1 Achievement on Project Objectives [Defining contribution of deliverables in overall Mission (max. 1000 words)]

Initially, the project started with 4 objectives. Here, we are including major achievements after each objective of the project

Digital maps of specific locations of the SHPs and hydropower potential zones in the Beas river basin

We were able to determine 11 locations in the Beas River basin which were suitable for setting up runoff river hydropower plants. These locations were also prioritized based on various criteria's such as natural park restrictions and distance from road etc. The analysis provided a framework which can be easily applied to any mountainous river basin and is flexible with the threshold on hydropower capacity. It can also be applied to determine the location for large hydropower plants, but special considerations will be required for back water flows and area of submergence. One of the major objective of the mission toward sustainable development of Himalayan regions and for achieving this identification and development SHP should be given priority.

Quantitative maps of critical glacial lakes and the water hazard associated with GLOF

With this analysis, we were able to put forward a semi-objective framework to identify critical glacial lakes and assess the potential downstream impact in case of flood. Glacial lake if not identified and monitored properly could lead to damage of life properties in the Himalayan region. Therefore for the development of the Himalayan region, proper identification of glacial lake hotspots and quantification of the risk associated with their failure is to be carried out. In this project, using remote sensing techniques we were able to identify a total of 23 lakes were as very high-risk lakes and 50 as high-risk lakes. potentially dangerous glacial lakes in the Himalayan region which can pose a serious threat to the downstream population. A detailed glacial lake inventory was prepared and these lakes are to be regularly monitored to prevent any hazards.

Livelihood survey of 2 distinct villages In Himachal Pradesh

We carried out livelihood surveys in two remote villages of Himachal Pradesh. The villages were chosen considering the high difference in the living standards of the local inhabitants. The villages that were surveyed include Jassi near Mandi which is located at an elevation of ~1000 m. The inhabitants of the village are relatively poor, and their livelihood mostly depends on agriculture. The locals in this village are mostly illiterate and the living standards are below the national average. The other village that was surveyed is Jagatsukh which is located ~ 6 Km from Manali at an elevation of ~4000 m. The source of income in this village is apple farming, living standards are relatively high and most of the people are literate. This distinction in the living standards of the villagers influences their adaptability and mitigation skills in case of a disaster such as GLOF.

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

A developed novel algorithm to assess the suitability of site for run-off river hydropower generation. The study identified 11 sites for potential hydropower generation in the Beas river basin using a hydrological model and multi-criterion decision-making tools. There are studies which have similar work (work done in IIT Roorkee study) and identified 425 potential small hydropower (5-MW) generation sites in Himachal Pradesh. The study area for this work was Beas basin upto Nadaun discharge gauging station. In addation to this, we also considered the efficiency of hydropower systems to be 50%. For prologizing hydropower sites, we use a multi-criteria decision-making tool considering criteria such as restriction for national parks, evapotranspiration, euclidean distance from roads, LULC, and soil.

Identification and monitoring of these glacial lakes and their dynamics (spatial as well as temporal) are of high significance for quantification of GLOF hazards. Our study presents a glacial lake inventory of Indian Himalayan regions for four-time steps, i.e., 1993, 2003, 2013, and 2018 using Landsat TM/ETM+/OLI images. The results indicated that glacial lakes expanded by 15.84% between 1993 and 2018, where 64 lakes significantly expanded and 6 lakes significantly drained; 36 lakes are susceptible to an avalanche where most of the hit is expected along the minor axis. The comparison of results with baseline datasets are reported in Table 6.

Table 6 Comparison of the change in the lake area reported by various studies carried out in Himalayan and Tibetan regions

Study area	**Data used**	**Time period**	**Lake type considered**	**Area change**	**References**
Central Tibet	Landsat ETM+/TM/MS	1972-2009	Glacial/Supra glacial	173%	(Wang et al. 2013)
Polqu basin, Himalaya	Landsat ETM+/TM/MS	1976-2010	Glacial	122%	(Wang et al. 2015)
Rongxer basin	Landsat TM/MS, ASTER	1975–2005	Glacial	121%	(Wu et al. 2012)
Nepal, Bhutan	Landsat ETM+/TM	1990–2009	Glacial	+20–65%	(Gardelle et al. 2011)
Boshula mountain range, Tibet	Aerial photograph, Landsat ETM+/TM, ALOS	1970–2009	Moraine-dammed	27%	(Wang et al. 2011)
Tibetan plateau	Landsat ETM+/TM	1990–2010	Glacial	26%	(Zhang et al. 2014)
Sikkim Himalaya	Hexagon, Landsat OLI/ETM+/TM	1975–2017	Glacial and high-altitude	24%	(Shukla et al. 2018)
Entire third pole	Landsat ETM+/TM	1990–2010	Glacial	23%	(Zhang et al. 2015)
Nepal	Landsat ETM+/TM	1990–2010	Glacial	17%	(Nie et al. 2013)
Poiqu basin, Central Himalaya	Landsat TM/MSS	1986–2001	Glacial	11%	(Chen et al. 2007)
Kangchengayo-Pauhunri Massif, Sikkim Himalaya	Landsat OLI/ETM+/TM	1988–2014	Glacial and high altitude	8.38%	(Debnath et al. 2018)
Bhutan	SPOT, Landsat ETM+/ TM/MSS, Corona	1960–2001	Glacial	+0.04 km^2 a^{-1}	(Komori 2008)
Indian Himalayas	Landsat OLI/ETM+/TM	1993-2018	Glacial	15.84%	This study

5.3 Generating Model Predictions for different variables (if any) (max 1000 words in bullets0)

- Through the hydrological model and multi-criterion decision-making analysis, we could identify 11 locations in the Beas River basin which were suitable for setting up runoff river hydropower plants.
- The determination of potential hazards was carried out by modeling moraine stability, avalanche, rockfall, GLOF in the upstream portion of the lake, and lake expansion.
- Modeling of dynamic failure revealed that out of 329 lakes, 36 (11%) are susceptible to an avalanche entering the lake, 52 (16%) are susceptible to a rockfall, and 37 (11%) are susceptible to an upstream GLOF.
- Concerning moraine stability, 247 (75%) lakes have an unstable moraine (average SLA angle >10°), and 80 (24) have ice cores present in their damming structure. Assessment of lake expansion revealed that from 1993 to 2018, 64 (19.5%) lakes significantly expanded and 6 (2%) lakes significantly drained.
- Modeled hazards were used to classify the lakes into various hazard categories; that is, 28 lakes were categorized as very high hazard, 50 as high hazard, 198 as moderate hazard, and 53 as low hazard. Sikkim has the maximum number (20) of very high hazard lakes followed by the union territories of Ladakh, and Jammu and Kashmir (4).
- The Brahmaputra basin has 20 very high-hazard lakes, followed by 6 in Indus basin and 2 in the Ganga basin.
- Through the monte-Carlo least cost path model (MC-LCP) it was observed that there are 217 lakes that inundated at least 20 buildings while 138 inundated at least 100 buildings; nine lakes were identified to inundate more than 1,000 buildings. Six lakes inundating more than 1,000 buildings were located in the union territories of Jammu and Kashmir, and Ladakh whereas three lakes were located in Uttarakhand.
- The number of lakes that inundated at least one hydropower system was 67 whereas the number of lakes that inundated two hydropower systems was 15. The number of bridges inundated ranged from 0 to 17 with a median value of 4.
- A total of 23 lakes were classified as very high risk, 50 were classified as high risk, 195 were classified as moderate risk, and 61 were classified as low risk.

5.4 Technological Intervention (max 1000 words)

The algorithm/framework developed in the study to identify potential locations for hydropower generation is novel, effective, and can be easily applied to any mountainous basin. Additionally, using the available remote sensing datasets we applied a preliminary assessment approach to identify the potentially dangerous glacial lake (PDGL) in Himachal Pradesh. A total of fifty lakes were evaluated and ten were identified as PDGLs. To assess the downstream impact of these PDGLs, the monte-Carlo least cost path model (MC-LCP) (for details on MC-LCP model please refer Watson et al. 2015) was applied to determine the inundation probability map for each lake considering a uniform runout length of 50 km. Results from MC-LCP model reveals that the lake with the highest PFV (Chandra tal lake, lake ID 48) can cause a devastating downstream impact, flooding many tourist base camps, as the area is widely known for tracking activities, adding to this the road leading to this lake has been recognized to cause many traffic accidents in the past due to steep terrain which may add to unfavorable impact in case of a GLOF (Figure 18). Inundation mapping of other PDGLs shows that lake (ID 47) can threaten a hydropower system, lake (ID 46) can threaten 4 bridges along its inundation path. Almost all the lakes are capable of causing impact on human settlement except for lake (ID 26 and ID 45) which are remotely located.

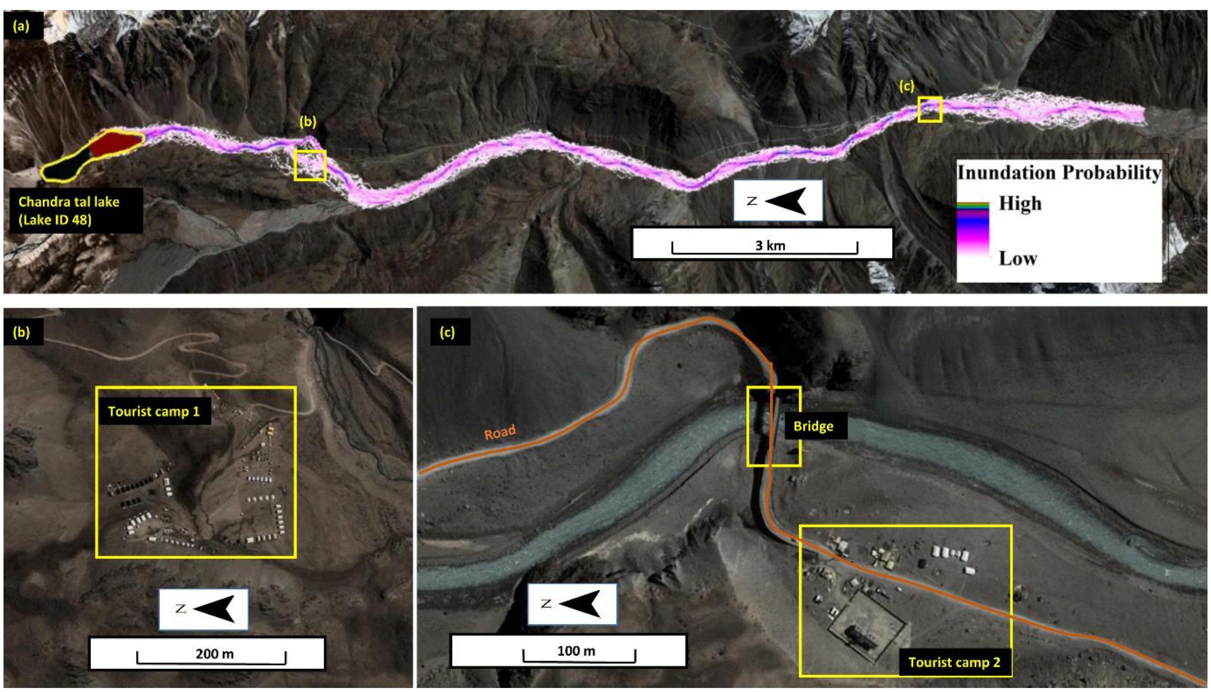

Figure 18 (a) Inundation map of Chandra tal lake (lake ID 48) prepared considering DEM root mean square error of 15 meters. (b) Tourist camp site 1 highly vulnerable to flooding. (C) Tourist camp site 2 along with road and bridge highly vulnerable to flooding in case of GLOF.

5.5 On field Demonstration and Value-addition of Products (max. 1000 words, in bullet points)

1. Workshop on **Identification of hydropower sites and critical glacial for water resource management in Himachal Pradesh;** Workshop location: Shimla, Himachal Pradesh India Date: 22.02.2021

As part of the project, workshop was carried on the above-mentioned topic among the experts in the field of hydropower generation, Himalayan hazards, climate change, and mountain ecology. The delegates that were invited for the workshop includes Sh. Kumar Manoranjan Singh (senior manager, NHPC Ltd, Sector-33, Faridabad-121003), Sh. Raj Kumar (Executive engineer, Hydrology C&M Division Tutikandi, Shimla), Suman Mahajan, and Deeraij Koul.

The primary discussion of the topic was on the identification of feasible sites for the development of small hydropower plants in Himachal Pradesh. The method proposed in the project was presented which includes the determination of flow in the river channel along many streams using hydrological model and the determination of head drop using the focal statistics in the GIS tool. Few changes were suggested such as better calibration of discharge values, consideration of back water effect of exiting dams, determination of possible reservoir area in each case, and consideration of ethnic values of the surrounding areas, Later, identification of critical glacial lakes were discussed with the experts including the work carried on the recent Chamoli disaster of Uttarakhand. The primary focus of this discussion was on the accuracy of the probable flood volume generation in case of each potential GLOF event and the experts suggested that few dam have the capacity to absorb the impact of flash flood created due to GLOF such as Tehri dam due to its huge capacity and they suggested that it will make an important part of discussion in the final project report. In addition to this, experts also discussed about the pattern of settlement of different tribes and communities in the mountain ranges where they explained that people from certain communities prefer living in the valleys whereas others prefer living in the hills. These differential settlements among the tribes makes one tribe more susceptible to disaster than other.

1. Training program on " **Water management in hilly areas for sustainable development**" through online mode (due to COVID) dated 17 Dec 2021.

2. Training program on "**Sustainable water resources management in the Himalayan region**" through online mode (due to COVID) dated 29 Dec 2021.

5.6 Promoting Entrepreneurship in IHR

Not applicable

5.7 Developing Green Skills in IHR

Not Applicable

5.8 Addressing Cross-cutting Issues (max. 500 words, in bullet points)

Climate change:- The study focus on the identification of critical glacial lake. Global climate change has shown a significant impact at the regional level. Increased warming, extreme events, and glacier retreat are closely related to the development and evolution of glacial lakes (Prakash and Nagarajan 2018). Change in atmospheric circulation patterns in glaciated regions, increase in temperature, and consequently, evapotranspiration has affected the mass balance of glaciers, leading to an increase in glacier and snowmelt runoff. This increase in runoff attributes to the formation and expansion of glacial lakes. The greater Himalayan range lying adjacent to Himachal Pradesh has shown an increase of 1°C in maximum temperature and striking 3.4°C in winters in the past two decades, consequently, causing

440cm decrease in winter snowfall between 1988 to 2007 (Shekhar et al. 2010). Through this study a detailed glacial lake inventory for the Himalayan region was prepared and identified 329 glacial lakes of size greater than 0.05 km^2. Then a remote sensing-based hazard and risk assessment were performed on these lakes. Furthermore, the stochastic inundation model was applied to quantify the potential number of buildings, bridges, and hydropower systems that could be inundated by GLOF in each lake. Finally, the hazard parameters and downstream impact were collectively considered to determine the risk linked with each lake. The hotspots indenfited in this study can be monotirred regularly to asses the impact of climate change on glacial lake formation/expansion.

Sustainable development of the Himalayan region:- Himalayan water towers have a huge potential for generating clean and renewable energy. Small-scale hydropower projects (SHP) could provide clean and renewable energy and have a minimal impact on ecology and biodiversity. The present study use hydrological model and geospatial techniques to identify hydropower potential zones for establishing small hydropower projects. A multi-criteria approach is adopted to integrate the geospatial and hydrological data together to identify hydropower potential zones and suitable sites locations for SHP along the stream network. We could identify 11 locations in the Beas River basin which were suitable for setting up runoff river hydropower plants. Development of these locations could help in the sustainable development of the region.

6 PROJECT'S IMPACTS IN IHR

6.1 Socio-Economic Development (max. 500 words, in bullet points)

Not Applicable

6.2 Scientific Management of Natural Resources In IHR (max. 500 words, in bullet points)

The study designed a framework to assess the possible location of small hydropower sites in the Indian Himalayas. Small hydropower plants utilize the river water to generate hydropower which could play an important role in generating energy with minimal carbon footprint.

We also developed a framework to identify the critical glacial lakes in the Himalayan region. Identifying critical glacial lakes would help in proper monitoring of the lakes thus minimizing hazards associated with them.

6.3 Conservation of Biodiversity and Environment in IHR (max. 500 words, in bullet points)

The study designed a framework to assess the possible location of small hydropower sites in the Indian Himalayas. Small hydropower plants utilize the river water to generate hydropower which have minimal impact on Biodiversity and the environment.

We also developed a framework to identify the critical glacial lakes in the Himalayan region. Glacial lake outbursts could result in large damage to biodiversity and the environment. Proper management and monitoring the lakes could result in the conservation of biodiversity and the environment

6.4 Protection of Environment (max. 500 words, in bullet points)

Same as mention in section 6.3

6.5 Developing Mountain Infrastructures (max. 500 words, in bullet points)

Not applicable

6.6 Strengthening Networking in IHR (max. 700 words, in bullet points)

In the present study, the identification of critical glacial lakes was done for the entire IHR region. The hotspots of the critical lake and its associated hazard risk were quantified. This inventory can be used to develop a network to monitor critical lakes thus developing an early warning system to detect hazards and better management of natural resources in the Himalayan region.

7 EXIT STRATEGY AND SUSTAINABILITY

7.1 How effectively the project findings could be utilized for the sustainable development of IHR (max. 1000 words)

The overall study can be summarized by 6 different objectives which includes (1) identification of optimal locations for hydropower generation, (2) Identification of critical glacial lakes in Himachal Pradesh, (3) Hydrodynamic modelling of the critical glacial lake, (4) Livelihood surveys of villages in Himachal Pradesh. These objectives are closely associated with sustainable development in the IHR. Determination of optimal hydropower site will significantly increase resource extraction and its construction will lead to the least ecological disturbance. Identification of critical glacial lakes would help in identifying the hotspots and developing a framework for monitoring them. This could result in minimizing the hazards associated with GLOF. Livelihood surveys will help us better understand the deep-rooted problems in the alpine systems such as availability of clean water, susceptibility to disasters such as earthquakes, floods, and landslides etc.

7.2 Efficient ways to replicate the outcomes of the project in other parts of IHR (Max 1000 words)

All the frameworks/methods proposed in the study can be easily applied to any state/basin or even at the global level. The only bottleneck in the process will be computational limitation of the available infrastructure which can be eliminated by using cloud-based processing platforms such as Google Earth Engine, Microsoft Azure, etc.

For the identification of optimal locations for hydropower generation, a very simple methodology is developed which uses freely available tools and datasets this framework can be easily applied to various IHR regions. The glacial lakes inventory was developed for the entire IHR region these findings can be shared with the different state agencies and better monitoring of glacial lakes can be carried out to prevent any hazards associated due to GLOF.

7.3 Identify other important areas not covered under this study needs further attention (max 1000 words)

A wide variety of remotely sensed data is available to observe glacial lake change and expansion mechanism. However, relying only on data obtained from remote sensing is inadequate as it cannot estimate lake bathymetry, vertical changes in damming moraine and surrounding properties such as the presence of dead ice, bedrock, and the overhanging cliff which are important to study GLOF. Additionally, ALOS PALSAR dem used to obtain geometry parameters of the dam and surrounding areas may include inaccuracies (Isoguchi and Shimada 2007). Almost all the glacial lakes evaluated in the study are located at high altitudes (>4000) where permafrost can be easily formed. The chain reaction of the permafrost thaw will alter the stability of the moraine dam which was not considered in the study due to the absence of suitable data. The PFV estimated using SLA analysis represents a maximum projection as we assume a cylindrical bathymetry for the lake, which implies no change in shoreline even after lowering of the lake, whereas bathymetry of a lake gradually deepens from downstream to upstream, this factor was not considered in the analysis (Fujita et al. 2013; Fujita et al. 2009).

7.4 Major recommendations for sustaining the outcome of the projects in future (500 words in bullets)

Accurate identification of potentially dangerous glacial lakes and potential hydropower location is challenging, but yet a crucial task and is vital to maintain the trustworthiness of the decision-makers and local communities. Generally, the regional studies assess different parameters to identify potential hazard associated with glacial lakes and effective location for hydropower generation, and therefore, the obtained results depict very different results. Therefore, we recommend the stakeholders to base the decision criteria on the analysis based on new and more comprehensive data, more sophisticated analysis, enhanced understanding of system, and robust model simulations with wider consideration of uncertainties. The important characteristics to prioritize the glacial lake studies should be (1) credibility of the evidence that the applied model relies upon; (2) standardized application of methodology; (3) inclusion of most frequent GLOF triggers; and (4) the level of details in the estimated probable impact. The primary objective of policy-research linkage should be to convey advanced scientific data and technology to planning and mitigation and ultimately reduce the projected risk. One crucial aspect of these hazard assessments is the consideration of worst-case scenarios, something that is not very likely and this must be appropriately communicated to the decision-makers. Second, there should be formal communication channels between policy-makers and research scientists to enable precise knowledge transfer lastly, although the associated risk with the glacial hazards is very high, yet is mostly indeterminate, and the present tendency of grossly overstating the results in terms of both hazard and potential catastrophe needs to be realized and strictly discouraged. In the present study, the identification of critical glacial lakes was done for the entire IHR region. The hotspots of critical lakes and their associated hazard risk were quantified. This inventory can be used to develop a network to monitor critical lakes thus developing an early warning system to detect hazards and better management of natural resources in the Himalayan region.

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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 filled
Appendix 7 – Any other (specify)

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