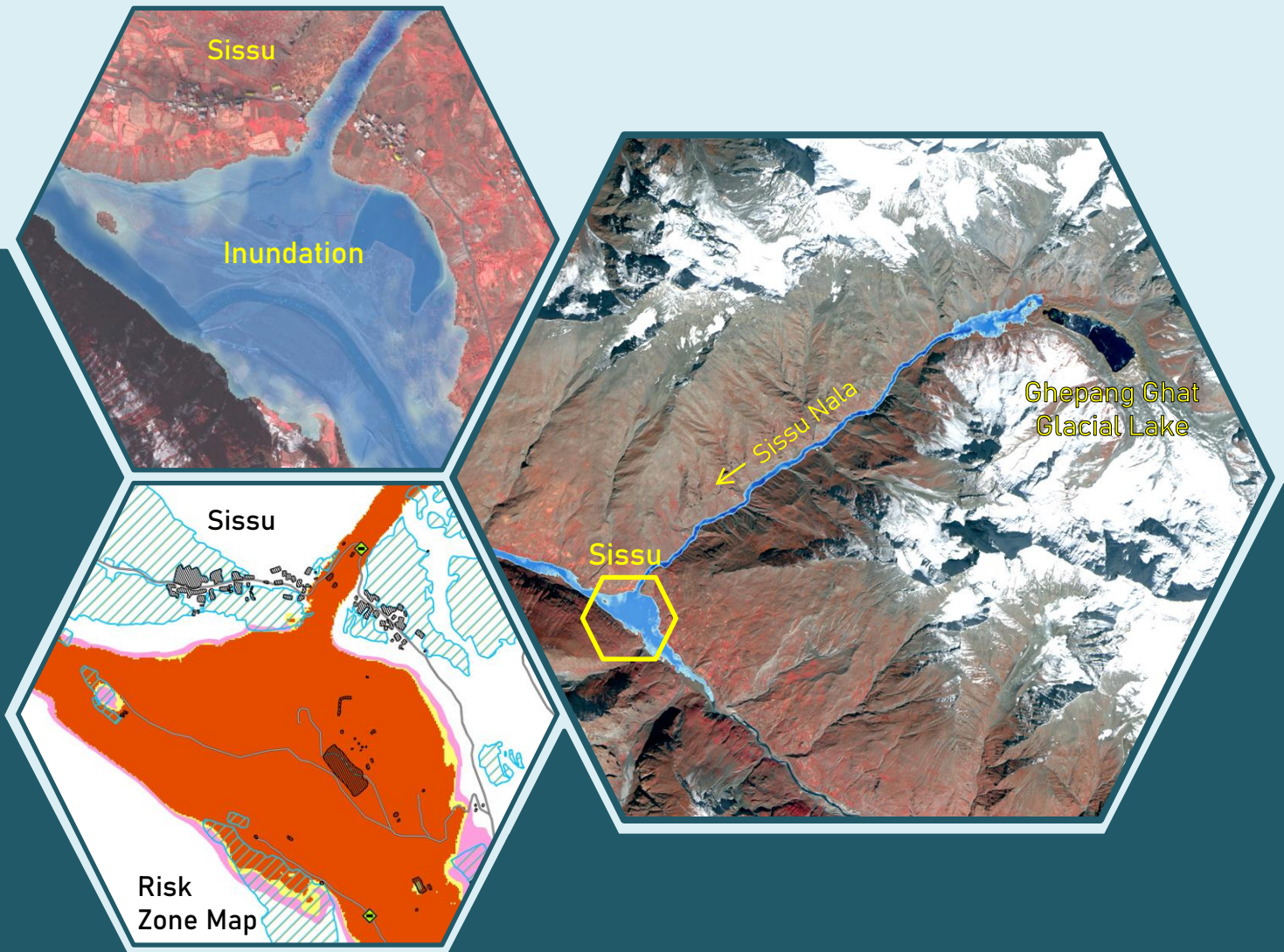


GLOF Risk Assessment of Ghepang Ghat Glacial Lake in Indus River Basin

Prepared under National Hydrology Project



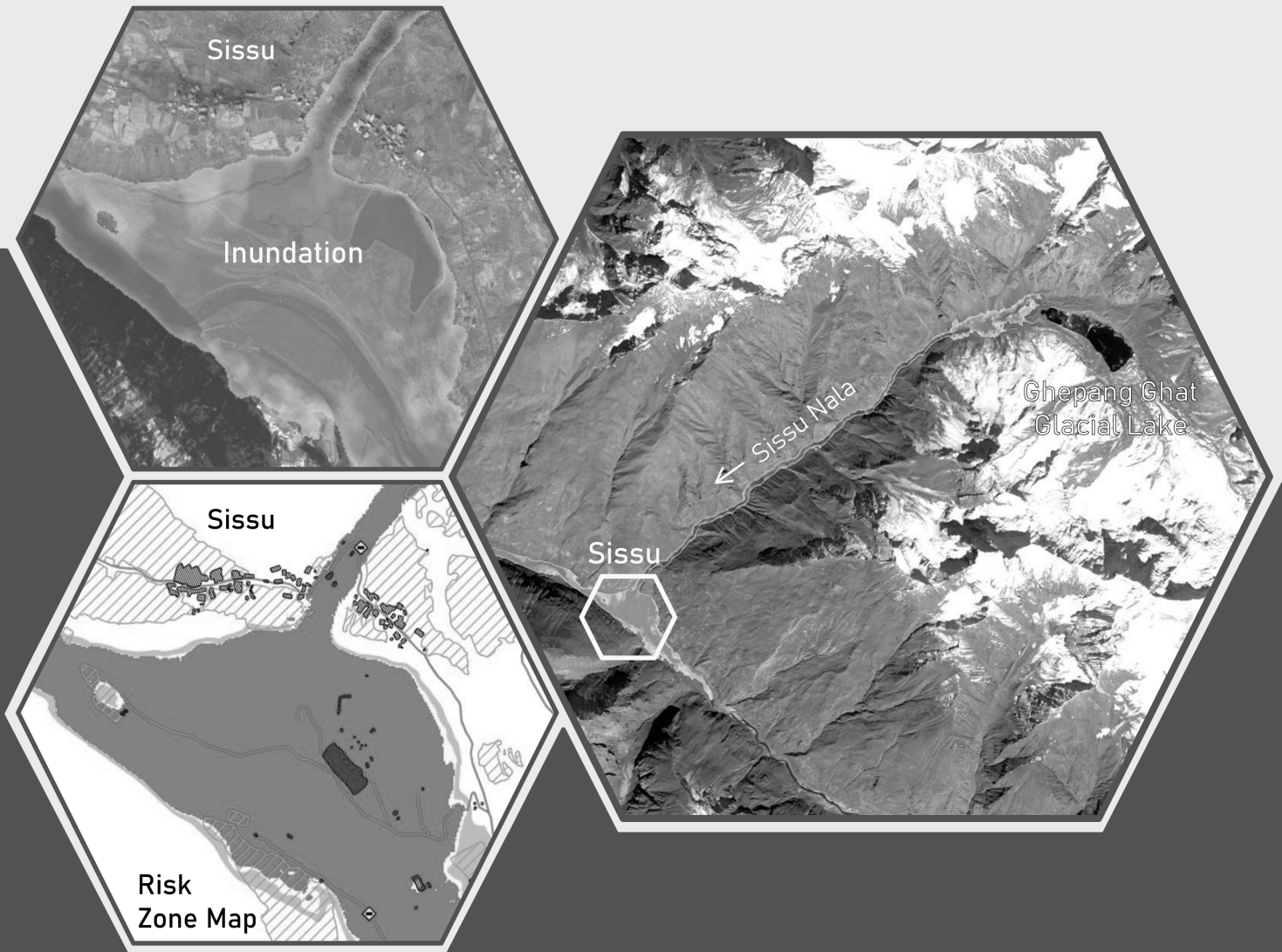
National Remote Sensing Centre

Indian Space Research Organisation
Department of Space, Government of India
Hyderabad – 500 037

November 2023

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November 2023



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Published by

National Remote Sensing Centre, ISRO
Department of Space, Government of India
Hyderabad - 500 037, Telangana, India
<https://www.nrsc.gov.in>

Production

NRSC has taken up several activities under the National Hydrology Project (NHP), sponsored by the Department of Water Resources, River Development and Ganga Rejuvenation (DoWR, RD&GR), Ministry of Jal Shakti, Government of India (GOI) with financial aid from the World Bank.

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DOCUMENT CONTROL SHEET

1	Security Classification	Official		
2	Distribution	Internal		
3	Report/Document version	(a) Issue no. 1	(b) Revision & Date	
4	Report/Document Type	Technical report		
5	Document Control Number	NRSC-RSA-WATER RE-WRAD-NOV2023-TR-0002295-V1.0		
6	Title	GLOF Risk Assessment Of Ghepang Ghat Glacial Lake in Indus River Basin		
7	Particulars of collation	Pages: 110	Figures: 71	Tables: 31
8	Author(s)	B. Simhadri Rao, Saksham Joshi, Pamir Roy, Sweta and P.V. Raju		
9	Affiliation of authors	Water Resources Assessment Division (WRAD), Water Resources Group, RSAA, NRSC, ISRO, Hyderabad		
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11	Scrutiny mechanism	Approved / Controlled by	Dr. K. Sreenivas, Deputy Director (RSAA)	
12	Originating unit	Water Resources Group (WRG) Remote Sensing Applications Area (RSAA) National Remote Sensing Centre, Hyderabad-500 037		
13	Sponsor/Name &Address	National Hydrology Project Ministry of Jal Shakti, New Delhi, Govt. of India		
14	Date of Initiation	July 2023		
15	Date of Publication	November 2023		
16	Abstract: This report describes the GLOF risk assessment of the Ghepang Ghat glacial lake in the Indus River Basin. It contains detailed description about the study area, data used, and the methodologies for hydrodynamic GLOF modelling simulations and GLOF risk assessment for various GLOF scenarios. High resolution satellite images are used for mapping of infrastructure and other public utilities along the river reach for identifying the elements of exposure due to GLOF. A total of eight GLOF scenarios based on the volume of lake discharged in case of moraine breach (100%, 75%, and 50%), weather condition (clear weather/PMP), and failure mode (overtopping/piping), were simulated using the 2D hydrodynamic dam-break modelling software. The results of each simulation and consequent GLOF risk maps are also included in this report.			
	Keywords: Glacial Lakes, Remote Sensing, Indus River basin, GLOF modelling and GLOF risk			

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List of Abbreviations

amsl	Above Mean Sea Level
AWiFS	Advanced Wide Field Sensor
CWC	Central Water Commission
DTM	Digital Terrain Model
DoWR, RD&GR	Department of Water Resources, River Development and Ganga Rejuvenation
FCC	False Colour Composite
GL	Glacial Lake
GLOF	Glacial Lake Outburst Flood
GOI	Government of India
ha	Hectare
HEC	Hydrologic Engineering centre
HIS	Hydrological Information System
HKH	Hindu Kush-Himalayas
HP	Himachal Pradesh
I(d)	Glacier Ice-dammed Lake
I(s)	Supra-glacial Lake
ICIMOD	International Centre for Integrated Mountain Development
IHR	Indian Himalayan Region
India-WRIS	India - Water Resources Information System
IRS	Indian Remote Sensing Satellite
ISRO	Indian Space Research Organisation
JK	Jammu& Kashmir (UT)
Km ²	Square Kilometre
LA	Ladakh (UT)
Landsat	Land Resources Satellite
LISS-III	Linear Imaging Self Scanning Sensor - III
LISS-IV	Linear Imaging Self Scanning Sensor - IV
m	Metre
M(e)	End-moraine Dammed Lake
M(l)	Lateral Moraine Dammed Lake
M(lg)	Lateral Moraine Dammed Lake (with ice)
M(o)	Other Moraine Dammed Lake
NDWI	Normalized Difference Water Index
NHP	National Hydrology Project
NIR	Near InfraRed
NRSC	National Remote Sensing Centre
NWIC	National Water Informatics Centre
PMS	Probable Maximum Storm
PMP	Probable Maximum Precipitation
RAS	River Analysis system
RS	Remote Sensing
RS-2	Resourcesat-2
SOI	Survey of India
TM	Thematic Mapper
USGS	United States Geological Survey
UT	Union Territory

Summary

National Remote Sensing Centre (NRSC), Indian Space Research Organisation (ISRO), Hyderabad as one of the Implementing Agency under the National Hydrology Project (NHP), is carrying out hydrological studies using satellite data and geo-spatial techniques. As part of NHP, a detailed glacial lake inventory, prioritization of glacial lakes, Glacial Lake Outburst Flood (GLOF) inundation simulation and GLOF risk assessment for selected lakes are taken up for entire catchment of Indian Himalayan Rivers covering Indus, Ganga, and Brahmaputra River basins.

A total of 28,043 glacial lakes have been mapped in the entire catchment area of Indian Himalayan River basins using a total of 397 high resolution multispectral Resourcesat-2 LISS-IV satellite images, with a total lake water spread area of 1,31,070 ha and further details are available in Glacial lake atlas of Indian Himalayan River Basins (https://www.nrsc.gov.in/Atlas_Glacial_Lake). Technical reports on inventory and prioritization of glacial lakes in Indus and Ganga river basins are published describing the details of prioritization methodologies. In each river basin, top five prioritized glacial lakes are selected for further detailed study of GLOF inundation simulation and GLOF risk assessment. This technical report provides the details of GLOF inundation simulation for various scenarios and GLOF risk assessment of Ghepang Ghat lake which is one of the five prioritized glacial lakes in Indus river basin.

The Ghepang Ghat Glacial Lake is located at an elevation of 4,068 m a.m.s.l. in the state of Himachal Pradesh, India. The stream emerging from this lake called Sissu nalla joins the Chandra river at about 11 km from the origin of lake in North side. A change analysis of the lake water spread area carried out using Landsat-5 of 1989 and Sentinel-2 of 2022 multi-temporal optical imagery revealed a 178% increase in size from 36.49 ha to 101.30 ha. Such alarming rate of lake expansion and the rapid urbanization of its downstream settlements have increased the possibilities of a catastrophic impact due to GLOF event by many folds. This necessitated a detailed GLOF risk assessment in case of a breach of the natural moraine dam holding about 35 MCM of water. A high resolution Digital Terrain Model of Tandem-X with a spatial resolution of 5 m was used in the study to simulate GLOF inundations of various scenarios. A series of 2D hydrodynamic dam-breach simulations in HEC-RAS software are developed for 8 different failure modes (overtopping and piping), different volumes of water released in case of a failure of the lake moraine (100%, 75%, and 50%), and under two weather conditions (clear-weather and Probable Maximum Precipitation). The worst-case scenario (scenario 8) was the one with a 100% discharge of the lake water under piping failure due to PMP occurrence over the catchment area of glacial lake. The breach depth in the worst-case was calculated as 34.62 m with an average breach width of 91.81 m, and it formed within 48 minutes since the start of breach. The GLOF peak hydrograph of 9,673 cumecs propagated from the moraine dam to the nearest settlement of Sissu in just 21 minutes where it was estimated as 9,450 cumecs. The narrow and steep V-shaped valley from the downstream of glacial lake to Sissu village has resulted in high flood depths of around 20 m along with velocities of approximately 12 m/s during the peak of the flood wave near the village. The simulated GLOF peak of flood hydrographs for 100%, 75% and 50% of lake water releases scenarios (scenario 1, 3 and 5) yielded 9,378 cumecs, 6,628 cumecs and 3,127 cumecs near Sissu village for overtopping failure. The GLOF hydrograph was routed downstream up to a distance of 150 km from the glacial lake where it was attenuated near to the normal

average flow of the stream. Ghepang Ghat lake GLOF outputs of flood depth, flood velocity, inundation extent, and flood wave arrival time were used to generate hazard and risk maps for the downstream areas along the river reach. GLOF hazard maps are prepared by integrating flood depth and flood velocity for different scenarios.

High resolution satellite images (spatial resolution of 0.5 m) are used for mapping of settlements, agriculture lands, road network, road bridges, hydropower projects and other utilities along the river reach for identifying the elements of exposure due to the various Ghepang Ghat lake GLOF scenarios. The mapped infrastructure was integrated with GLOF simulated inundation extent to identify the affected elements. The total number of settlements, agricultural land, bridges, and road length inundated in the worst-case scenario (scenario 8) are 34, 204 ha, 57 and 106 km respectively. All the 34 settlements are partially flooded by the GLOF inundation extent.

Finally, GLOF risk maps are prepared by integrating flood hazard (flood depth X flood velocity) and flood wave arrival time, which was classified, into zones of high, medium, and low risk. The combination of flood hazard and flood wave arrival time for flood risk mapping presents a unique approach to flood risk assessment as demonstrated in this study. Zones of high risk are defined as those regions where flood severity was either medium or high, and the flood wave arrival time was within 2 hours since the start of the breach. Consequently, Sissu village and nearby areas falls under the high-risk zone, and further downstream, the risk reduces to medium near Ghondhla at distance of 21 km from lake for scenarios 1 & 2, 7 & 8. The medium risk zone extends for a distance of 94 km along the river reach from lake covering the settlements of Gushal, Tandi Udaipur and Phindru.

1. Introduction

1.1. About the Project

The National Hydrology Project (NHP) sponsored by the Department of Water Resources, River Development and Ganga Rejuvenation (DoWR, RD&GR), Ministry of Jal Shakti, Government of India, with financial aid from the World Bank. It aims to improve the extent and accessibility of water resources information and strengthen institutional capacity to improve water resources planning and management across India. Its mission is to establish a sound and effective hydrologic database and a Hydrological Information System while also developing scientific and consistent tools/aids to assist the concerned stakeholders in effective water resources planning and management of the Implementing Agencies.

National Remote Sensing Centre (NRSC) as one of the Central Implementing Agency under NHP is engaged with generation of geo-spatial products & services pertaining to water resources sector. The activities include generation of high resolution Digital Elevation Models (DEM), development of flood early warning systems, Glacial Lake Outburst Flood (GLOF) risk assessment, spatial snowmelt runoff modelling, decision support system development for irrigation water management, modelling & dissemination of hydrological products to support water resources management and capacity building to NHP stakeholders. The satellite data based geo-spatial products & services, mainly encompassing the following:

- Satellite Data/Geo-Spatial Data Hosting & Services through Bhuvan Web Portal
- Water Resources Information Products & Services (Satellite/Model derived - Bhuvan/India- Water Resources Information System (India-WRIS)/National Water Informatics Centre (NWIC))
- Customized Applications Development (Flood Forecasting, Irrigation Water Management)
- Hydro-conditioned Digital Elevation Model (Satellite & Aerial)
- Capacity Building (Customized Training & Hand Holding)

As part of various NHP technical studies carried out, NRSC has taken up “Glacial Lake Outburst Flood (GLOF) Risk Assessment of Glacial Lakes in the Himalayan Region of Indian River Basins”. Under this activity, it was proposed to prepare an updated inventory of glacial lakes, prioritization and selection of critical glacial lakes based on certain characteristics, GLOF modelling and flood inundation simulation for selected few lakes using high resolution Digital Terrain Model (DTM) for downstream of the lakes along their river reach, and to assess GLOF risk.

1.2. The GLOF Component

Glaciers are essentially huge masses of ice flowing under the influence of gravity. Glacial lakes are water bodies that are fed by glacier melt water and extend with a free surface on, in, under, in front, or beside the glaciers, and are usually dammed by glacial ice or

loosely consolidated moraine deposits. At times, the glacial lake dams breach due to various reasons such as failure of the unstable moraine, avalanches/landslides into the lake, heavy rainfall, etc., the torrential amounts of water and debris released from the lake causes catastrophic flooding in its downstream. This phenomenon is called a Glacial Lake Outburst Flood and it is a common disaster occurring in the Himalayan Region of the Indian River Basins. Many GLOF events are reported in Himalayan mountain region resulting in loss of lives and damages to public infrastructure.

The risk of catastrophic GLOF events in the Indian Himalayan Region (IHR) has increased due to the rise in global temperatures. The glacier ice and snow in the IHR serves as a direct indicator of climate change and global warming. Many studies have noted the accelerated melting of glaciers and their retreat in the last few decades due to climate change. Consequently, the glacial lakes have generally increased in number and size indicating a spike in their damage potential in case they undergo a GLOF event. It is a fact that GLOFs are an emerging threat to the socio-economy of the high mountain regions of the world, particularly in India where they tend to cause significant damage. Therefore, it is imperative to identify those glacial lakes that pose a significant threat to the downstream communities and assess the risk well in advance so that detailed Disaster Management Plans (DMPs) can be created to mitigate the damages due to GLOFs.

Towards the assessment of risk of GLOFs, NRSC/ISRO has taken up the following tasks under this component:

- i. To prepare a comprehensive inventory of glacial lake lakes of size greater than 0.25 hectare using Resourcesat-2 LISS-IV multispectral satellite images of spatial resolution of 5.8 m in entire Himalayan region
- ii. Prioritization of inventoried glacial lakes to identify the critical glacial lakes
- iii. GLOF modeling (dam breach modeling) for the prioritized glacial lakes and identification of infrastructure elements which gets exposed due to simulated GLOF events
- iv. GLOF risk assessment for selected glacial lakes

A total of 28,043 glacial lakes have been mapped in the Indian Himalayan Region (IHR) covering Indus, Gang and Brahmaputra river basins using a total of 397 high resolution Resourcesat-2 LISS-IV multispectral images with a total lake water spread area of 1,31,070.90 hectares. Each of these glacial lakes has been assigned a unique ID along with several key attribute information related to its hydrology, geometry, geography and topography. Based on the process of lake formation, location, and type of damming material, the glacial lakes has been classified into four major categories viz. moraine-dammed, ice-dammed, glacier erosion, and other glacial lakes. Using glacial lake database, basin-wise atlases of Indus, Ganga and Brahmaputra are published on December 2020 (NRSC-RSAA-WRG-WRAD-Nov2020-TR-0001702-V1.0), June 2021 (NRSC-RSAA-WRG-WRAD-Mar2021-TR-0001818-V1.0), and July 2022 (NRSC-RSAA-WRG-WRAD-May2022-TR-0002026-V1.0) respectively. Combined atlas for the entire IHR was published on March 2023 (NRSC-RSA-WATER RE-WRAD-Mar2023-TR-0002176-V1.0). All these glacial lake atlases are freely available to download at the official websites of the NRSC (https://www.nrsc.gov.in/Atlas_Glacial_Lake) and NHP (<https://nhp.mowr.gov.in>).

The inventoried glacial lakes were prioritized for further detailed study through a rigorous two-step procedure i.e. preliminary screening, followed by ranking. Preliminary screening of glacial lakes was carried out based on four parameter criteria comprising lake type, lake area, lake association with glacier and lake with settlements enroute river reach. The preliminary screened in glacial lakes were ranked based on a total of 6 criteria viz. lake area, lake type, distance between glacier snout and lake inlet, slope between glacier snout and lake inlet, distance between lake outlet and nearest settlement, and slope between lake outlet and nearest settlement. Two technical reports on inventory and prioritization of glacial lakes in Indus (NRSC-RSA-WATERRE-WRAD-FEB2021-TR0001805-V1.0) and Ganga (NRSC-RSA-WATER RE-WRAD-NOV2022-TR-0002116-V1.0) river basins are published describing the details of prioritization methodologies. In each river basin, top five prioritized glacial lakes are selected for further detailed study of GLOF inundation simulation and GLOF risk assessment. This technical report provides the details of GLOF inundation simulation for various scenarios and GLOF risk assessment of Ghepang Ghat lake which is one of the five prioritized glacial lakes in Indus river basin.

The Ghepang Ghat glacial lake dam breach was simulated using HEC-RAS 2D hydrodynamic modeling to estimate the flood extents, flood depths, flood peak discharges, flood velocities, and flood wave arrival time in case of a probable GLOF event. A series of 2D hydrodynamic dam-breach simulations in HEC-RAS software are developed for 8 different failure modes (overtopping and piping), different volumes of water released in case of a failure of the dam (100%, 75%, and 50%), and under different weather conditions (clear-weather and Probable Maximum Precipitation). The results of HEC-RAS simulations were used for generating hazard maps of flood severity (depth x velocity) and GLOF risk assessment. A new method of generating GLOF risk maps was devised in this study which combines flood severity with flood wave arrival time using a matrix method. The details of the study are given in appropriate sections.

1.3. Organization of the Report

This is a technical report provides details on the hydrodynamic modeling of Glacial Lake Outburst Floods (Dam Break analysis), and the risk assessment of GLOFs in the downstream areas. The key elements of this report include:

- Review of Literature on GLOF modeling and Risk Assessment
- Study Area and Data Used
- Hydrodynamic Modeling of GLOF (Dam Break analysis):
 - Selection of appropriate study area limits
 - Description of Dam Breach Scenarios
 - Data Requirements of the hydraulic model
 - Estimation of Dam Breach Parameters
 - Development of the model
- Flood Inundation and Hazard Mapping
- Elements of Exposure due to GLOF
- GLOF Risk Assessment
- Conclusions

2. Literature Review

2.1. Glacial Lake Outburst Floods

The IHR houses the largest volume of glaciers and perennial snow outside the Poles thus receiving the name ‘Third Pole’ (Rao et al., 2023; Zheng et. al., 2021). Being densely glaciated, the IHR is very sensitive to climate change and serves as a good indicator of its impacts (Maskey et al., 2020; Kraaijenbrink et al., 2017; Haeberli et al., 2013; ICIMOD, 2011). Recent decades have witnessed rapid global land surface warming rates ($+0.03^{\circ}\text{C}/\text{year}$) that exceed the global mean surface temperature rate ($0.011^{\circ}\text{C}/\text{year}$) from 1951 to 2012 (Zhang et al., 2015; IPCC, 2014). This rapid warming phenomena has induced an extensive shrinkage of glaciers causing a significant reduction of glacier length in the IHR (Dubey and Goyal, 2020; Maurer et al., 2019; Sakai & Fujita, 2017; Cogley, 2016). This reduction in length of glaciers is known as glacial retreat which aids in the formation of new glacial lakes, and expansion of existing ones (Nie et al., 2018; Song et al., 2017; Westoby et al., 2014; Kang et al., 2010). Glacier bed topographies have been modeled in the Himalayas, and it has been predicted that around 5,000 depressions may turn into glacial lakes in the near future (Linsbauer et al., 2016). The International Centre for Integrated Mountain Development (ICIMOD) prepared an inventory of around 9,000 glacial lakes of size > 0.3 hectares in the Himalayas between 1999 and 2005 (Mool, 2005). The latest and most comprehensive glacial lake inventory showing 28,043 glacial lakes in the IHR of size ≥ 0.25 hectares has been published by NRSC, ISRO (Rao et al., 2023). These inventories highlight the marked increase in the number of glacial lakes over time in the IHR. The formation of pro-glacial lakes accelerates the melting of glaciers further in what is called a positive-feedback mechanism that results in more expansion of the lakes (Tsutaki et al., 2019; King et al., 2018). An increase in the number and areal extent of glacial lakes brings both large opportunities and risks (Zheng et. al., 2021; Farinotti et al., 2019; Haeberli et al., 2016). Glacial lakes are important water resources as they serve as sources of pristine water for the downstream communities (Rawat et al., 2022; Brighenti et al., 2021; Huss et al., 2017). Unfortunately, glacial lakes also behave as sources of great danger to the lives and livelihoods in their downstream in the form of catastrophic Glacial Lake Outburst Flood (GLOF) events (Dubey et al., 2020; Cook et al., 2018).

Glacial lakes are mostly bound by loosely consolidated glacial deposits called moraines, or glacial ice dams, or moraines with ice cores, and surrounded by unstable slopes or hanging glaciers (Rinzin et al., 2023; Otto, 2019). Mass movements into the lake as a result of slope failure may cause impulse waves that would overtop the moraine or ice dam causing its overtopping failure. Overtopping of the dam may also be caused due to pluvial, nival, and glacial runoff induced overfilling of the lake (Taylor et al., 2023; Rounce et al., 2016; Emmer et al., 2013). Overtopping failure occurs when water flows over the damming material and erodes the downstream face of the dam. Another mode of dam failure occurs due to piping failure under which the hydrostatic pressure of the water tends to create a pipe-like hole that eventually grows big enough to cause the dam to collapse (Chowdhury et al., 2021; Schmidt et al., 2020). Moraines may also fail due to slope undercutting by glacio-fluvial erosion and heavy monsoonal rainfall (Barnard et al., 2001; Owen et al., 1996). Ice-dam failures are mostly concentrated in the Pamir and Karakoram regions

(Bhambri et al., 2019; Hewitt and Liu, 2010), while moraine-dam failures are more common in the IHR (Nie et al., 2018). In the event of failure of the dam, there is a sudden high magnitude discharge of water with a high velocity of flow from the glacial lake that tends to flood the downstream areas (Rinzin et al., 2021; Begam et al., 2018). This phenomenon is termed Glacial Lake Outburst Flood (GLOF) and it can devastate entire towns and settlements in its way downstream (Dubey and Goyal, 2020; Cook et al., 2018). Fifty-one incidents of GLOFs have been reported from the IHR (Nie et al., 2018). An inventory of GLOFs reported that the maximum number of casualties have occurred in the Central Himalayas with fewer floods but higher damage (Carrivick and Tweed, 2016). GLOFs have been recognized as one of the most serious natural hazards in the IHR (Chen et al., 2021; Veh et al., 2020). These events are more catastrophic in the IHR due to the steep slopes and narrow flow channels in the terrain (Sattar et al., 2019; Worni et al., 2012). GLOFs are significantly hazardous and destructive causing widespread damage to property, infrastructure, agricultural land and livelihoods, thereby resulting in extensive loss of life (Rinzin et al., 2023; Taylor et al., 2023; Allen et al., 2019). One of the most notable examples of GLOFs in the IHR was the Chorabari Lake GLOF that occurred on 16th June 2013 in Kedarnath, Uttarakhand. This GLOF event was triggered by heavy rainfall induced mass movements into the lake and it devastated the villages of Kedarnath, Rambara, and Gaurikund on its way (Das et al., 2015; Martha et al., 2014). Around 6,000 people were killed in the region, and most of the deaths were directly linked to the GLOF (Allen et al., 2015; Guha-Sapir et al., 2014). Countless bridges and roads were washed away or damaged, and about thirty hydropower plants were affected or completely devastated (Sati and Gahalaut, 2013). In light of the highly hazardous nature of GLOF events, it becomes necessary to lay out risk management and mitigation plans in advance to prevent loss of life.

As mentioned in the previous section, Ghepang Ghat glacial lake is one of the five prioritized glacial lakes in Indus river basin and considered for detailed study. Kaushik et al. (2020) and Worni et al. (2013) have also stated that the village of Sissu is located in the path of potential GLOFs from this lake. Gupta et al. (2021) have prioritized potentially critical glacial lakes in the Indus River Basin using satellite derived parameters and they also confirm the fact that Ghepang Ghat is one such high risk glacial lake for GLOFs. The Ghepang Ghat glacier is among the glaciers with the highest mean negative mass balances in the Chandra sub-basin of -1 to -1.22 m w.e./yr (Tawde et al. 2017). Kaushik et al. (2020) also highlight the increasing trend of mean annual temperature in the basin at a rate of 0.021°C/yr from 1961 to 2015. Global warming induced high negative mass balance has caused retreat of the Ghepang Ghat glacier at an unprecedented rate leading to the rapid expansion of the lake. Furthermore, there is a significant amount of ice loss at the glacier snout due to calving which adds to the pace of expansion (Prakash & Nagarajan, 2017).

2.2. Role of Remote Sensing and GIS

The preparation of GLOF risk management plans, however, requires a lot of data to analyze the susceptibility of the lake to outburst, its geometry, how the failure would be triggered, what magnitude of discharge would be expected, how the flood wave will

propagate downstream, and how it would impact the lives and livelihood on its course. Considering the challenging terrain where these lakes are usually situated, gathering in-situ data becomes very tedious and often impossible (Guru et al., 2019; Pratap et al., 2016). In such scenarios, Remote Sensing (RS), and Geographical Information Systems (GIS) serve as highly indispensable tools in providing the required information on glacial lakes (Gupta et al., 2019; Cogley et al., 2011). High spatio-temporal and spectral resolution satellites provide extremely valuable information on glacial lake location, geometry, water spread area, type, etc. (Rao et al., 2023; Sharma et al., 2013). RS and GIS techniques coupled with hydrologic and hydraulic modeling approaches allow rapid investigation of these challenging glaciated terrains and they could play a key role in prioritizing critical glacial lakes and monitoring GLOF events in near real-time (Ahmed et al., 2022; Ahmed et al., 2021; Gilany and Iqbal, 2020).

There is a plethora of research on the applications of RS and GIS for glacial lakes and GLOF studies. The studies include preparation of glacial lake inventory and assessment of glacial lake distribution, GLOF susceptibility analysis, GLOF modeling, and GLOF risk assessment. Worni et al. (2013) inventoried glacial lakes in the Indian Himalayas and also carried out risk assessment for those lakes. ICIMOD (Ives et al., 2010) has a similar inventory of glacial lakes for the Hindu Kush Himalayas. Many regional glacial lake studies were also conducted (Sattar et al., 2019; Aggarwal et al., 2017; Raj et al., 2013). All these studies extensively use remotely sensed data such as Landsat, Sentinel, RS-2 imagery, etc., that have been processed using GIS software and tools.

2.3. GLOF Modeling Approaches

GLOFs have been modeled using different approaches in various studies. Many researchers apply analytical and numerical models to simulate the impact waves generated due to mass movements into the lake (L'Heureux et al., 2011; Biscarini, 2010; Heller et al., 2008a; Falappi and Gallati, 2007) that can trigger GLOFs. Some of the numerical models used for impact wave modeling include 2D-BING (L'Heureux et al., 2011), LS3D (Ataie-Ashthiani and Yavari-Ramshe, 2011), and FUNWAVE (Wei et al., 1995). Other studies simulate the dam breach process and outflow discharges using various different approaches and models, often combined with the impact wave effects (Sattar et al., 2023; Psomiadis et al., 2021; Worni et al., 2014; Westoby et al., 2014). Various dam breach models were used even before the year 2000, such as Lou Model, BEED, BRDAM, BREACH, NWS DAMBRK (Singh, 1996; Fread, 1982). There are empirical models that use regression equations based on the analyses of real dam failures to estimate dam breach parameters like breach formation time, breach geometry, and peak discharges (Wahl, 2010; Xu and Zhang, 2009; MacDonald and Langridge-Monopolis, 1984; Froehlich 1995a, b). Parametric models apply user defined dam breach parameters to provide breach hydrographs, such as HEC-RAS, MIKE 11, and NWS DAMBRK. Physical models on the other hand use hydraulic principles, erosion rates and geotechnical considerations to model the breach (Worni et al., 2014), e.g., BREACH, BRDAM, BEED, etc. BASEMENT (Faeh et al., 2012) and HR-BREACH (Morris et al., 2008) are some other models to simulate embankment failures. In addition, there are various models to simulate the flows occurring from a dam break such as HEC-RAS, NWS-FLDWAV, TELEMAC-2D, DASSFLOW, SOBEK, Delft3D, FLO-2D, RAMMS, IBER, and BASEMENT. The state-of-the-art models mostly use 1-D and/or 2-D hydrodynamic models to simulate GLOFs. HEC-RAS and MIKE 11 are widely used software that provide

dam break modeling capabilities to the user. These applications can solve the St. Venant Equations to simulate the GLOF process and flood wave hydrodynamic routing.

2.4. Risk Assessment of GLOFs

Assessment of risk of GLOFs requires the understanding of the terms risk, hazard, vulnerability, and exposure. The terms can be defined as:

Risk is the probability of a loss that depends on hazard, vulnerability, and exposure (Figure 1). The most common definition of risk is the combination of flood hazard and flood vulnerability at a given location.



Figure 1: Components of Risk

Mathematically, risk can be defined as (Lie et al., 2012; UN, 1992):

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability}$$

Hazard reflects the consequence of damage that could result from a flood of a given intensity. Or, it may also be defined as the potential occurrence of a natural or anthropogenic event that may cause loss of life, injury, health impacts, and damage to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.

Vulnerability in simple terms is the extent of harm that may occur to the elements exposed to the hazardous event. It can be expressed as:

$$\text{Vulnerability} = \text{Exposure} + \text{Susceptibility} - \text{Resilience}$$

Therefore, vulnerability is highly context specific. It varies with the element under consideration, e.g. Physical vulnerability for physical elements such as houses, roads, infrastructure, etc. Other types of vulnerability are social and economic vulnerability related to the society and the economy respectively.

Exposure is the presence of vulnerable elements within the extent of flood inundation. It is assessed based on an inventory of anthropogenic elements such as villages, roads, bridges, hydropower stations, etc. that may be affected by the hazard.

There are various sources that describe the different risk assessment methodologies, among which the latest ones are NDMA Guidelines on Management of GLOFs (NDMA, 2020), CWC Guidelines for Mapping Flood Risks Associated with Dams (CWC, 2018), GAPHAZ Assessment of Glacier and Permafrost Hazards in Mountain Regions - Technical Guidance Document (GAPHAZ, 2017), and AEMI Australian Emergency Management Handbook Series,

Technical Flood Risk Management Guideline (AEMI, 2014). In general, to assess the GLOF risk, firstly, hazard assessment is carried out involving (i) estimation of peak discharge and breach hydrographs, (ii) estimating water depths, velocities, inundation extent, and severity of flooding, and (iii) identifying the inundated elements. It can be carried out using 1D or 2D unsteady flow hydrodynamic modeling in HEC-RAS or similar software. Secondly, vulnerability assessment can be carried out to estimate the damages likely to be caused by GLOFs. It involves the use of depth-damage curves (Huizinga et al., 2017) to assess the susceptibility of exposed elements to undergo damage. Finally, risk assessment is carried out by combining the hazard and vulnerability assessments to generate GLOF risk maps that represent the adverse consequences associated with the GLOF events. Many studies have been conducted to assess the GLOF risks such as GLOF risk assessment in Nepal (Washakh et al., 2019; Shrestha et al., 2010), Bhutan (Rinzin et al., 2023), and in the Indian Himalayan regions (Rawat et al., 2023; Pandey et al., 2022; Ahmed et al., 2022; Sattar et al., 2021; ICIMOD, 2010), etc. It has been observed that most of the glacial lake outburst flood risk assessment methodologies differ from each other, and a common methodology is not available. GLOF risk assessment studies commonly terminate up to the assessment of hazard and do not generate risk maps due to the lack of vulnerability data. Therefore, it is proposed a unique approach to GLOF risk assessment in this study. The approach can be followed even when detailed vulnerability information is lacking, or the information is incomplete. In the present study risk assessment approach involves the generation of risk maps directly using hazard maps (hydrodynamic modeling outputs of depth, velocity) and flood wave arrival time. An overview of the approach and details are given in Chapter 3 and Chapter 8 correspondingly.

3. Study Area and Data Used

3.1. Ghepan Ghat Glacial Lake and its GLOF Potential

Ghepan Ghat glacial lake is one the top five prioritized glacial lakes in Indus river basin and hence taken up for further detailed study. The glacial lake is located at an elevation of 4,070 m a.m.s.l in the upper reaches of in the Chandra sub-basin of the Indus Basin, Himachal Pradesh (Figure-2). The geographical co-ordinates of Ghepan Ghat Glacial Lake are $32^{\circ} 31' 11''$ N and $77^{\circ} 13' 38''$ E. The river Chenab is formed after the two streams the Chandra and the Bhaga merge with each other. The Chandra and the Bhaga originate from the south-west and north-west faces of Barelacha pass respectively in the Himalayan canton of Lahul and Spiti valley in Himachal Pradesh. The course of Bhaga upto the confluence is 80 km only having a steep slope with an average fall of about 24 metre per kilometre. The stream originating from Ghepan Ghat glacial lake called Sissu nalla joins Chandra river about 11 km from its origin. The confluence of Sissu nalla with Chandra river is at distance of about 90 km from Samudra Tapu glacier from where the Chandra river originates. The Chandra initially flowing southeast for about 88 km sweeps round the base of the mid-Himalayas and joins the Bhaga at Tandi, after traversing a total length of about 125 km. Thereafter the united stream, known as the Chenab or Chandra Bhaga, flows in a north-westerly course for about 46 km where it receives its first major tributary the Miyar Nalla on the right bank. Then it flows for another 90 km generally in a northerly direction in Himachal Pradesh when it crosses the Pangti valley before entering to Padder area of Doda district of Jammu province in Jammu & Kashmir State.

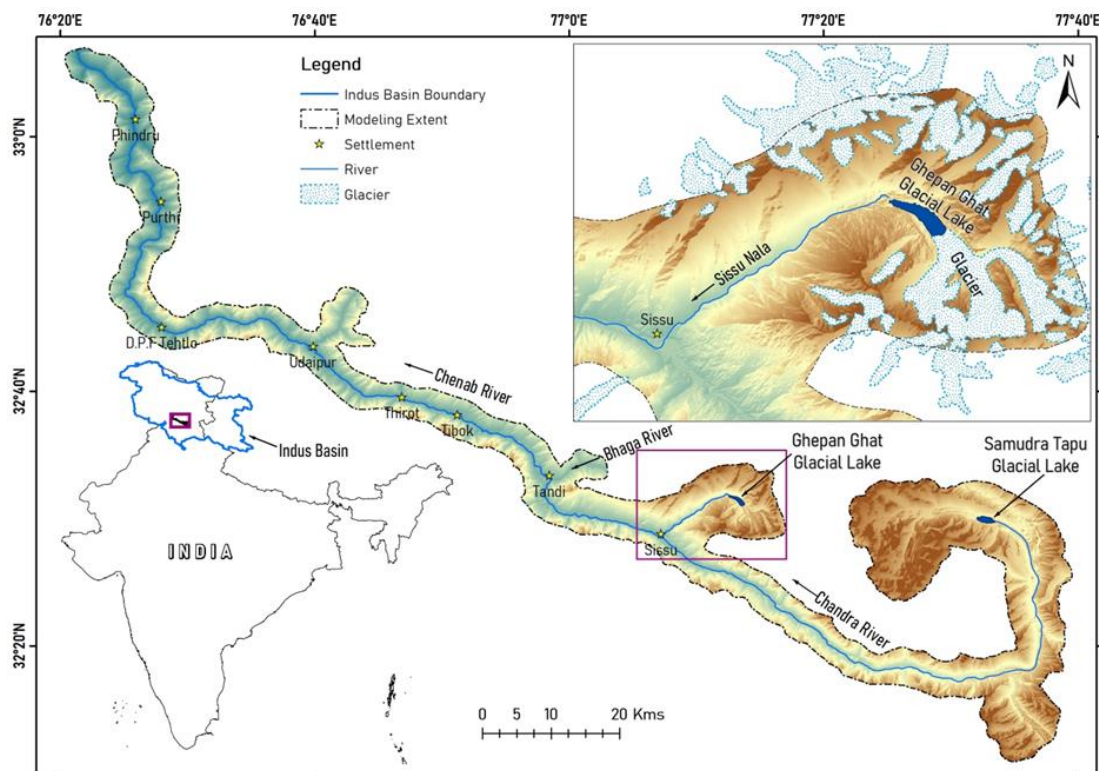


Figure 2: Location of Ghepan Ghat Glacial Lake

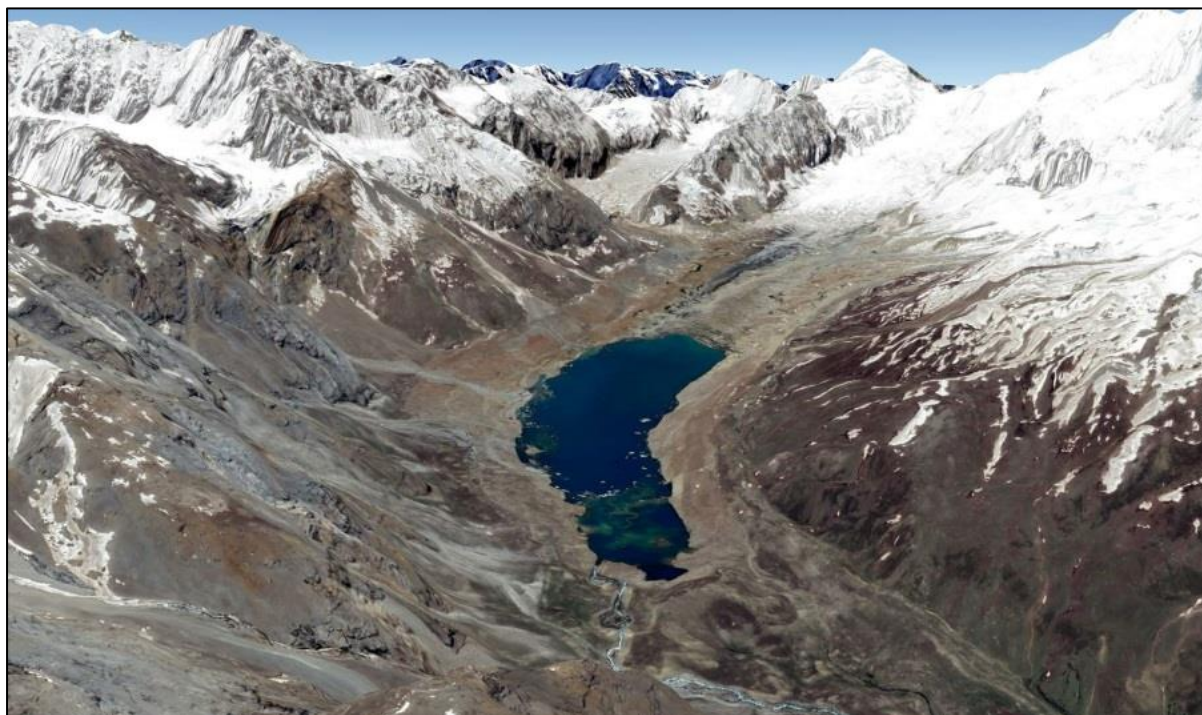


Figure 3: Ghepang Ghat Glacial Lake and its environs

Figure 3 shows Resource-2 LISS-IV multispectral satellite image of Ghepang Ghat glacial lake and its surroundings. The nearest settlement of Sissu lies around 11 km downstream of the lake at an elevation of 3,070 m a.m.s.l, i.e., 1000 m below the lake. The Sissu nalla has very steep slope with an average fall of about 90 metre per kilometre between the lake and Sissu village. In addition to very steep slopes, the channel is also narrow leading to higher flow depths. These conditions are highly favorable for catastrophic flooding in case of a GLOF event. Additionally, the slopes at the periphery of the lake are susceptible to avalanches and mass movements, which act as triggering factors for overtopping wave failure of the moraine dam.

According to Sattar et al. (2023), Ghepang Ghat has evolved from a supra-glacial lake into a pro-glacial one over the years. An analysis of multi-temporal satellite data using Landsat-5 of 1989 and Sentinel-2 of 2022 revealed a 178% increase in size. Figure 4 shows the lake water-spread area at different time periods, which increased from 36.49 hectare to 101.30 in a span of 33 years. Sattar et al. (2023) have carried out a comparison of the downstream settlements over a 12 year period (2010-2022) and provided evidence of significant infrastructure and agricultural land development. Such alarming rate of lake expansion and the rapid urbanization of its downstream settlements have increased the chances of a catastrophic GLOF event by many folds.

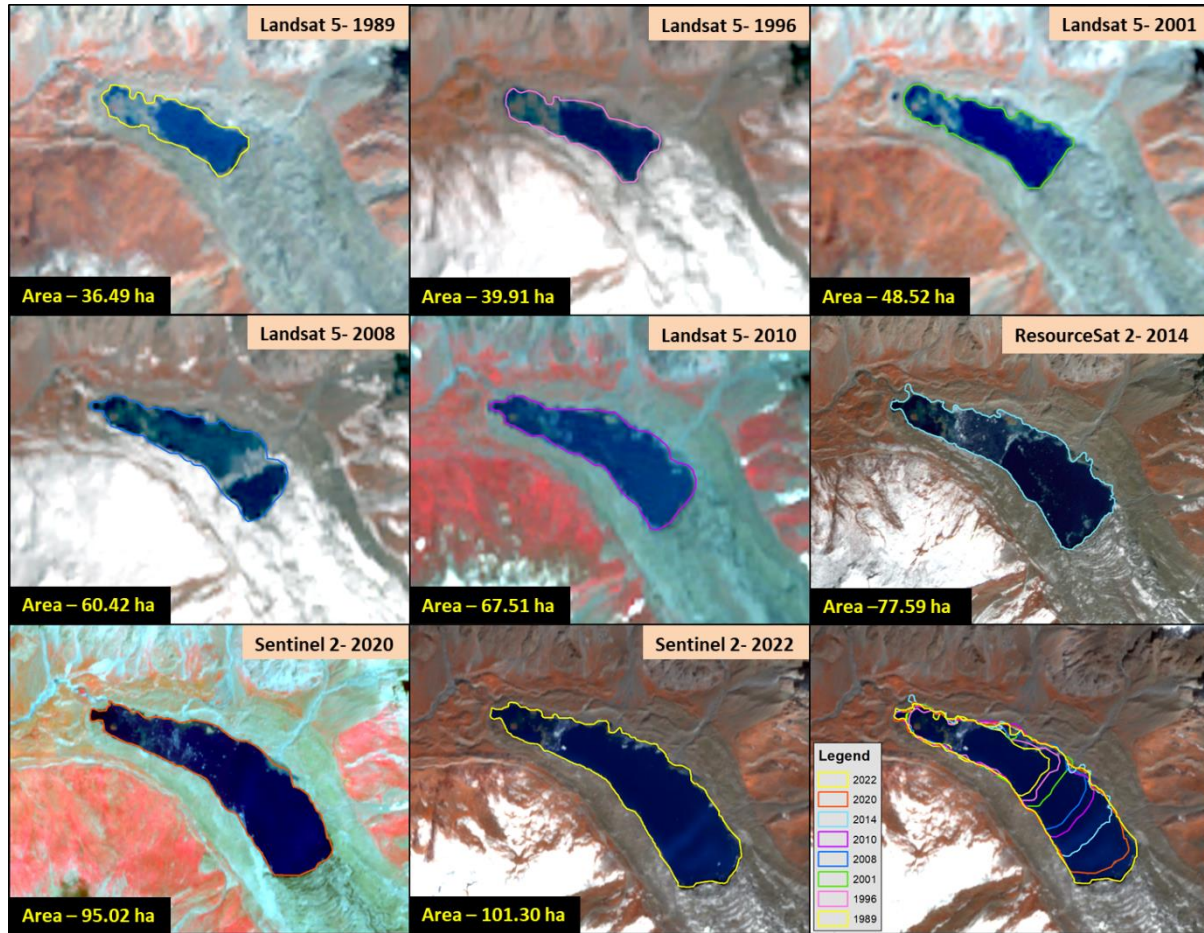


Figure 4: Long-term changes in Ghepang Ghat Glacial Lake water spread area

3.2. Catchment Area of Ghepang Ghat glacial lake

Ghepang Ghat glacial lake is fed by snowmelt and precipitation runoff from a catchment of area 4,870 hectare. Assuming rainfall occurs below 4,500 m elevation, about 1,486 hectares of catchment area contributes to rainfall runoff into the lake. The minimum and maximum elevations of the catchment are 4,017 m and 5,788 m respectively. The catchment area of the lake is located in the Lahul and Spiti district of Himachal Pradesh, and it is located in Chenab sub-basin in the Indus Basin. Figure 5 shows the drainage pattern upstream of the lake. Slopes in the catchment range from 0° to 84.39° near the peaks. Many studies mention the occurrence of ice and rock-ice avalanches over slopes $\geq 25^{\circ}$ or 30° (Mohanty and Maiti, 2021; Allen et al., 2019; Alean, 1985) that act as the most common cause of GLOFs in the Himalayas (Wang et al., 2011). A preliminary visual-interpretation of the slope map and high-resolution 3D-imagery from Google Earth Pro was used to identify some avalanche potential zones in the catchment as shown in Figure 6. Another source of GLOF is landslide phenomena occurring at steep slopes in the vicinity of the lake. The Ghepang Ghat catchment has steep non-vegetated slopes that commonly result in mass movements (Peduzzi, 2010) and may trigger a GLOF (Walder et al., 2003; Clague and Evans, 2000). Mass movements like avalanches and landslides into the lake generate large impulse waves that may overtop the moraine dam and eventually erode it

to failure causing a sudden release of the lake water in a short duration leading to catastrophic flooding downstream.

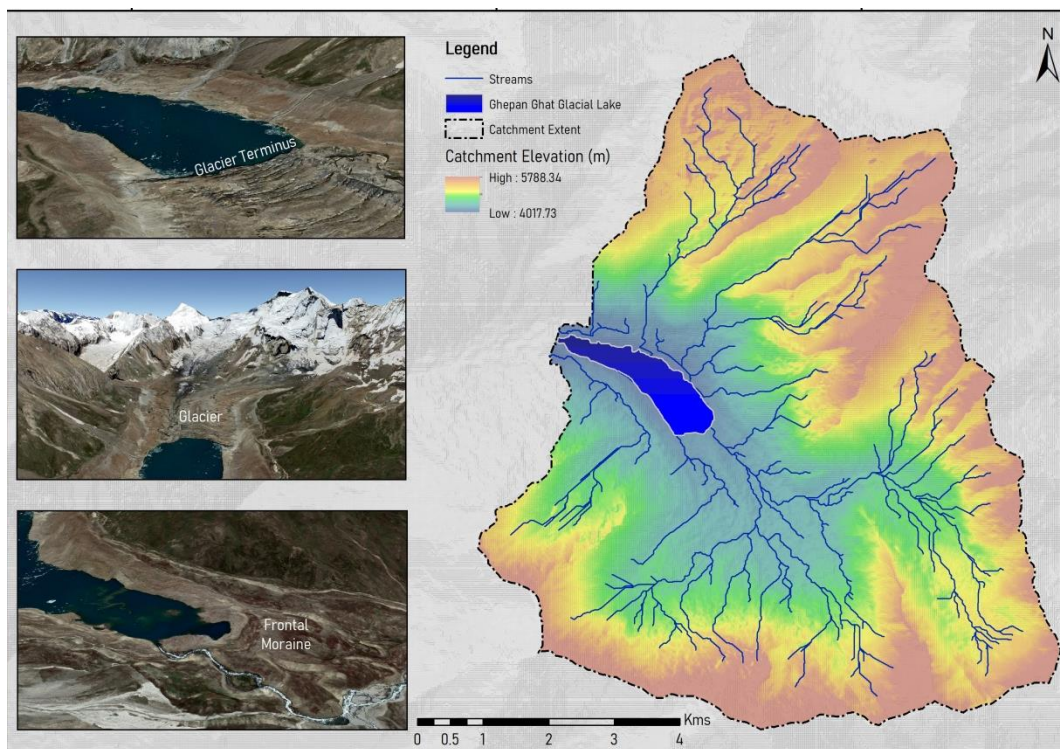


Figure 5: Upstream of Ghepan Ghat Glacial Lake

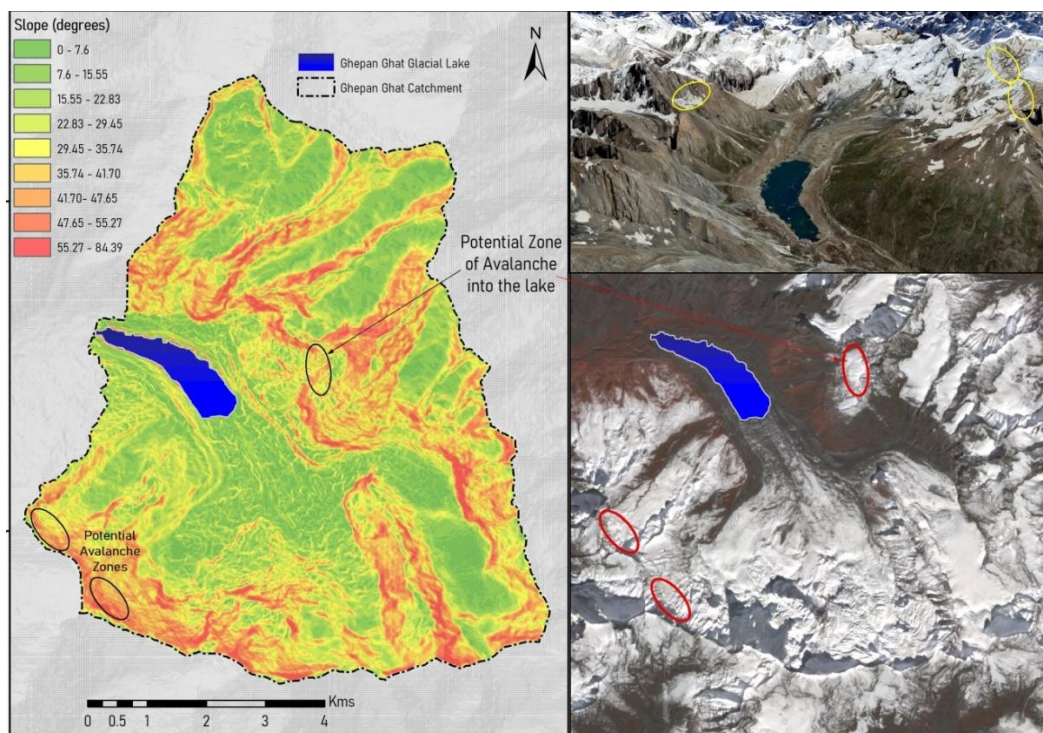


Figure 6: Slopes upstream of Ghepan Ghat Glacial Lake

3.3. Description of the Lake and its Moraine

Ghepang Ghat glacial lake has a water spread area of 101.30 hectares (ha) as on Oct 2022 at an elevation of 4068.7 m. It has a length of 2,464 m with a maximum width of 625 m near the glacier snout that gradually narrows down towards the outlet of the lake. Due to the absence of the actual volume of water stored in the lake, Huggel et al.'s empirical formula is used for estimating the lake volume. According to Huggel et al. (2002), the avg. depth (D), and volume (V) of a glacial lake can be related to its water spread area (A) by the following empirical relationships:

$$D = 0.104 \times A^{0.42} \quad \dots (i)$$

$$V = 0.104 \times A^{1.42} \quad \dots (ii)$$

where, A is in m², D is in m, and V is in m³.

Using equations (i) and (ii), the avg. depth of the lake was estimated to be 34.62 m, and the volume of the lake estimated as 35.08 million cubic meters (MCM). The TanDEM-X Digital Terrain model (DTM) was reconditioned to represent lakebed profile that gave 35.08 MCM of water volume when the initial water surface elevation was set to 4068.7 m. Sattar et al. (2023) calculated the volume of Ghepang Ghat glacial lake to be 28.4 MCM for the year 2020 using GIS based spatial interpolation of bathymetric data. Considering this data as reference, the current lake volume of 35.08 MCM derived using Huggel's formula appears as a reasonable estimate. The reconditioned DTM has an elevation of 4,034 m at the bed of the lake outlet. Elevation of the lakebed at the glacier terminus was 4,035 m, i.e., 1 m above the outlet, which will facilitate 100% drainage of lake volume during dam-breach simulation. Figure 7 shows the reconditioned DTM lake elevation details. Modification of the DTM to contain lakebed elevation values is a prerequisite for performing full-hydrodynamic simulation of Glacial Lake Outburst Floods. We assume that the lake contains clear water at a density of 1,000 kg/m³ throughout the simulation process.

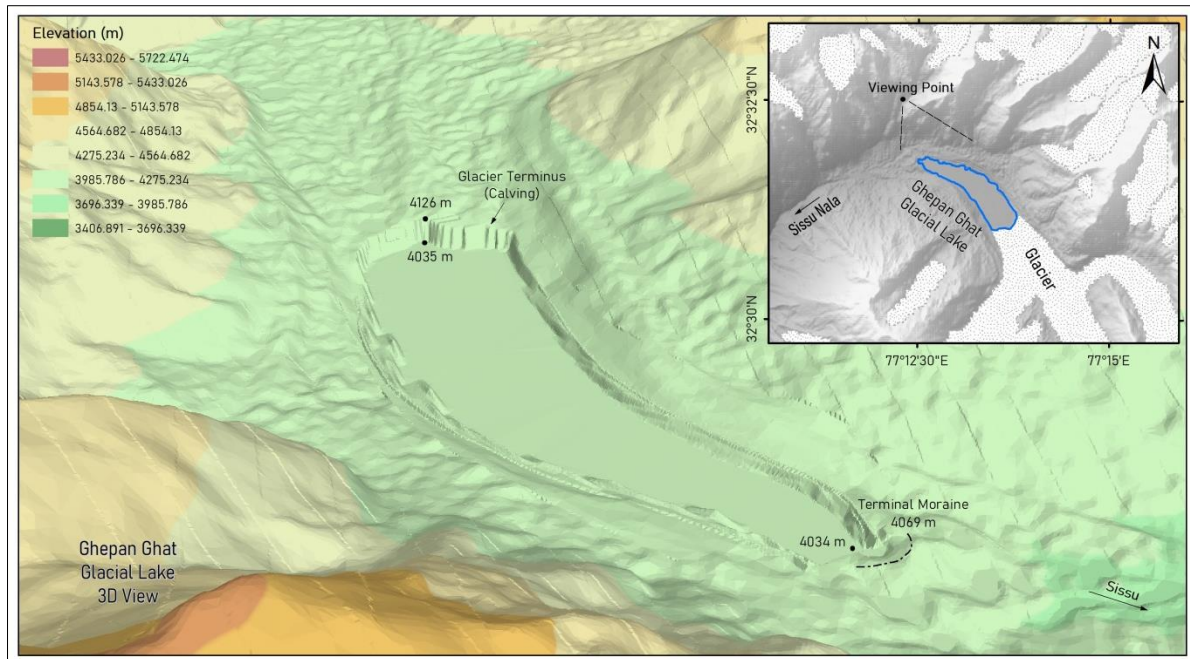


Figure 7: DTM of Ghepang Ghat Glacial Lake and its environs

Ghepang Ghat glacial lake is bound by a terminal moraine at its frontal end. The elevation of the crest of the frontal moraine is around 4,069 m, i.e., 35 m above the bed of the lake at its outlet. Width of the crest of the moraine is ~150m. It has slopes of 9.3% and 22.2% at the upstream and downstream faces respectively. The downstream face of the moraine dam is slightly vegetated with grasses and shrubs, and the absence of dense vegetation makes it prone to erosion even in case of a small overtopping wave. An overtopping wave could significantly erode the downstream face of the moraine dam and eventually cause its failure (Worni et al., 2013). In the absence of field data about the moraine, we have assumed that the moraine material is made of loosely consolidated glacial deposits and is in an unstable condition undergoing some seepage through the moraine dam, and therefore, it is susceptible to both piping and overtopping failures. Under these conditions, both the modes of failure are possible and hence proposed to study the hydrodynamic characteristics of the GLOF in each of these failure modes.

3.4. Data Used

Accuracy of hydrodynamic model depends on the resolution and accuracy of the terrain dataset used for the study. In this study, the German Aerospace Center's (DLR) TanDEM-X 5 m high resolution Digital Terrain Model (DTM) is used for simulating GLOF inundation. TanDEM-X DTM is an X-band SAR based interferometric DTM dataset. TanDEM-X and TerraSAR-X are twin satellites for radar based Earth observation for digital elevation measurements. TerraSAR-X and TanDEM-X orbited together in a close formation with a typical separation between 120 m and 500 m operating in bistatic SAR interferometric mode. Data acquisition was carried out between 2010 and 2015, and the 3D elevation model it produced was of absolute accuracy with 4 m. The DTM used for the study is hydrologically corrected DTM representing bare-earth model devoid of human-made and natural features, such as infrastructure and vegetation. Cartosat DEM is used in delineating the subbasin boundaries and their outlets for computing lateral inflows along the river reach for GLOF scenarios due to extreme precipitation.

Very high-resolution satellite data of Kompsat of 0.5 m spatial resolution of recent period was procured to identify elements of infrastructure that are affected GLOF inundation for various scenarios. The details of infrastructure such as settlements, road network, agriculture land, bridges, and other public utilities will be mapped using this satellite data along the river reach.

Both the TanDEM-X DTM and Kompsat satellite data are procured for the study for a distance of about 150 km from the Ghepang Ghat glacial lake along the river reach.

4. Methodology

The GLOF risk assessment of Ghepang Ghat glacial lake is carried out in a three step process of GLOF inundation modeling, mapping of vulnerable infrastructure elements and risk assessment. The first step of GLOF modeling is carried out using TanDEM-X 5 m high-resolution DTM for various scenarios. The GLOF scenarios include release of 50%, 75% and 100% volume of water stored in the lake. In addition, a GLOF scenario of extreme rainfall event due to Probable Maximum Precipitation occurring over catchment area of lake with simultaneous breach of lake is also simulated. In the second step, using very high resolution Kompsat satellite data elements of infrastructure affected by various flood scenarios are mapped. In the third step, GLOF risk assessment is carried out by integrating GLOF inundation scenarios and vulnerable elements of infrastructure. Figure 8 shows the flow chart of methodology used in this study.

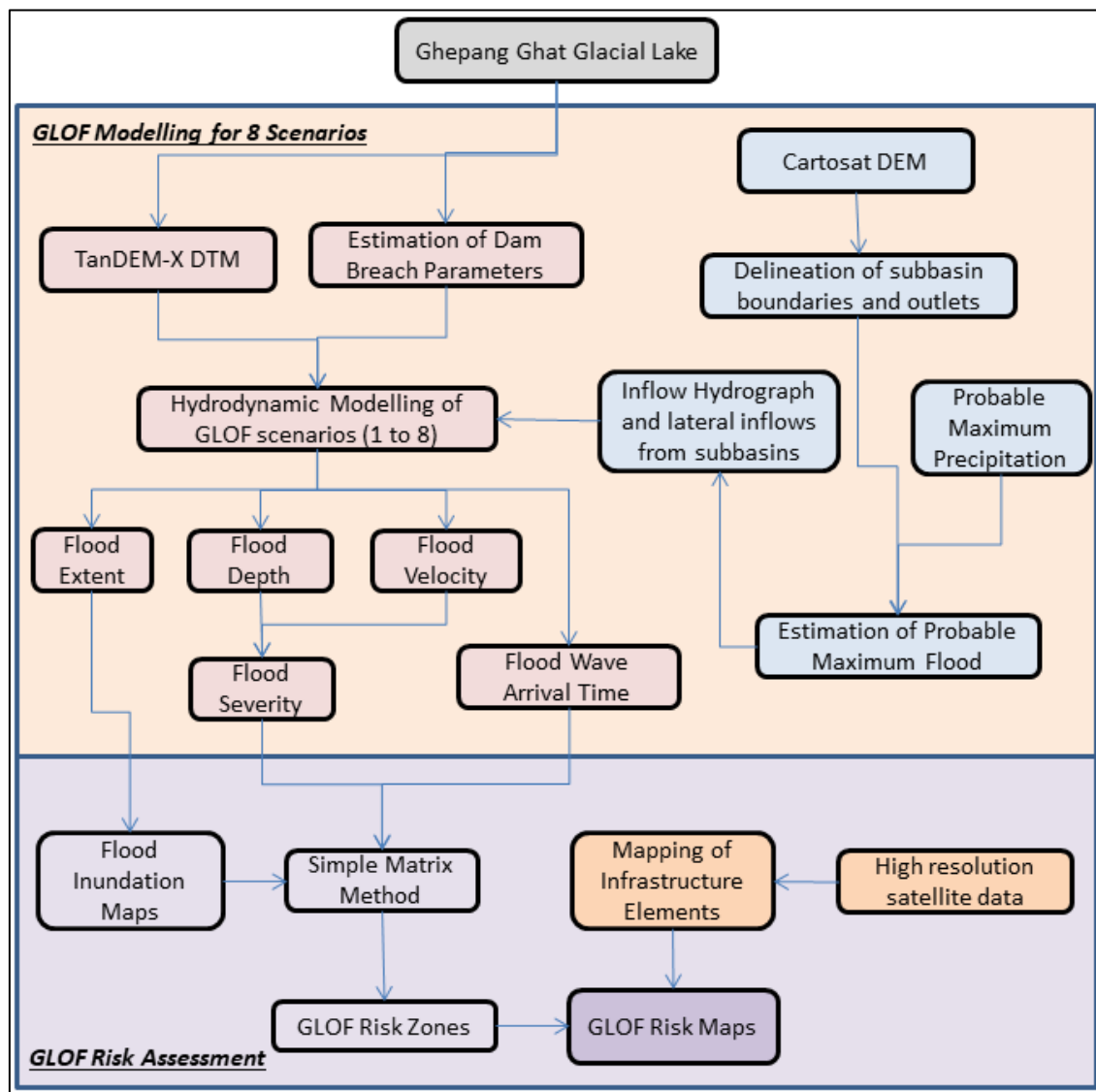


Figure 8: Flow Chart of Methodology used in the study

4.1. GLOF Inundation Modelling

Glacial Lake Outburst Floods (GLOF) are simulated as dam break hydrodynamic models in which a breach is created in the dam causing an uncontrolled flow of the stored water out of the lake. Hydrologic Engineering Center - River Analysis System (HEC-RAS) has been widely used for dam break hydrodynamic modeling due to its free availability and 1D and 2D modeling capabilities (Rawat et al., 2022; Psomiadis et al., 2021; Hussain et al., 2020; Kougkoulos et al., 2018; Klimeš et al., 2016). HEC-RAS version 6.3.1 was used to carry out the hydrodynamic GLOF simulations in this study. Full St. Venant partial differential equation sets are used for unsteady flow routing of the flood wave in a 2D hydrodynamic model established using 2D flow areas for the lake as well as the downstream areas. 2D models account for the water movement in a direction perpendicular to the direction of wave propagation, which is neglected in 1D models (Dasallas and Kim, 2019; Teng et al., 2017). The 2D unsteady hydrodynamic model was used to determine the hydrodynamic parameters of the glacial lake outburst flood wave such as flood depth, flood velocity, flood discharge, flood wave travel time at the downstream areas. The process for developing the GLOF model in HEC-RAS has been illustrated in Figure 9. TanDEM-X 5 m resolution DTM was preprocessed with ArcMap and HEC-RAS GIS tools for correction of DTM errors like sinks, and anomalies in the terrain.

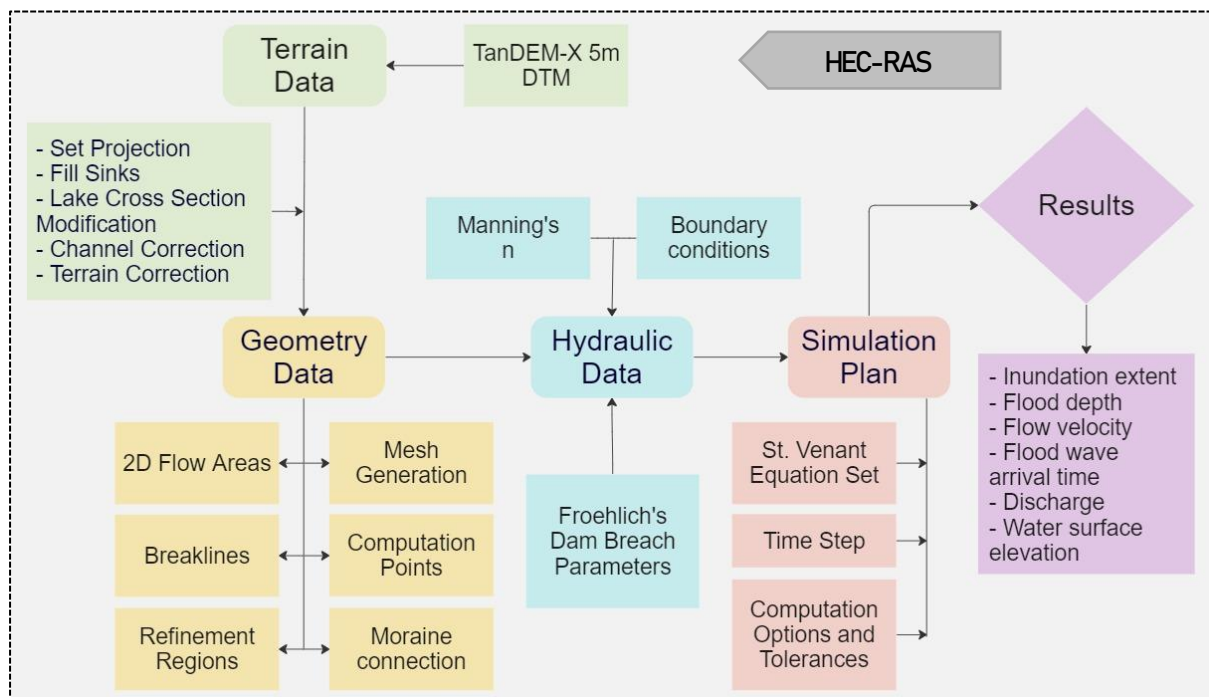


Figure 9: Methodology of GLOF Inundation Modeling used in the study

4.1.1. Study Area Boundaries

The selection of the study area boundary is an important step in the GLOF modeling process. In order to capture the entire inundation area of the GLOF, the study area boundaries must be enough to accommodate the total flow length of the flood wave, or atleast capture the flood wave until it attenuates to the normal no-flood stream flow. Moreover, the study area must also account for the backwater flows into lateral streams or reservoirs to determine the inundation in such areas. Another important consideration

in defining the study area extent is the computation time required for simulation. Too large of a study area will increase the complexity of the model, and hence, the computation time. The study area for 2D hydrodynamic simulation is defined by 2D flow areas in HEC-RAS which currently has a maximum cell limit of 2 million cells. Taking the above factors into consideration, the study area is taken from lake outlet to 150 km downstream along the river reach assuming that the flood wave will attenuate to a no-flood stream flow within this flow length. On running a preliminary simulation for Ghepang Ghat GLOF, it is observed that the flood hydrograph attenuated to about 300 cumecs (low stream flow of Chenab River) within the extent of our study area. The boundaries of the study area of Ghepnahg Ghat glacial lake has been illustrated in Figure 10.

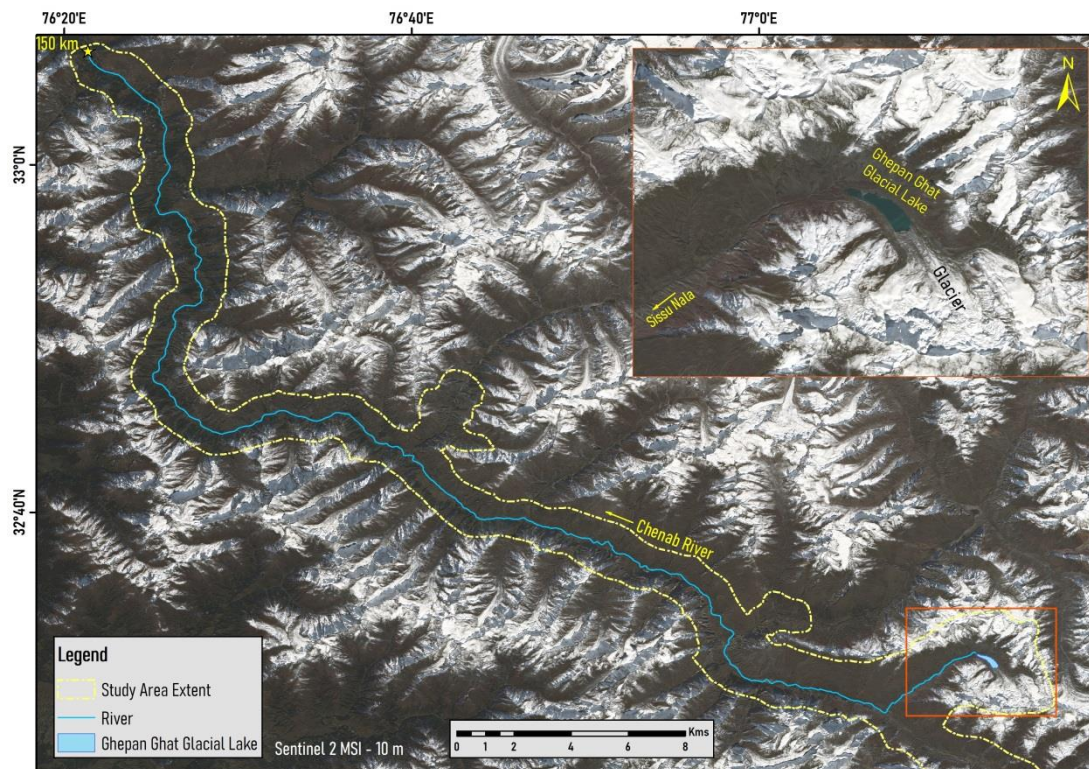


Figure 10: Study Area Boundary of Ghepang Ghat Lake for GLOF Inundation Modeling

4.1.2. GLOF Scenarios

Pluvial and fluvial floods are usually modeled with different scenarios based on the return period of the flood under consideration (5 years, 10 years, 100 years, etc.). In contrast, Glacial Lake Outburst Floods are very low-frequency rare-events and therefore, scenarios based on return period may not be suitable for modeling GLOFs. One way of defining GLOF modeling scenarios can be based on the lake volume drained after breach (50%, 75% and 100%). HEC-RAS software has capabilities to simulate two types of failure modes i.e. piping and overtopping. In addition to dry weather conditions, dam breaches can also occur due to extreme rainfall events. Considering the above possibilities of failure scenarios, in this study eight GLOF scenarios based on the percentage volume of water discharged from the lake after failure of the moraine, the weather conditions, and the failure modes are simulated. Table 1 describes various GLOF scenarios simulated in the study.

Table 1: GLOF scenarios simulated in this study

Scenario	Definition (based on volume discharged)	Failure Mode	Weather Condition
Scenario-1	100% volume discharged from lake	Overtopping	Fair
Scenario-2		Piping	
Scenario-3	75% volume discharged from lake	Overtopping	
Scenario-4		Piping	
Scenario-5	50% volume discharged from lake	Overtopping	
Scenario-6		Piping	
Scenario-7	100% volume discharged from lake with PMS	Overtopping	Inclement
Scenario-8		Piping	

To simulate extreme rainfall events, Probable Maximum precipitation (PMP) is considered to occur in the catchment areas of the glacial lake. The resultant runoff generated due to PMP is estimated using rainfall-runoff modeling in HEC-HMS software. The stream runoff is then hydrodynamically modeled along with simultaneous breach of the lake.

Each of these scenarios has been modeled using 2D unsteady flow hydrodynamic modeling in HEC-RAS that essentially solves the St. Venant partial differential equations (Saint Venant, 1871). The St. Venant equations in 2D, also known as the Shallow Water Equations (SWE) can be written as:

A. Continuity Equation (Conservation of Mass):

$$\partial h / \partial t + \partial (h v_x) / \partial x + \partial (h v_y) / \partial y = 0 \quad \dots(\text{iii})$$

B. Momentum Equations (Conservation of momentum in x and y directions):

$$\partial (h v_x) / \partial t + \partial (h v_x^2 + (1/2) g h^2) / \partial x + \partial (h v_x v_y) / \partial y = - g h \partial z / \partial x + \tau_x \quad \dots(\text{iv})$$

$$\partial (h v_y) / \partial t + \partial (h v_x v_y) / \partial x + \partial (h v_y^2 + (1/2) g h^2) / \partial y = - g h \partial z / \partial y + \tau_y \quad \dots(\text{v})$$

where, h = water depth, t = time, v_x = component of velocity in x-direction, v_y = component of velocity in y-direction, x and y = horizontal spatial coordinates, z = bed elevation, τ_x and τ_y are bed shear stresses in the x and y directions, respectively.

Equation (iii) is known as the continuity equation which basically accounts for the volume of water in a river reach, and equations (iv) and (v) are known as the momentum equations which account for all the forces acting on the body of fluid in an open channel. HEC-RAS employs a finite difference approximation of the partial differential equations in which the SWE are discretized into a grid or a mesh transforming them into a set of algebraic equations. These algebraic equations are then solved iteratively for each grid cell using an implicit numerical solution scheme in which the unknown values of depth and velocities are calculated based on their known values at the neighboring cells and the current time step. The 2D flow areas of the glacial lake and the downstream serve as the mesh/grid having 'n' number of cells on which the iterative implicit finite difference solution scheme solves the SWE to compute a water surface elevation error that is within a user specified tolerance for each cell.

4.1.3. Processing of GLOF Model Inputs

4.1.3.1. Digital Terrain Model

The TanDEM-X DTM requires few corrections for hydrodynamic modeling due to irregular channel geometry along the stream centerline as shown in the Figure 11. Firstly, the DTM was preprocessed by filling the sinks using ArcMap software. Secondly, leftover bumps in the flow path were cross-checked with high resolution Google Earth Pro imagery, and erroneous bumps that were not present in the imagery were removed by cross-section modification in HEC-RAS. Thirdly, the channel banks were verified for correctness using Google Earth Pro imagery, and erroneous channel bank sections are also modified using HEC-RAS cross section modification utilities. The original TanDEM-X DTM did not have lake bathymetric information as DEMs can only provide elevation of the top surface of water. In addition, the TanDEM-X DTM was acquired between 2010 and 2015, and hence, did not have the current lake extent. For 2D hydrodynamic modeling of the lake, it is necessary to correct the lake area of the DTM to include its underlying lakebed topography. Therefore, the last step in DTM preprocessing was the modification of the lake area using cross-sections in HEC-RAS.

Figure 11 shows the TanDEM-X 5 m DTM extent used for the 2D hydrodynamic model overlaid on SRTM 30 m grayscale DEM.

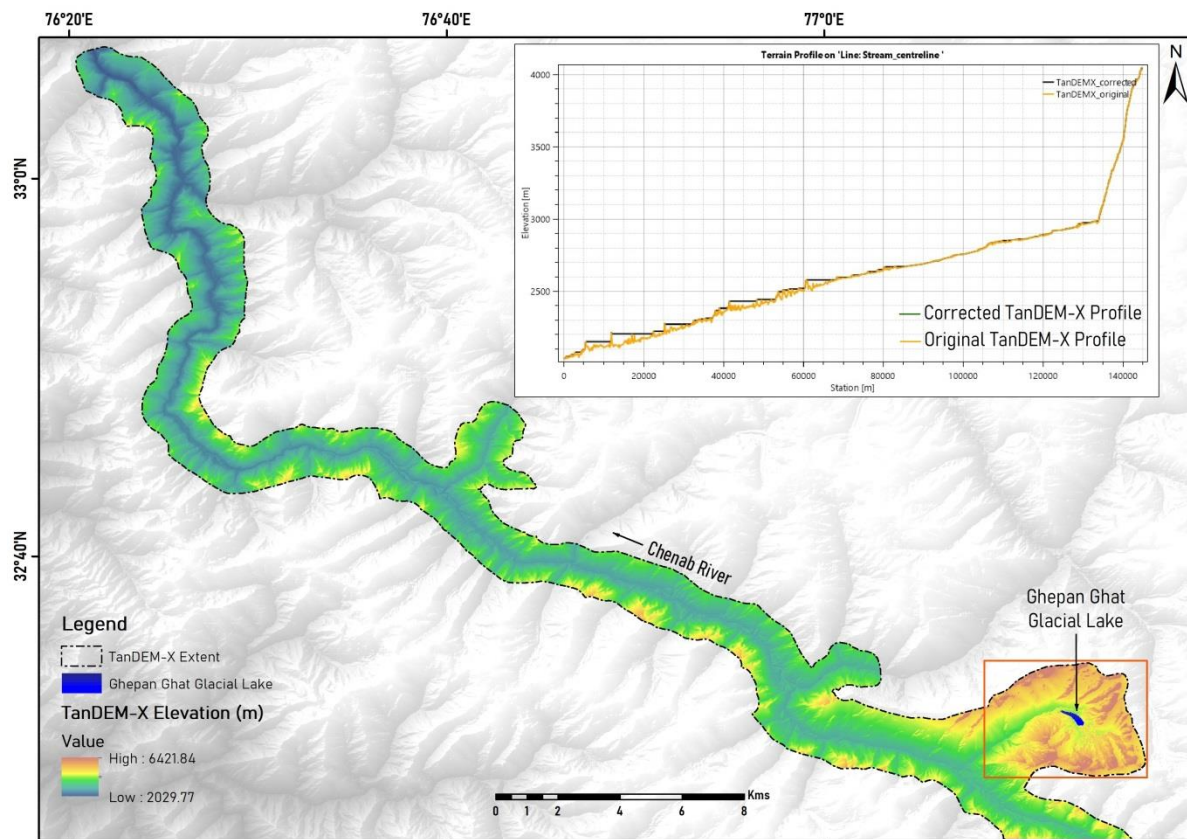


Figure 11: Reconditioned TanDEM-X DTM of Study Area

The original TanDEM-X DTM of the lake (left) procured depicts area of about 77.6 ha, and the TanDEM-X DTM (right) is reconditioned to represent the lake area extent as 101.3 ha (as on 2022) have been shown in Figure 12. Changes in the longitudinal profile of the lake post-correction are plotted on the graph.

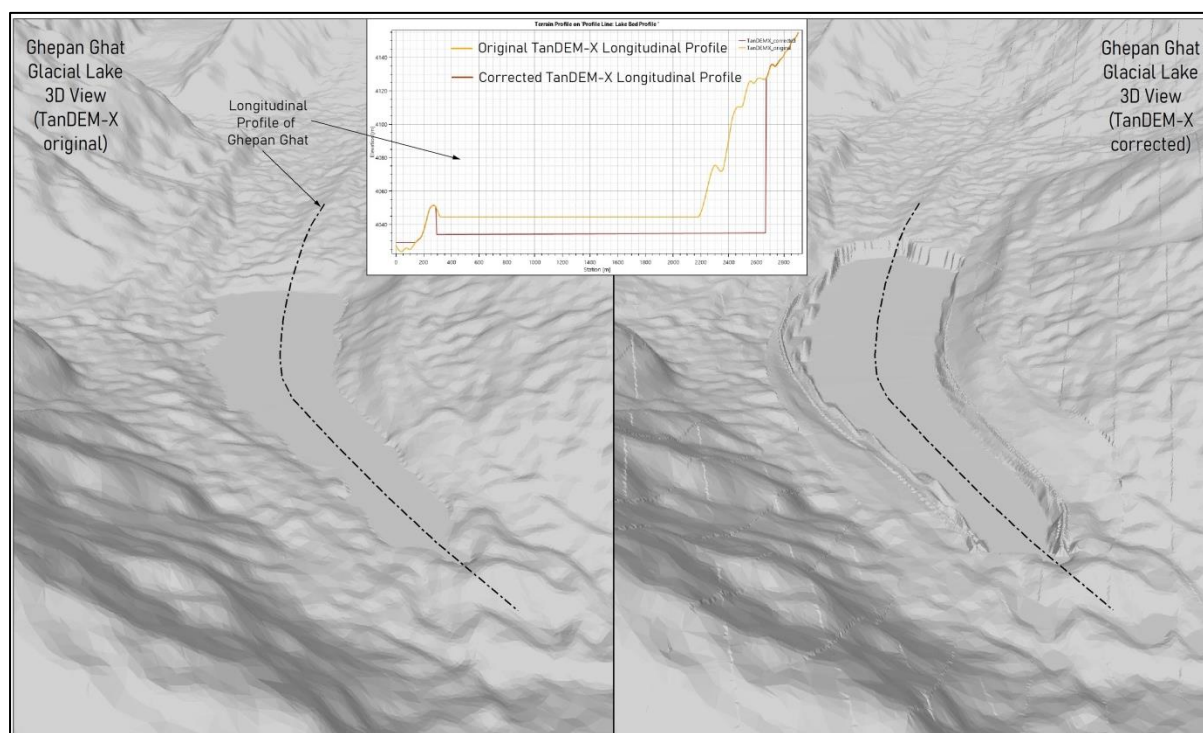


Figure 12: Reconditioned TanDEM-X DTM of Ghepan Ghat Lake

4.1.3.2. Land Cover and Manning's n Values

Manning's roughness coefficient plays a very significant role in the accuracy of computed water surface elevations in HEC-RAS. It represents the resistance to flow in channels and floodplains. The value of Manning's n is highly variable and depends on several factors such as surface roughness; vegetation; channel irregularities; channel alignment; scour and deposition; obstructions; size and shape of the channel; stage and discharge; seasonal changes; temperature; and suspended material and bed load. Manning's n values can be associated with Landcover data, and typical values of n for different streams and floodplain landcover types can be found in the book "Open Channel Hydraulics" by Chow, 1959. In this study, the landcover map of 1:50,000 generated by NRSC is used. Based on literature, Manning's n values assigned to the different landcover classes as provided in Table 2.

Table 2: Manning's n used for different Land cover in this study

Landcover Class	Manning's n
Waterbody	0.035
Snow and Glacier	0.06
Forest	0.10
Riverbed	0.04
Built-up area	0.12
Cropland	0.04
Bare Soil and Rock	0.03
Grassland	0.05

The landcover layer is manually corrected for the channel regions using landcover calibration regions in HEC-RAS. The channel region immediately below the Ghepang Ghat glacial lake upto Sissu has a very high slope of 90 m per km between the lake and Sissu village (Figure 13). In the event of failure of the moraine dam, significant turbulence, high water surfaces, sediment load and debris, and very high velocity of flow due to highly sloping terrain is expected. HEC-RAS does not directly account for high sediment volumes in the flow, and extreme turbulence caused by the breach that happens immediately downstream of a dam, and this may lead to inaccurate assessment of the hydrodynamic parameters, and model instability. The HEC-RAS Technical Document-39 (2014) on “Using HEC-RAS for Dam Break Studies” recommends that the solution to this problem is increasing the Manning’s n value for immediate downstream slopes of the dam.

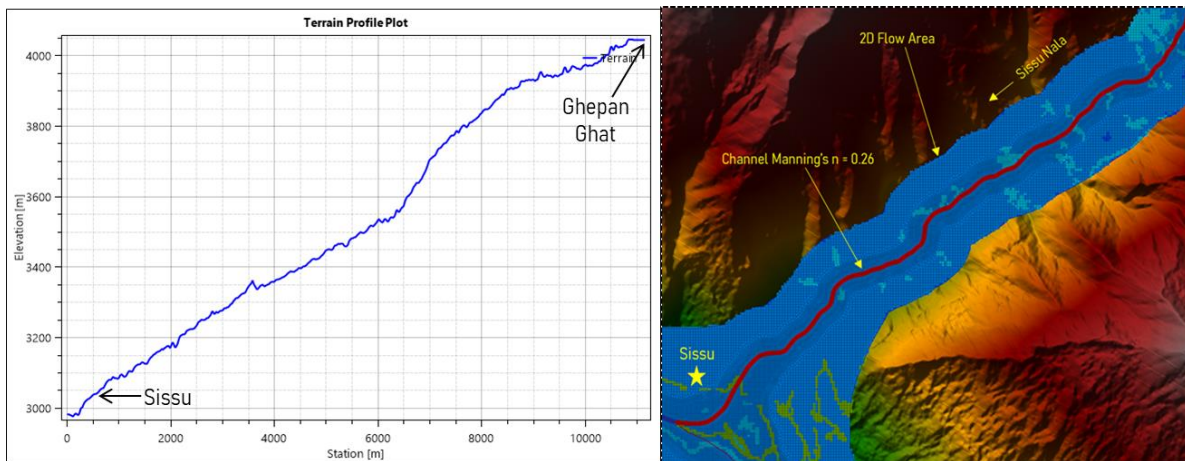


Figure 13: Terrain profile of DTM between Ghepang Ghat Glacial Lake and Sissu

Jarrett’s regression equation (Jarrett, 1984) for estimating Manning’s n value for steep streams (equation vi) was used to calculate the n value for the main channel immediately downstream of Ghepang Ghat glacial lake:

$$n = 0.039 \times S^{0.38} \times R^{-0.16} \quad \dots(vi)$$

where, n = Manning’s roughness coefficient of the main channel, S = energy slope (ft/ft), R = hydraulic radius of the main channel (ft).

We calculated the Manning’s n value for the main channel from Ghepang Ghat to Sissu using this equation to be 0.26 and assigned this value to the Manning’s layer in HEC-RAS using n-value calibration regions. Similarly, the calculated channel n-value for the channel from Sissu to the 2D flow area outlet was 0.06.

4.1.3.3. Dam Breach Parameters

The moraine of Ghepang Ghat glacial lake described in section 4.1.3.1 has a crest elevation of 4,068.7 m. It is around 150 m in width and is assumed to hold a water volume of 35.08 MCM at full capacity estimated using Huggel’s formula. In the absence of in-situ data regarding the moraine, it is assumed to be in poor condition readily susceptible to failure even with the slightest of overtopping depth. The average depth of the lake

computed using Huggel's formula was 34.62 m. Based on the average depth of the lake, the bed elevation of the lake at its outlet is calculated as 4,034.08 m.

With this data, the moraine dam breach parameters are estimated using the widely used Froehlich's empirical equation set (Sattar et al., 2021; Majeed et al., 2021; Wang et al., 2018; Anacona et al., 2015). Wahl (2004) reported that Froehlich's empirical formulae have the lowest prediction uncertainty, and hence, Froehlich's empirical equations are used in this study. A dam breach analysis requires the estimates of dam breach parameters like breach formation time (t_f) and average breach width (B_{ave}) as inputs. t_f and B_{ave} can be computed using the empirical equations (xv) and (xvi) given by Froehlich (1995a, b):

$$t_f = 0.00254 \times V_w^{0.53} \times h_b^{-0.90} \quad \dots(xv)$$

$$B_{ave} = 0.1803 \times K_0 \times V_w^{0.32} \times h_b^{0.19} \quad \dots(xvi)$$

where, t_f = breach formation time in hours, B_{ave} = average breach width in meters, V_w = volume of water at the time of failure in cubic meters, h_b = height of breach in meters, K_0 = constant (1.4 for overtopping and 1.0 for piping failures).

Using these two parameters, we can estimate the breach progression rate (r) and the breach bottom width (B_{bw} , meters) with equations (xvii) and (xviii):

$$B_{bw} = B_{ave} - (h_b \times S_s) \quad \dots(xvii)$$

$$r = 1 / [(B_{bw}/t_f) / (h_b/t_f)] \quad \dots(xviii)$$

where, S_s is the average side slope of the breach = 1.4H:1V for overtopping failures and 0.9H:1V for piping failures.

Breach parameters are estimated for each scenario using equations (xv) to (xviii), and are provided in Table 3.

Table 3: Dam Breach Parameters for Various GLOF Scenarios

Scenario	Failure Mode	Volume Discharge	Breach bottom elevation (m)	h_b (m)	B_{ave} (m)	t_f (hrs)	B_{bw} (m)	r
Scenario-1	Overtopping	100%	4034.08	34.62	128.53	1.04	80.06	0.43
Scenario-2	Piping				91.81		60.65	0.57
Scenario-3	Overtopping	75%	4052.86	15.84	110.79	2.11	88.61	0.18
Scenario-4	Piping				79.13		64.87	0.24
Scenario-5	Overtopping	50%	4059.16	9.54	100.61	3.33	87.25	0.11
Scenario-6	Piping				71.87		63.28	0.15
Scenario-7	Overtopping	100% with PMS	4034.08	34.62	128.53	1.04	80.06	0.43
Scenario-8	Piping				91.81		60.65	0.57

These breach parameters are fed into HEC-RAS moraine connection data to obtain a breach hydrograph and peak discharge from the breach during simulation. This breach hydrograph is then hydrodynamically routed as unsteady flow in HEC-RAS using 2D flow areas to assess the effects of the flood wave downstream.

4.1.3.4. PMP and Runoff

Scenarios 7 and 8 as described under section 4.1.2 consider a glacial lake outburst event and simultaneous occurrence of Probable Maximum Precipitation (PMP) over its catchment. A PMP is defined as the maximum depth of rainfall meteorologically possible at a location over a given duration. There are various physical and statistical methods for estimation of PMP such as the moisture maximization method, storm transposition method, generalized method, atmospheric moisture budget method, Hershfield method, etc. The Indian Meteorological Department (IMD) has published a gridded PMP atlas for the Indus River Basin using some of these methods, however it does not have any gridded PMP data within Lahul and Spiti district where the study area is located. Therefore, the PMP value over the Chandra River catchment is estimated using the Annual Maximum Daily Precipitation (AMDP) series data over the past 50 years (1972-2022) from IMD. The World Meteorological Organization (WMO) recommended Hershfield statistical method is applied to calculate the PMP from the AMDP series (Hershfield, 1965). Hershfield's equation for estimation of PMP is based on Chow's general frequency equation (1951), given as:

$$A_{PMP} = \bar{A} + K \times S_N \quad \dots(vii)$$

where, A_{PMP} is the PMP estimate for the location under consideration, $\bar{A}$ is the mean of the AMDP series for N years at that location, S_N is the standard deviation of the AMDP series, K is the frequency factor which can be determined from equation (viii):

$$K = (A_m - \bar{A}_{N-1})/S_{N-1} \quad \dots(viii)$$

where, A_m is the maximum value of the AMDP series, $\bar{A}_{N-1}$ and S_{N-1} are the mean and standard deviation of the AMDP series respectively for N-1 years after removing the year with the maximum value.

Using equations (vii) and (viii), the value of PMP for the catchment is computed to be 1,170 mm/day. This value of PMP is converted to a Probable Maximum Storm (PMS) by taking the time distribution of a 1-day severe storm from the Himalayan Region as reference (Table 4 and Figure 14).

Table 4: Design of the PMS using a Severe Reference Storm from the Himalayan Region

Time (hrs)	Cumulative Rainfall of Reference Storm (mm) [i]	Proportion of Total Rainfall (i/335.3) [ii]	PMP Cumulative distribution (mm) [1,170 x ii]	Incremental Rainfall (mm)	Bell Curve Arrangement (mm)
1	55	0.164	191.92	191.92	0.00
2	90	0.268	314.05	122.13	6.28
3	119	0.355	415.24	101.19	16.75
4	154	0.459	537.37	122.13	18.84
5	193	0.576	673.46	136.09	31.40
6	228	0.680	795.59	122.13	31.40
7	243	0.725	847.93	52.34	34.89
8	252	0.752	879.33	31.40	41.87
9	262	0.781	914.23	34.89	122.13

10	267	0.796	931.67	17.45	122.13
11	275	0.820	959.59	27.92	136.09
12	284	0.847	990.99	31.40	191.92
13	294	0.877	1025.89	34.89	122.13
14	296	0.883	1032.87	6.98	101.19
15	301.4	0.899	1051.71	18.84	52.34
16	307	0.916	1071.25	19.54	34.89
17	316	0.942	1102.65	31.40	31.40
18	328	0.978	1144.53	41.87	27.92
19	332.8	0.993	1161.28	16.75	19.54
20	332.8	0.993	1161.28	0.00	17.45
21	332.8	0.993	1161.28	0.00	6.98
22	333.5	0.995	1163.72	2.44	2.44
23	335.3	1.000	1170.00	6.28	0.00
24	335.3	1.000	1170.00	0.00	0.00

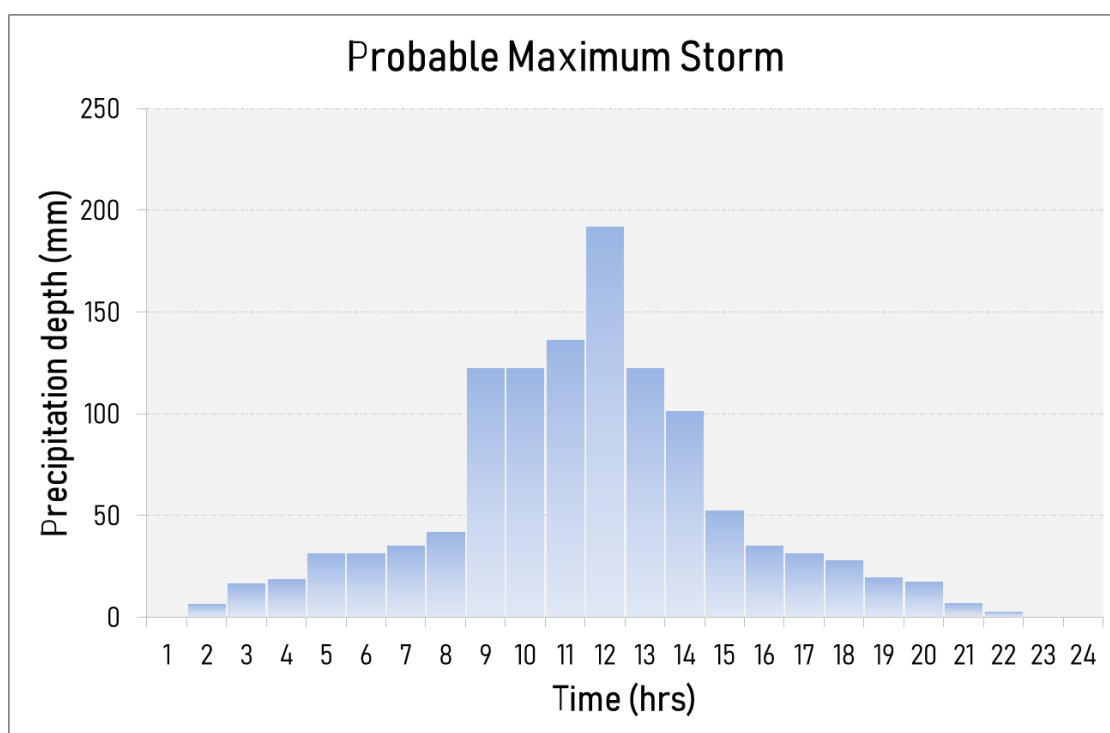


Figure 14: Probable Maximum Storm used for Runoff Estimation

To incorporate the effect of the PMS on Ghepang Ghat GLOF, a rainfall-runoff model is developed in HEC-HMS software to derive the PMS induced inflow hydrographs at various lateral streams contributing to the lake as well as the downstream flow path of the flood wave. The rainfall-runoff model is developed to include the runoff generated from entire catchment of the Chandra River up to the study area boundary (Figure 15). This ensured a comprehensive assessment of the lateral inflows contributing to the flood wave in case of failure of Ghepang Ghat's moraine. Cartosat DEM is used in delineating the subbasin

boundaries and their outlets for computing lateral inflows along the river reach. A total of eight lateral inflows including flows into the two major glacial lakes in the catchment namely Ghepan Ghat and Samudra Tapu are considered. Rainfall is assumed to occur below the 4,500 m elevation in the study area and above which only snowfall occurs. The total area of the catchment was 7,683 km², out of which 2,960 km² area was below 4,500 m elevation.

Generating the lateral streamflow hydrographs in HEC-HMS requires the specification of a loss model that computes the excess precipitation after deducting the losses, a transform model that converts the excess precipitation into a direct runoff hydrograph, a baseflow model (optional) to simulate sub-surface drainage, and a routing model to simulate the 1D open channel flow using continuity equation and produce the routed direct runoff hydrograph as the output. In this study, the following models are used:

- i. Loss Model - SCS Curve Number
- ii. Transform Model - SCS Unit Hydrograph
- iii. Routing Model - Muskingum Routing

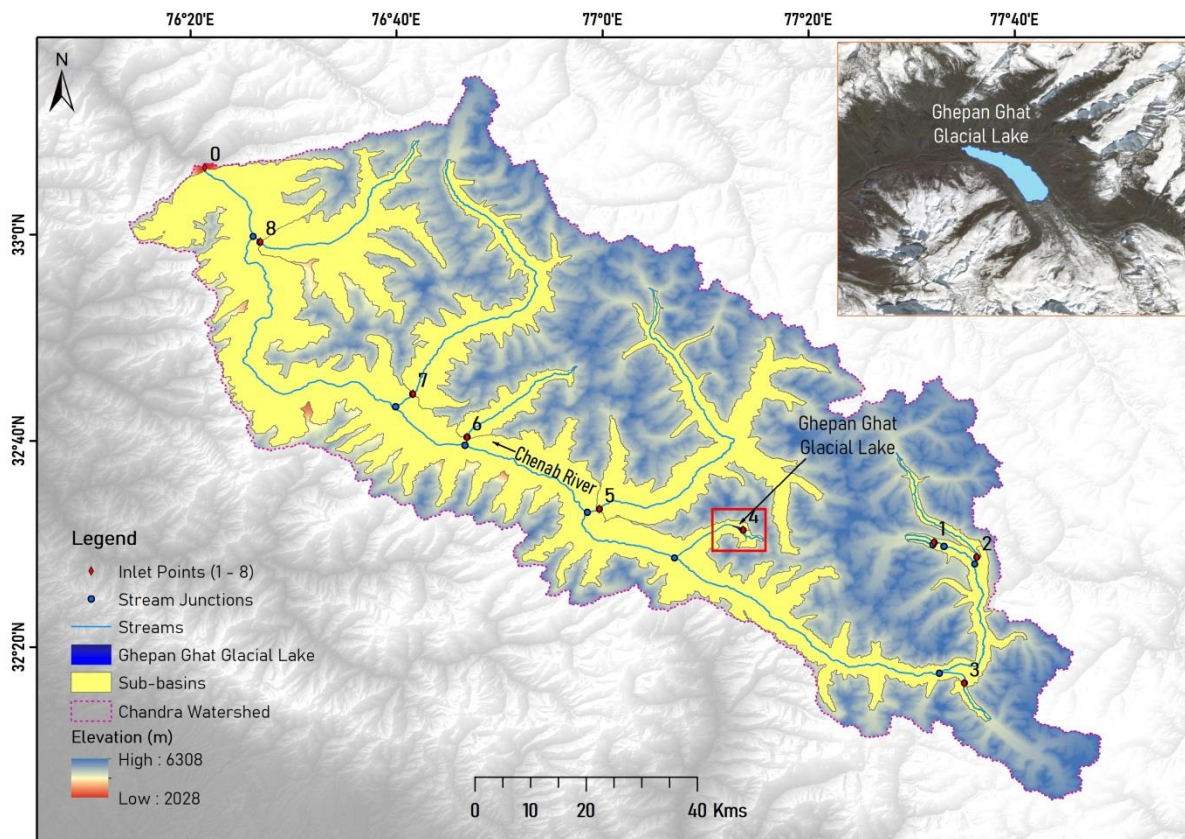


Figure 15: Area Contributing to Rainfall-Runoff Considered in HEC-HMS Model

The SCS Curve Number (CN) is a dimensionless parameter that represents the combined effects of soil type, land use, and antecedent moisture conditions on the runoff potential of a particular area. It ranges from 0 to 100 (40 - 98), with lower values indicating better infiltration losses and higher values indicating more runoff. The CN value can be estimated using CN tables provided by the SCS. In GIS raster data, the CN value is estimated for each picture element “pixel”. Once the CN value is calculated, the maximum potential

retention (R) can be calculated using equation (ix) given by the Soil Conservation Service (1971):

$$R = (25400 - 254 \times CN)/CN \quad \dots(ix)$$

where, R = maximum potential retention in the area represented by the pixel (mm). Then, we can determine the accumulated precipitation excess at time t (P_e) using equation (x):

$$P_e = (P - 0.2 R)^2 / (P + 0.8 R) \quad \dots(x)$$

where, P = accumulated rainfall depth at time t.

HEC-HMS uses equations (ix) and (x) to give the excess precipitation at time t. This excess precipitation is transformed to a direct runoff hydrograph using the SCS Unit Hydrograph (UH) transform method in HEC-HMS. The SCS UH is also a dimensionless hydrograph with ordinate Q_t/Q_p (discharge at any time t/peak discharge of UH), and abscissa t/T_p (time/time of UH peak). The SCS suggests that the UH peak and the time of UH peak are related by (equation xi):

$$Q_p = C \times A/T_p \quad \dots(xi)$$

where, A = watershed area, and C = conversion constant (2.08 in SI).

The time of peak is related to the duration of excess precipitation as (equation xii):

$$T_p = (\Delta t/2) + t_{lag} \quad \dots(xii)$$

where, Δt = excess precipitation duration (computational interval of model run), t_{lag} = basin lag defined as the time difference between the centre of mass of rainfall excess and the peak of UH. When the lag time is specified, HEC-HMS solves equation (xii) to find Q_p and T_p . The basin lag is related to the time of concentration in the basin (t_c) and calculated using equation (xiii):

$$t_{lag} = 0.6 t_c \quad \dots(xiii)$$

where, t_c is the time taken by a drop of water to reach the basin outlet from the farthest point in the watershed. t_c (hrs) was computed in HEC-HMS using equation (xiv):

$$t_c = l^{0.8} \times (R + 1)^{0.7} / (1140 \times Y^{0.5}) \quad \dots(xiv)$$

where, R = maximum potential retention (inch), Y = sub-basin slope (%), l = maximum flow length in sub-basin.

Routing of the direct runoff hydrograph obtained by SCS UH transform method was done using Muskingum's hydrologic channel routing equation (xiv):

$$S = K [x I + (1 - x) Q] \quad \dots(xiv)$$

where, S = total storage in a channel reach, I = inflow rate, Q = outflow rate, x = weighting factor (0 - 0.5), and K = storage-time constant having dimensions of time.

In this model, K = 0.5, and x = 0.25 are used for the Muskingum Routing that simulates channel flow and gives the routed direct runoff hydrograph at specified locations within the stream. The model is used to derive the lateral inflow hydrographs for each of the eight points shown in Figure 15. Peak discharges estimated by the model are given in Table 5. Each of the inlet hydrographs are given in Annexure 1. These inflow hydrographs

are specified as boundary conditions in HEC-RAS for simulating hydraulic channel routing and estimation of the hydrodynamic parameters.

Table 5: Lateral Inflow Hydrograph Peaks Estimated using HEC-HMS Model

Point No.	Lake Inlet/Lateral Stream	Peak discharge	Catchment Area (Km ²)
1	Samudra Tapu Inlet	350 m ³ /s	7.10
2	Lateral Stream 1	820 m ³ /s	28.10
3	Lateral Stream 2	460 m ³ /s	12.00
4	Ghepang Ghat Inlet	310 m ³ /s	6.30
5	Lateral Stream 3	13,000 m ³ /s	420.23
6	Lateral Stream 4	3,400 m ³ /s	74.15
7	Lateral Stream 5	9,100 m ³ /s	277.64
8	Lateral Stream 6	11,800 m ³ /s	313.76

4.1.4. Dam Breach Model Setup

A two-dimensional unsteady flow full hydrodynamic model is set-up in HEC-RAS to simulate the dam breach phenomenon. Setting up of a HEC-RAS 2D unsteady flow dam breach model requires the following inputs:

- Terrain data
- Geometry data
- Dam breach parameter data
- Unsteady flow data (initial and boundary conditions)
- Computational plan settings

Terrain Data is one of the most important inputs of a good hydrodynamic model. The accuracy of a hydrodynamic model greatly depends on the accuracy and resolution of the terrain data used in the study. When 2D meshes are generated in HEC-RAS to model the flow areas, each cell face contains the information of the terrain underneath it (Figure 16).

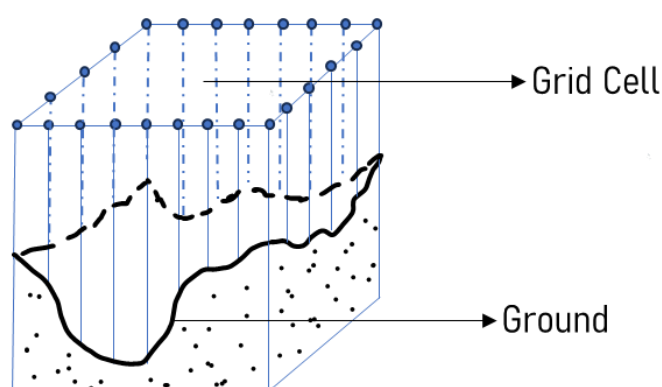


Figure 16: HEC-RAS Grid Cell and underlying Terrain Information

Each cell and cell faces of the computational mesh are pre-processed automatically in HEC-RAS to generate a detailed elevation-volume relationship for each cell along with station elevation data for each face. Other hydraulic property tables are also generated for each cell such as elevation vs wetted perimeter, elevation vs area, etc. (Figure 17)

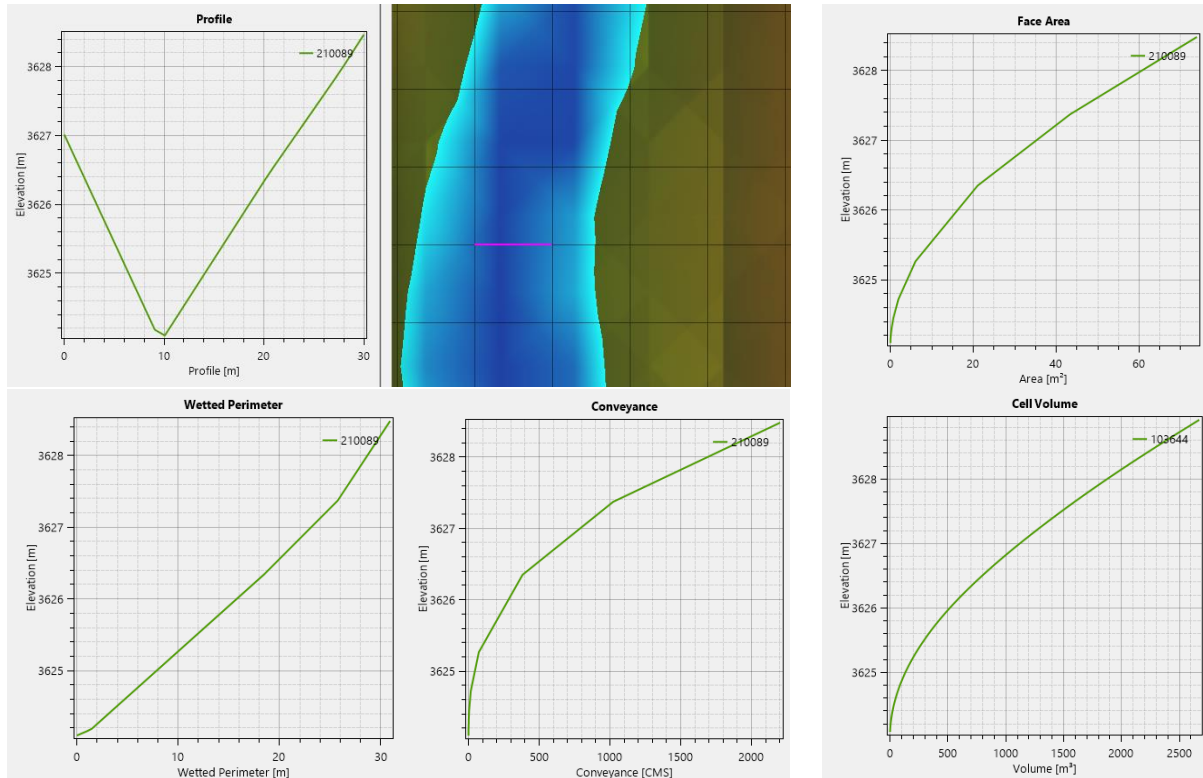


Figure 17: Hydraulic properties of Each Cell in HEC-RAS

Finer resolution of terrain data will give more accurate hydraulic properties of each cell. High-resolution TanDEM-X 5 m DTM is used to generate the terrain data as described under section 4.1.3.1.

Geometry Data contains the 2D computational mesh that defines the area within which HEC-RAS will solve the Shallow Water Equations and give hydrodynamic parameters such as discharge, depth, and velocity as output. As mentioned earlier, for fully hydrodynamic 2D simulation, the lake as well as the downstream with 2D flow areas needs to be setup. It is very important to select the extents of the 2D flow areas properly to include the backwater flows of the flood wave into the lateral streams, and it must also cover the maximum distance of flooding so that even the most downstream flood affected location is included in the 2D flow area. So, a 150 km long 2D flow area for the downstream of Ghepang Ghat glacial lake along its river reach to include all lateral flows, and one 2D flow area covering the full extent of the glacial lake itself are setup in the model. Each cell face of the 2D mesh acts as a cross section, and so, the elevation values between two cross sections are interpolated. Therefore, to accurately model the terrain underneath, the cell size should be selected suitably. It is recommended that for highly varying terrain geometry, smaller cell sizes be used, and for floodplains where the elevations don't vary much over space, larger cells may be sufficient. A cell size of 15 m to model the channel, and a 30 m cell size for modelling the overbank areas area used. Cell sizes were also chosen by considering the time taken to solve the model, and the HEC-

RAS cell limit of 2 million cells. Also, the cells need to be aligned perpendicular to the direction of flow to capture the cross-sectional geometry of the terrain accurately. Breaklines in the lake as well as the downstream 2D flow areas to align the cells properly are used. The 2D flow areas were also associated with the Manning's n values as described in section 4.1.3.2.

Dam breach Parameter Data is entered into the 2D flow area connection editor that describes the moraine geometry. The parameter calculations are shown in section 4.1.3.2. The moraine is defined as a 2D flow area connection in HEC-RAS which transfers flow between the two flow areas. During the formation of the breach, the moraine behaviour oscillates between that of a broad-crested weir and a sharp-crested one. A breach weir coefficient of 1.44 (SI units), and additionally, in case of piping failure, a piping coefficient of 0.5 are used to simulate pressurised orifice flow.

Unsteady Flow Data is manually entered in HEC-RAS unsteady flow data editor. A downstream boundary condition of "Normal Depth" with a friction slope of 0.015 is used. The friction slope value was roughly taken as the slope of the channel from the most upstream point to the most downstream point. The initial water surface elevation of the glacial lake 2D flow area was set as 4,068.7 m. For simulating scenarios 7 and 8, the HEC-HMS rainfall-runoff model derived lateral inflows were also input into the unsteady flow data editor as upstream boundary conditions at their respective locations in the channel.

Computational Plan Settings in HEC-RAS are extremely important to ensure model stability and accurate results. From equations (iii), (iv) and (v), as described in section 4.1.2, HEC-RAS solves derivatives with respect to time and space. The time step for model computations can be selected by the Courant condition (C), equation (xix) and (xx):

$$C = (v \times \Delta t) / \Delta x \quad \dots(\text{xix})$$

where, v = velocity of flow (m/s), Δt = time step (s), and Δx = cell size (m).

For St. Venant equations, the value of C should ideally be ≤ 1.0 , and maximum 3.0. That gives us the time step as:

$$\Delta t \leq \Delta x / v \text{ (For } C \leq 1.0) \quad \dots(\text{xx})$$

Too small time-steps give breach hydrographs with steep rising limb until the point of oscillation and instability. On the contrary, larger time steps induce numerical diffusion that results in the attenuation of the peak discharge and a flatter broadly spread hydrograph. So, using the Courant condition, a computational time step of 1 second is selected to remove time step induced errors in the model results. All the computation parameters are given in Table 6.

Table 6: Computations Settings used HEC-RAS Model

Parameter	Value
Computation Time Step (s)	1
Theta	1
Water Surface Tolerance (m)	0.003
Volume Tolerance (m)	0.003
Equation Set	SWE-ELM
Turbulence Model	None
Coriolis Effect	None
Matrix Solver	PARDISO (Direct)
Maximum Iterations	30

4.1.5. Validation of Peak Discharge

The breach hydrograph obtained from HEC-RAS simulation is validated by comparing the simulated peak discharge with the peak discharge computed using Froehlich's (1995b) empirical equation (xxi):

$$Q_p = 0.607 \times V_w^{0.295} \times h_b^{1.24} \quad \dots(\text{xxi})$$

where, Q_p = peak discharge, V_w = volume of water at the time of failure in cubic meters, h_b = height of breach in meters.

The simulated peak discharge value was similar to the value of peak discharge estimated using equation (xxi), and hence, the model is considered to give reasonable results for the hydrodynamic parameters.

4.2. Mapping of Exposed Elements

Areas of exposure are those places along the flood plain with buildings, infrastructure, and services where people are settled for their livelihood (Rinzin et al., 2023; Allen et al., 2019). Flood exposure can be estimated by overlaying the flood inundation extent map on the maps of population, structures, livestock, and agricultural land (Rinzin et al., 2023; Tate et al., 2021). In this study, infrastructure maps are generated within a buffer of 1,500 m from the maximum flood extent derived using GLOF hydrodynamic simulations in HEC-RAS. South Korean satellite KOMPSAT-3/3A 0.5 m data of very high-resolution multispectral imagery was procured for mapping of infrastructure. Using visual interpretation techniques, elements such as settlements, agriculture lands, road network, road bridges, hydropower projects and other public utilities along the river reach are mapped from KOMPSAT-3/3A imagery (Figure 18). In figure 18, location 1 on satellite image shows the Sissu village near Sissu nalla and locations 2 & 3 show thematic information generated from the image. In addition, infrastructure information was taken from the Geofabrik's free download server (<https://download.geofabrik.de>). The information was extracted from the OpenStreetMap project, which contains buildings, roads, and bridges and is normally updated periodically. Table 7 shows the detailed information of the mapped infrastructure with reference to the type, counts and their details. These maps and information can be used to carry out a detailed assessment of exposure for downstream infrastructure, farmland, and population against GLOFs (Zhang et al., 2021).

Table 7: Details of Infrastructure Mapped using Satellite data

Sl. No	Infrastructure	Shapefile Type	Details
1	Road Network	Polyline	723 km
2	Bridges	Point	69
3	Dams and power projects	Point	1
4	Settlements	Polygon	50
5	Agricultural Land	Polygon	1,902 ha

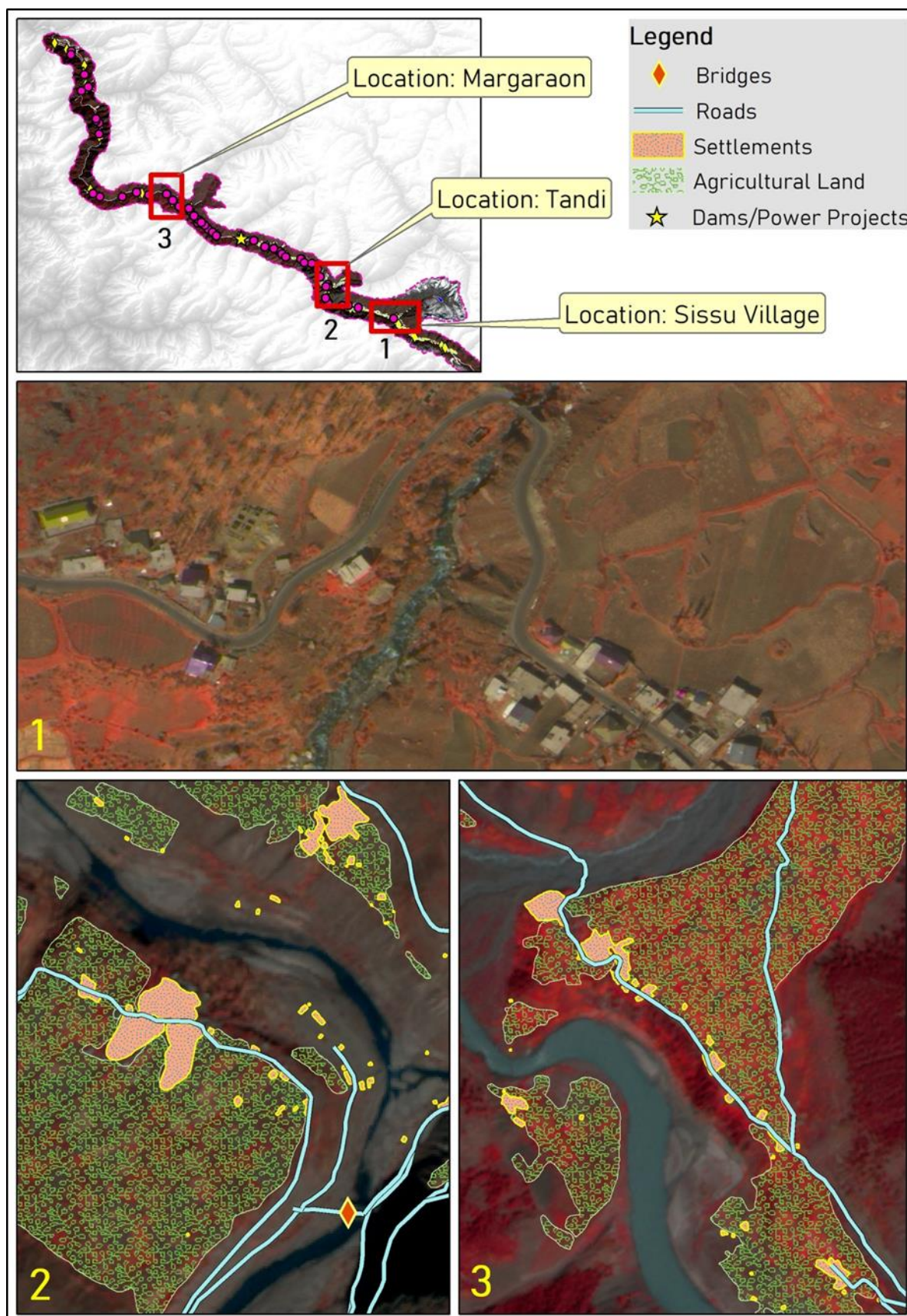


Figure 18: Sample Infrastructure Maps of the study area

4.3. GLOF Risk Assessment

A review of literature indicates the lack of a common approach or methodology for risk assessment. The Water Research Laboratory's technical report of September 2014 describes about hazard-vulnerability thresholds depending upon stability criteria for people, vehicles, and buildings, but does not mention about risk classification (WRL, 2014). On similar lines, the GAPHAZ (2017) technical guidance document also mentions about Hazard Assessment of GLOFs without any risk assessment methodology. The CWC (2018) "Guidelines for mapping flood risk associated with dams" contains general guidelines for mapping hazard and risk, and it also mentions commonly used tools for risk assessment. However, detailed procedure or thresholds for risk level classification are lacking in this guideline. NDMA's GLOF Management Report (NDMA, 2020) mentions the same hazard assessment methodology of the GAPHAZ technical guidance document. Additionally, it has some general guidelines for risk assessment. Other studies on GLOF risk assessment are available, but they differ in the methodologies and data used for risk assessment. So, it is decided to carry out GLOF risk assessment using only the results of hydrodynamic simulation and a detailed analysis of the downstream infrastructure maps. Figure 19 shows the flow chart of methodology for GLOF risk assessment adopted for Ghepang Ghat glacial lake. In this study GLOF risk assessment is proposed by combining flood severity and flood wave arrival time using a simple matrix method to generate flood risk maps.

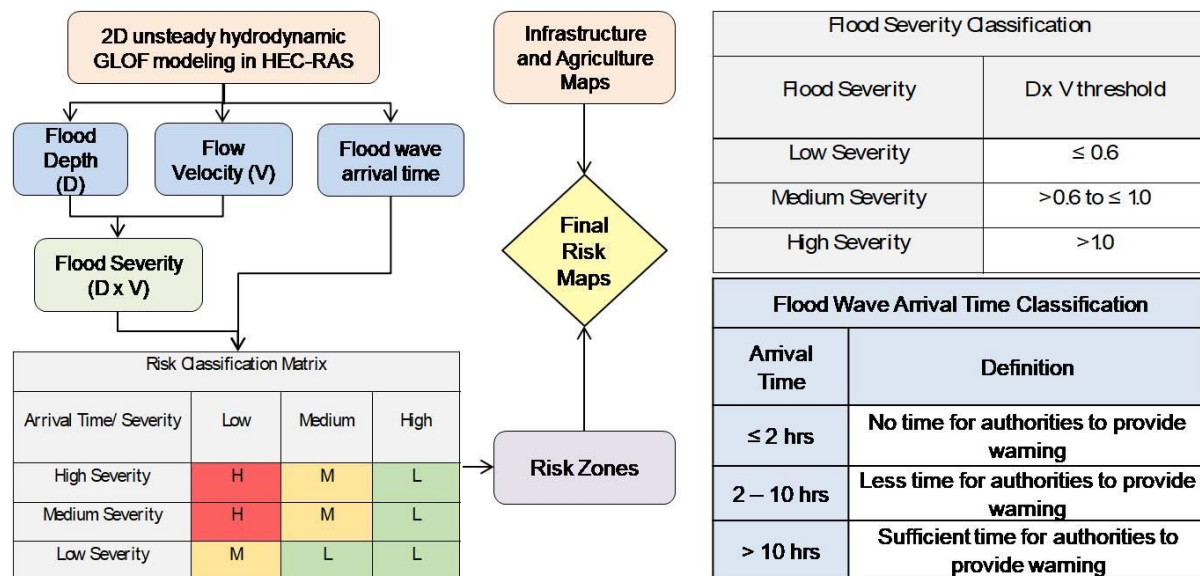


Figure 19: Flow Chart of Methodology of GLOF Risk Assessment

The flood risk classification is based on flood severity and flood wave arrival time. Flood severity can be defined as a product of flood depth and flow velocity (Graham, 1999), and it mainly represents flood hazard. The flood wave arrival time is defined as the time taken for a flood to add 0.3 m of water depth at the location under consideration. It is also derived from the results of the hydrodynamic simulation. The flood wave arrival time is categorized into 3 classes based on engineering judgment. The classification of flood wave arrival time would vary on a case-to-case basis depending upon the peak discharge of the

flood, the terrain geometry, and the average discharge of the flooded stream in no-flood conditions. As per literature on flood severity classification (CWC, 2018; AEMI, 2014; Escuder-Bueno et al., 2012; Graham, 1999), it is decided to arrive at three levels of severity classification as defined in Table 8.

Table 8: Flood severity classification

Flood Severity Class	Definition	$D \times V$ (m^2/s) threshold
Low Severity	People survive, with some loss of stability, no fatalities expected. Children, elderly and small vehicles may be in danger. All buildings are safe.	≤ 0.6
Medium Severity	Significant loss of stability. All vehicles and people are in danger.	> 0.6 and ≤ 1.0
High Severity	High risk for people and vehicles. All buildings vulnerable to structural damage and some less robust buildings susceptible to failure.	> 1.0

The definition of the severity classes are based on interpretation of the literature on flood severity. These severity thresholds are based on the stability criteria for people, vehicles, and buildings affected by flood inundation, and oriented on similar lines with the AEMI, 2014 handbook on flood risk management guidelines. As the stability criteria of the exposed elements are taken into consideration, the severity classes also represent the susceptibility and resilience of the exposed elements to damage. Therefore, this severity classification also serves as a proxy for vulnerability. So, in locations where the flood severity is high, the exposed elements may be highly vulnerable to undergo greater extents of harm. Usually, high severity areas will face very high loss of life and almost complete washing-out of habitations and infrastructure, thereby indicating high risk.

For Ghepang Ghat glacial lake, the flood wave arrival time thresholds are defined in Table 9. The arrival time indicates the time difference between the initiation of breach and the arrival of the flood wave at a particular location. So, if the flood wave arrival time is low, it indicates that the flood wave arrives very quickly at the location.

Table 9: Classification of Flood Wave Arrival Time

Flood Wave Arrival Time	Threshold	Description
High	> 10 hours	Sufficient time for the authorities to provide warning
Medium	2 to 10 hours	Less time for the authorities to provide warning
Low	≤ 2 hours	No time for the authorities to provide warning

The selection of this threshold values are based on the peak discharge of the flood, the terrain geometry, and the average discharge of the flooded stream in no-flood conditions. It is observed from simulation results that a discharge of higher than 5,000 cumecs caused

severe flooding with high flood depths and velocities for the terrain geometry of Ghepang Ghat's downstream areas. For 100% volume discharge scenario of Ghepang Ghat glacial lake, the arrival time for 5,000 cumecs of discharge was 2 hours only. Arrival time indicates the effective warning time available for people to evacuate the flood inundated areas, and therefore, it serves a proxy for the exposure of people and movable assets to a flood. If flood wave arrival time is high, people will get more time to evacuate with their movable assets leading to lower flood exposure. Therefore, moderately-high flood wave arrival times with effective warning will lead to lower risk. The same flood wave arrival times are considered for all GLOF scenarios while assessing the risk.

Finally, the risk zone maps are overlaid on the infrastructure maps of exposed elements to generate the GLOF risk maps. These maps can be used to identify those locations in the study area which require immediate attention for flood risk management.

An important point to note in the GAPHAZ (2017) technical document is that extreme scenarios like Scenarios 7 and 8 are not assessed separately for hazard due to their extremely low frequency of occurrence. The inundation extents of these scenarios exceeding the maximum inundation extents of the other scenarios mark zones of residual hazard. Therefore, we have considered the zones of residual risk as the additional inundation zones caused due to PMP, and we haven't assessed the risk for Scenarios 7 and 8 separately.

5. Results

The results of Ghepang ghat glacial lake GLOF inundation modelling and risk assessment are described in the following sections. The results of GLOF scenarios of 1 and 2 (100% of lake volume release) and 7 and 8 (100% of lake volume release with PMP) are discussed here whereas results of other scenarios are provided in annexure 2.

5.1. GLOF Inundation Modelling

5.1.1. GLOF Scenarios 1&2 (100% release)

The GLOF scenarios 1 and 2 are simulated for 100% of lake volume release (35.08 MCM) in two failure modes (scenario 1 for overtopping and scenario 2 for piping). Figure 20 shows GLOF hydrograph downstream of the lake for scenario 1 (overtopping failure mode). The flood hydrograph reached its peak of 9,611 cumecs in 58 minutes after the initiation of breach in the lake. Figure 21 shows GLOF hydrographs downstream of the lake at various locations on the river reach for scenario 1. The peak of the flood hydrograph is attenuated from 9,611 cumecs to 376 cumecs over river reach length of 134 km at Phindru.

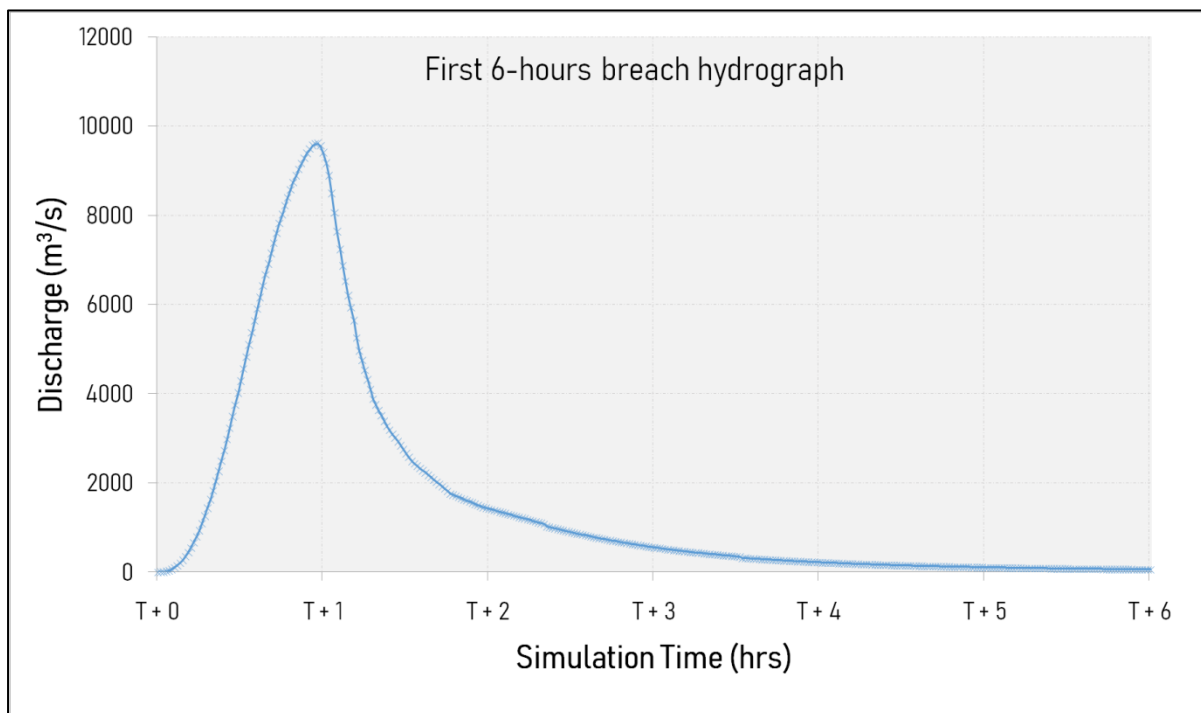


Figure 20: GLOF hydrograph for Scenario-1 (100% volume discharge - Overtopping failure)

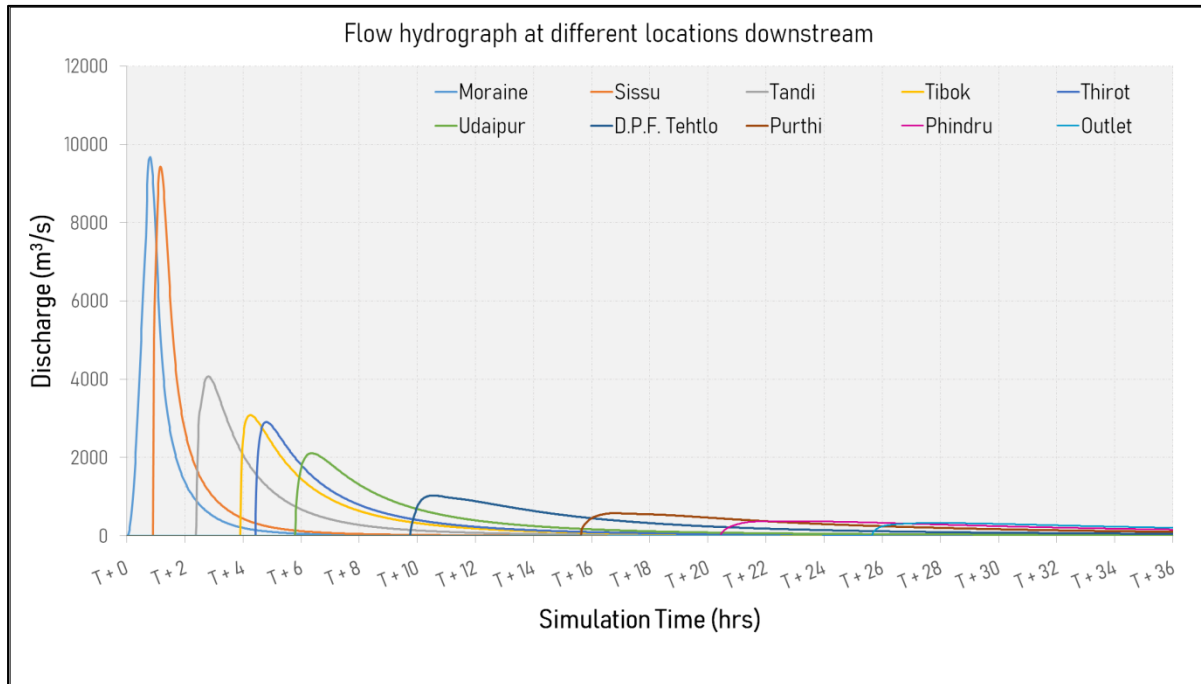


Figure 21: GLOF hydrographs at Different Downstream Locations for scenario-1

Figure 22 shows GLOF hydrograph downstream of the lake for scenario 2 (piping failure mode). The flood hydrograph reached its peak of 9,673 cumecs in 48 minutes after the initiation of breach in the lake. Figure 23 shows GLOF hydrographs downstream of the lake at various locations on the river reach for scenario 2. The peak of the flood hydrograph is attenuated from 9,673 cumecs to 376 cumecs over river reach length of 134 km at Phindru.

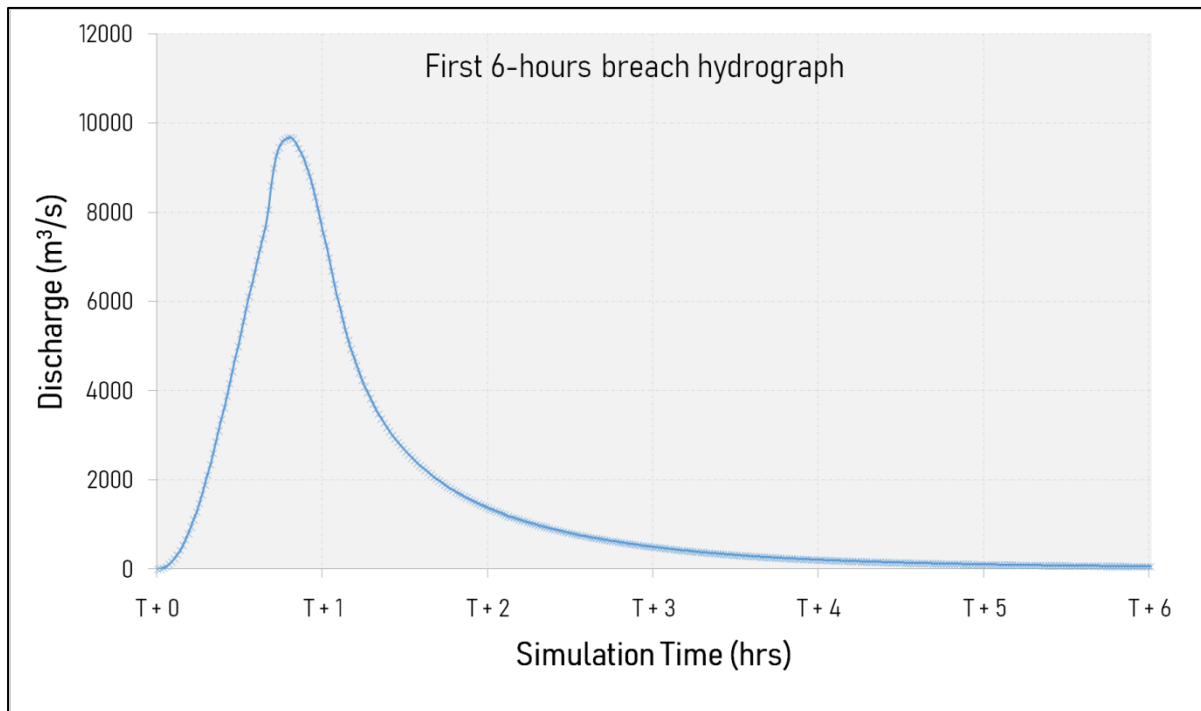


Figure 22: GLOF hydrograph for Scenario-2 (100% volume discharge - Piping failure)

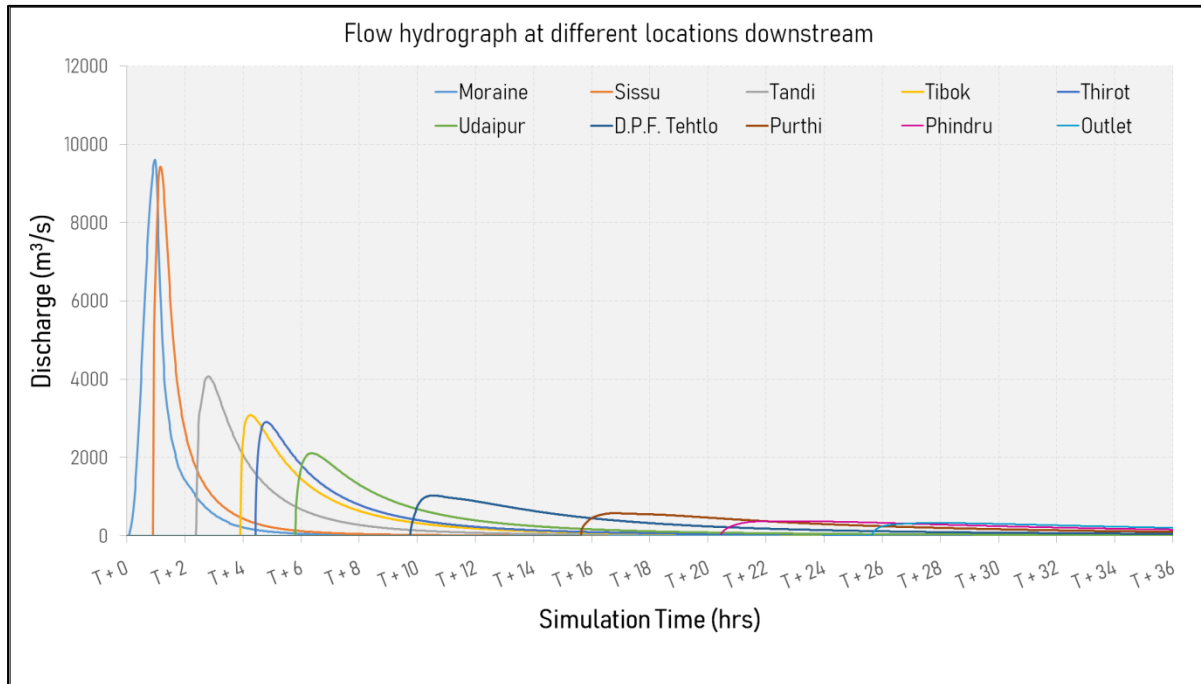


Figure 23: GLOF hydrographs at Different Downstream Locations for scenario-2

Table 10 describes the flood wave characteristics of GLOF scenario 1. After the breach of lake, the flood wave reaches nearest village of Sissu located at a distance of 11 km with peak discharge of 9,378 cumecs (maximum depth:21.5 m; maximum velocity: 8.8 m/s) and as the flood wave traverses further downstream gets attenuated.

Table 10: Flood Wave Characteristics of GLOF Scenario 1

Location	Distance from Lake (km)	Time to peak	Peak Discharge (m ³ /s)	Max Depth (m)	Max Velocity (m/s)
Sissu	11	1 hr 18 mins	9,378	21.5	8.8
Tandi	31	2 hrs 51 mins	4,123	10.4	3.3
Tibok	47.9	4 hrs 18 mins	3,105	9	5.2
Thiroth	56	4 hrs 51 mins	2,929	12.5	5.8
Udaipur	71	6 hrs 24 mins	2,117	6.5	2.9
D.P.F. Tehtlo	94.1	10 hrs 34 mins	1,026	6.6	2.8
Purthi	118	16 hrs 52 mins	581	4.1	1
Phindru	134	23 hrs 24 mins	376	2.9	0.9

Table 11 describes the flood wave characteristics of GLOF scenario 2. After the breach of lake, the flood wave reaches nearest village of Sissu located at a distance of 11 km with peak discharge of 9,431 cumecs (maximum depth:21.5 m; maximum velocity: 8.8 m/s) and as the flood wave traverses further downstream gets attenuated.

Table 11: Flood Wave Characteristics of GLOF Scenario 2

Location	Distance from Lake (km)	Time to peak	Peak Discharge (m ³ /s)	Max Depth (m)	Max Velocity (m/s)
Sissu	11	1 hr 9 mins	9,431	21.5	8.8
Tandi	31	2 hrs 48 mins	4,079	10.4	3.3
Tibok	47.9	4 hrs 15 mins	3,083	9	5.2
Thirot	56	4 hrs 48 mins	2,911	12.5	5.8
Udaipur	71	6 hrs 21 mins	2,109	6.5	2.8
D.P.F. Tehtlo	94.1	10 hrs 31 mins	1,025	6.6	2.8
Purthi	118	16 hrs 49 mins	580	4.1	1
Phindru	134	23 hrs 21 mins	376	2.9	0.9

Flood inundation maps for all the GLOF scenarios were created by overlaying the inundation extents derived from HEC-RAS simulation on Resourcesat-2 LISS-IV 5.8 m multispectral imagery. Figure 24 shows the map of flood inundation extent along with major settlements affected due to the flood for GLOF scenario 1. The inset images show flood depth and flood velocity near Sissu village along with GLOF affected settlements, roads, bridges and other infrastructure.

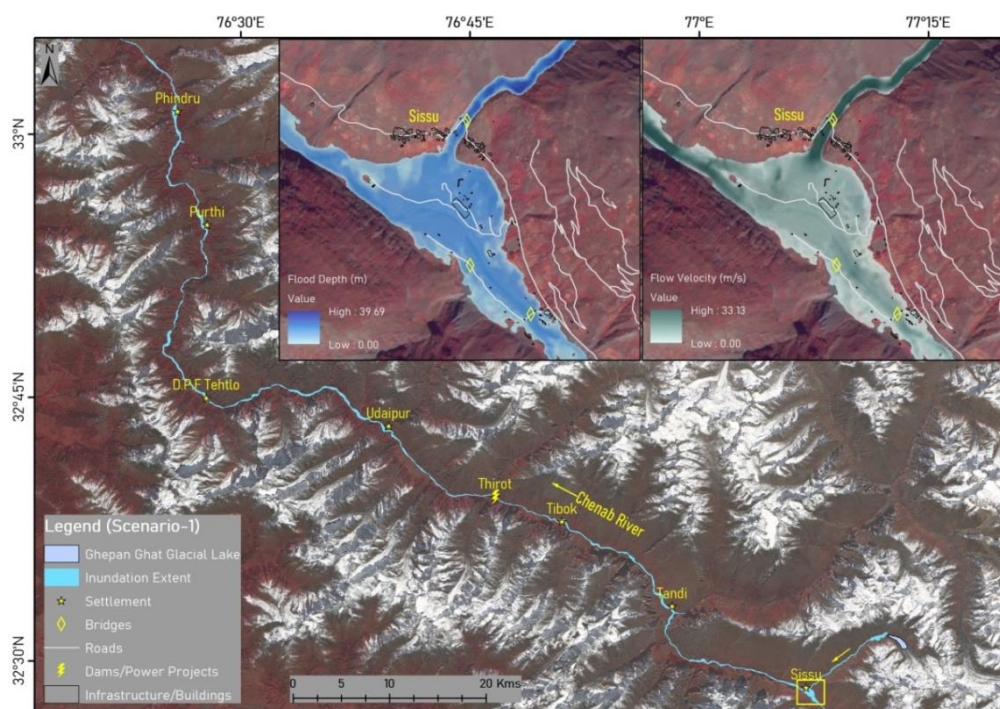


Figure 24: Map of Flood Inundation Extent for GLOF Scenario-1

Figure 25 shows the map of flood inundation extent along with major settlements affected due to the flood for GLOF scenario 2. The inset images show flood depth and flood velocity near Sissu village along with GLOF affected settlements, roads, bridges and other infrastructure.

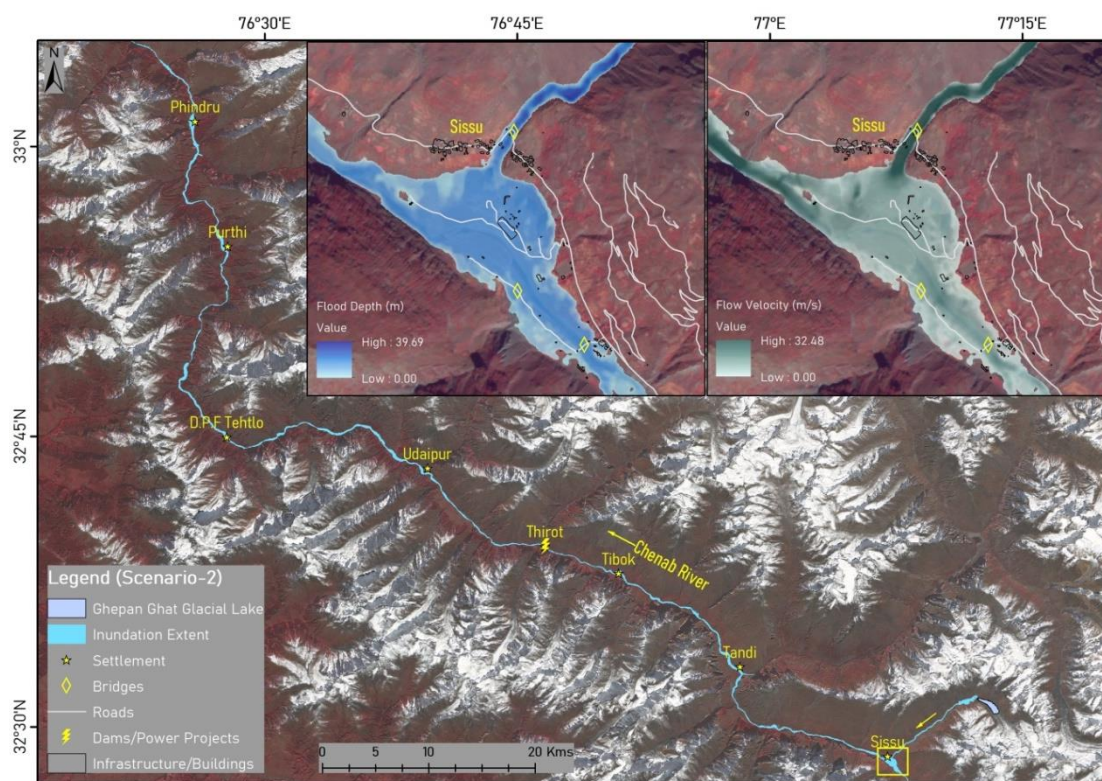


Figure 25: Map showing extent of inundation for Scenario-2

Table 12 provides number of settlements, extent of agriculture land, number of bridges, length of road network and public utilities affected by scenarios 1 and 2. Table 13 provides names of settlements affected by scenarios 1 and 2. All the settlements (32) are partly affected by the GLOF inundation.

Table 12: Infrastructure affected in GLOF Scenarios 1 and 2

Scenario	No. of Affected Settlements	Area of Agricultural Land Affected (ha)	No. of Bridges Affected	Length of Roads affected (km)	No. of Public Utilities affected	Inundated Area (ha)
Scenario-1	32	94.3	41	37.5	4	2,247
Scenario-2	32	93.9	41	37.4	4	2,245

Table 13: Details of Settlements affected in GLOF Scenarios 1 and 2

S. No.	Settlement Name	Distance from lake (km)
1	Sissu	11

S. No.	Settlement Name	Distance from lake (km)
2	Ghondhla*	21.2

S. No.	Settlement Name	Distance from lake (km)
3	Dalang*	22.7
4	Shipting*	27.5
5	Bha-Garang	30.5
6	Gushal	31
7	Tandi	31
8	Ruding*	38.1
9	Lingar*	39.6
10	Rapay*	44.3
11	Tibok*	47.9
12	Nalda	50.4
13	Thirot	56
14	Kishori*	64
15	Shanur*	65.2
16	Triloknath*	66.2
17	D.P.F. Udaipur	66.9

S. No.	Settlement Name	Distance from lake (km)
18	D.P.F. Bardang*	68.6
19	Lobar	70.4
20	Udaipur	71
21	Salpat	73.4
22	Margaraon	75.8
23	R.F. Khurail	78.1
24	R.F. Rhumas*	82.2
25	Kurched*	84.9
26	D.P.F. Dhanwani*	88.8
27	D.P.F. Tehtlo	94.1
28	Purthi*	118
29	Ajog*	119
30	Chhau*	119.5
31	Sach*	130.8
32	Phindru	134

Note: * indicate few buildings, which are affected close to the river channel near the mentioned settlement.

Figure 26 shows close view of partly affected settlements and other infrastructure at Sissu (Left) and Tandhi (Right) in both scenarios 1 and 2.

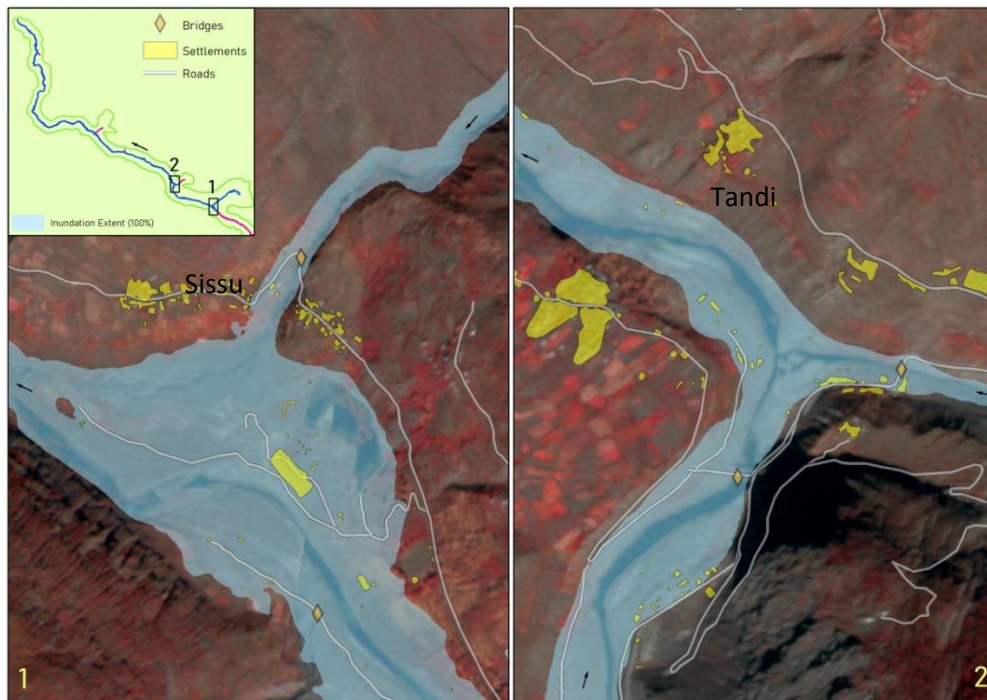


Figure 26: Map showing Close View of extent of inundation for Scenarios - 1 and 2

5.1.2. GLOF Scenarios 7&8 (100% release with PMP)

The GLOF scenarios 7 and 8 are simulated for 100% of lake volume release (35.08 MCM) along with rainfall-runoff due to PMP in two failure modes (scenario 7 for overtopping and scenario 8 for piping). Figure 27 shows GLOF hydrograph downstream of the lake for scenario 7 (overtopping failure mode) along with runoff generated due to PMP. The flood hydrograph reached its peak of 9,611 cumecs in 58 minutes after the initiation of breach in the lake as in the case of scenario 1. Figure 28 shows GLOF hydrographs downstream of the lake at various locations on the river reach for scenario 7. The peak of the flood hydrograph has increased from 9,611 cumecs to 12,031 cumecs, 14,655 cumecs, 21,315 cumecs, 24,820 cumecs at Tandi, Tibok, Tehtlo, and Phindru locations respectively due to addition of runoff due to PMP.

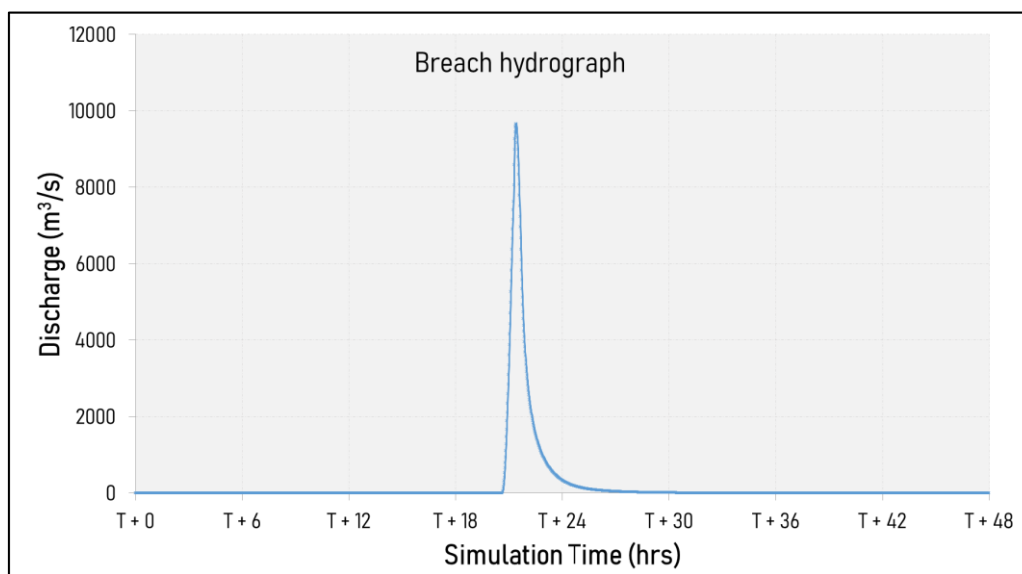


Figure 27: GLOF hydrograph for Scenario-7 (100% volume discharge & PMP-Overtopping)

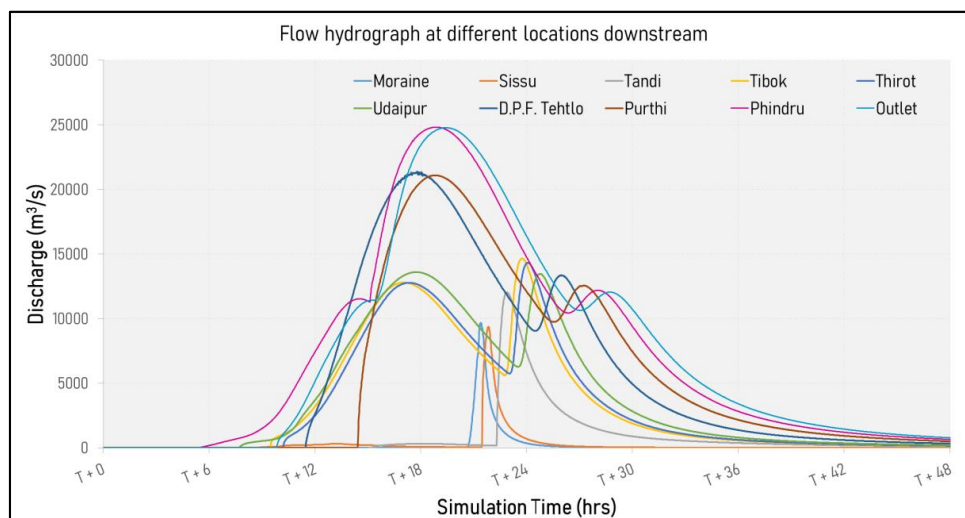


Figure 28: GLOF hydrographs at Different Downstream Locations for scenario-7

Figure 29 shows GLOF hydrograph downstream of the lake for scenario 8 (piping failure mode) along with runoff generated due to PMP. The flood hydrograph reached its peak of 9,673 cumecs in 48 minutes after the initiation of breach in the lake as in the case of scenario 2. Figure 30 shows GLOF hydrographs downstream of the lake at various locations on the river reach for scenario 8. The peak of the flood hydrograph has increased from 9,450 cumecs to 11,918 cumecs, 14,592 cumecs, 21,381 cumecs, 24,822 cumecs at Tandi, Tibok, Tehtlo and Phindru locations respectively due to addition of runoff due to PMP.

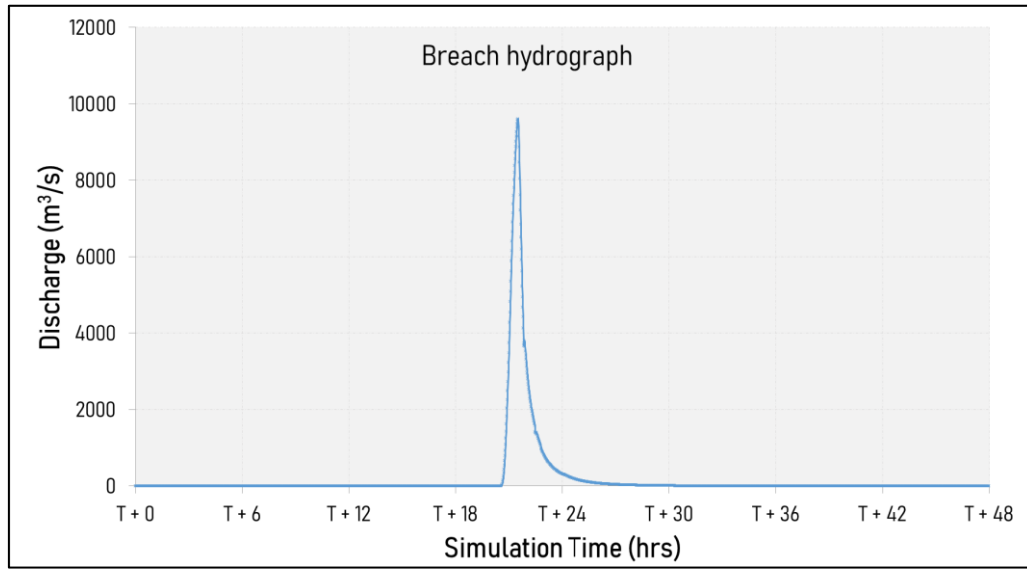


Figure 29: GLOF hydrograph for Scenario-8 (100% volume discharge & PMP - Piping)

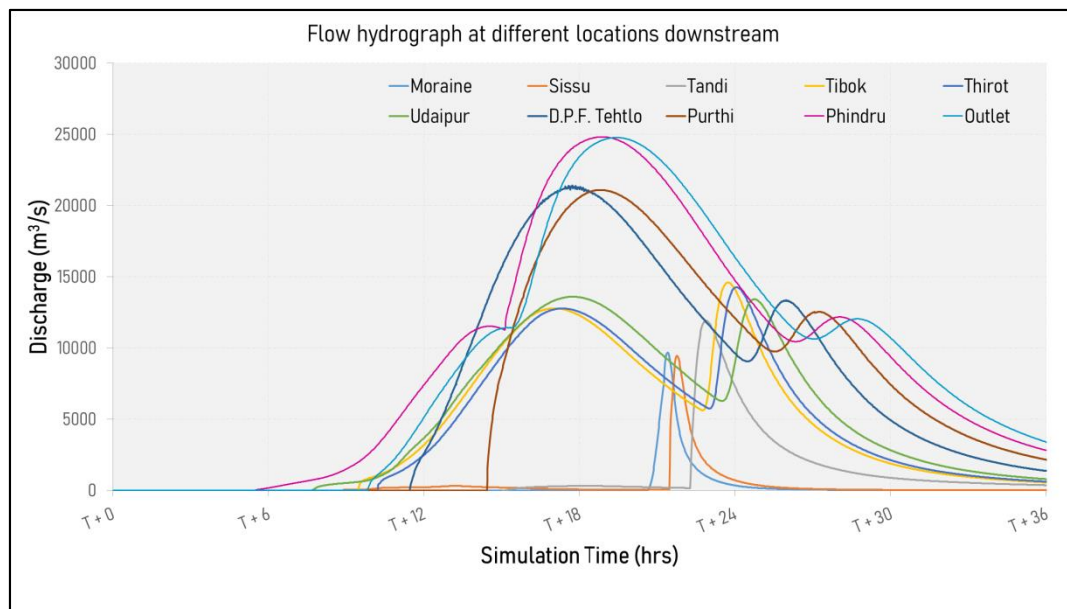


Figure 30: GLOF hydrographs at Different Downstream Locations for scenario-8

Table 14 describes the flood wave characteristics of GLOF scenario 7. After the breach of lake, the flood wave reaches nearest village of Sissu located at a distance of 11 km with peak discharge of 9,673 cumecs (maximum depth:21.4 m; maximum velocity: 8.7 m/s) and as the flood wave traverses further downstream gets attenuated.

Table 14: Flood Wave Characteristics of GLOF Scenario 7

Location	Distance from Lake (km)	Time to peak	Peak Discharge (m ³ /s)	Max Depth (m)	Max Velocity (m/s)
Sissu	11	21 hrs 24 mins	9,673	21.4	8.7
Tandi	31	22 hrs 53 mins	12,031	18.6	4.6
Tibok	47.9	23 hrs 44 mins	14,655	18.8	7.1
Thirot	56	24 hrs 03 mins	14,317	27.4	8.7
Udaipur	71	17 hrs 44 mins	13,595	19.2	5.8
D.P.F. Tehtlo	94.1	17 hrs 28 mins	21,315	31.4	6.7
Purthi	118	18 hrs 47 mins	21,088	27.4	4.5
Phindru	134	18 hrs 51 mins	24,820	27.9	4.8

Table 15 provides the flood wave characteristics of GLOF scenario 8. After the breach of lake, the flood wave reaches nearest village of Sissu located at a distance of 11 km with peak discharge of 9,450 cumecs (maximum depth:21.4 m; maximum velocity: 8.7 m/s) and as the flood wave traverses further downstream gets attenuated.

Table 15: Flood Wave Characteristics of GLOF Scenario 8

Location	Distance from Lake (km)	Time to peak	Peak Discharge (m ³ /s)	Max Depth (m)	Max Velocity (m/s)
Sissu	11	21 hrs 45 mins	9,450	21.4	8.7
Tandi	31	22 hrs 53 mins	11,918	18.6	4.5
Tibok	47.9	23 hrs 43 mins	14,592	18.7	7.1
Thirot	56	24 hrs 03 mins	14,262	27.4	8.7
Udaipur	71	17 hrs 44 mins	13,595	19.2	5.8
D.P.F. Tehtlo	94.1	17 hrs 35 mins	21,381	31.4	6.7
Purthi	118	18 hrs 48 mins	21,090	27.4	4.5
Phindru	134	18 hrs 51 mins	24,822	27.9	4.8

Figure 31 shows the map of flood inundation extent along with major settlements affected due to the flood for GLOF scenario 7. The inset images show flood depth and flood velocity near Sissu village along with GLOF affected settlements, roads, bridges and other infrastructure.

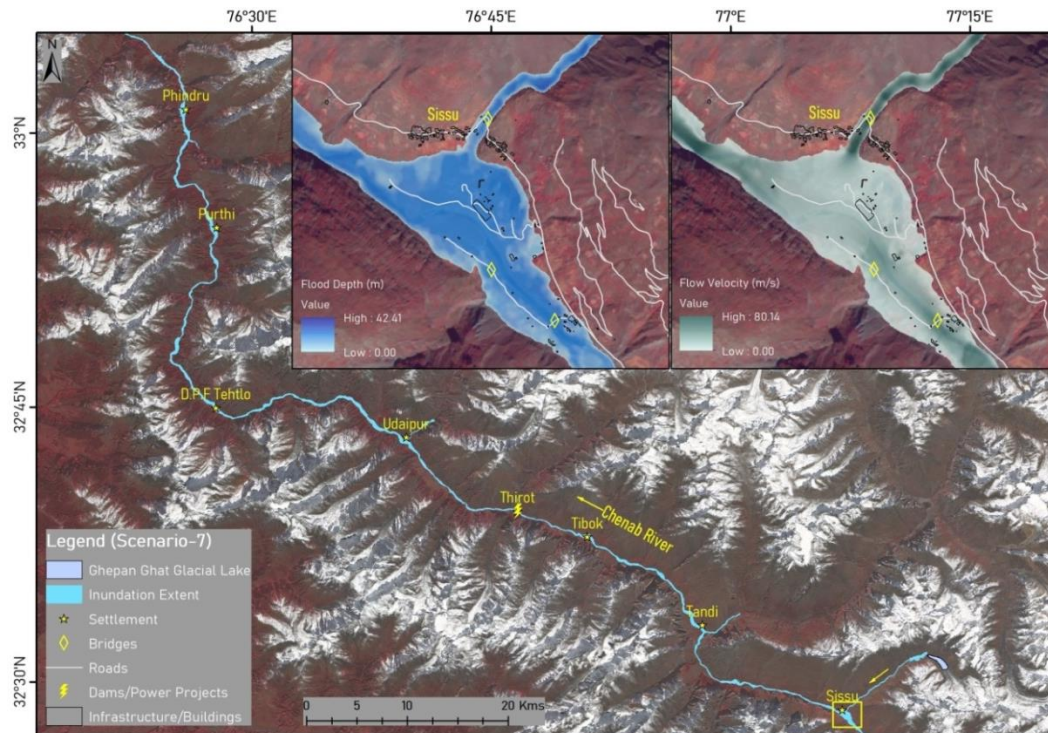


Figure 31: Map of Flood Inundation Extent for GLOF Scenario-7

Figure 32 shows the map of flood inundation extent along with major settlements affected due to the flood for GLOF scenario 8. The inset images show flood depth and flood velocity near Sissu village along with GLOF affected settlements, roads, bridges and other infrastructure.

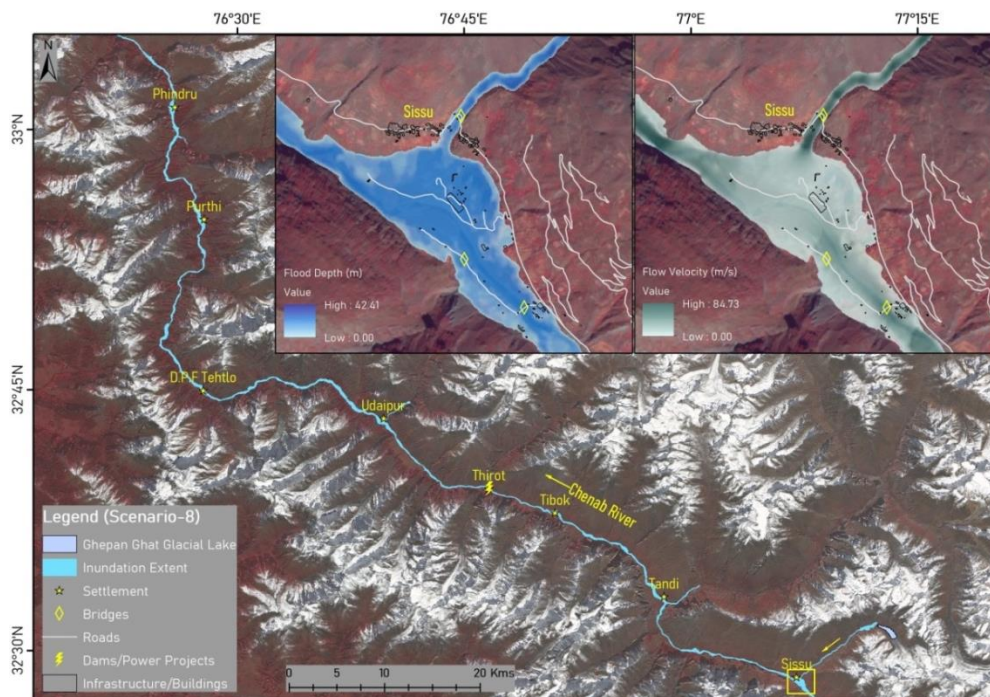


Figure 32: Map showing extent of inundation for Scenario-8

Table 16 provides number of settlements, extent of agriculture land, number of bridges, length of road network and public utilities affected by scenarios 7 and 8. Table 17 provides names of settlements affected by scenarios 7 and 8. All the settlements (34) are partly affected by the GLOF inundation.

Table 16: Infrastructure affected in GLOF Scenarios 7 and 8

Scenario	No. of Affected Settlements	Area of Agricultural Land Affected (ha)	No. of Bridges Affected	Length of Roads affected (km)	No. of Public Utilities affected	Inundated Area (ha)
Scenario-7	34	204.7	57	106.9	7	6,149
Scenario-8	34	204.3	57	106.6	7	6,125

Table 17: Details of Settlements affected in GLOF Scenarios 7 and 8

S. No.	Settlement Name	Distance from lake (km)	S. No.	Settlement Name	Distance from lake (km)
1	Sissu	11	18	D.P.F. Udaipur	66.9
2	Ghondhla*	21.2	19	D.P.F. Bardang*	68.6
3	Dalang*	22.7	20	Lobar	70.4
4	Shipting*	27.5	21	Udaipur	71
5	Bha-Garang	30.5	22	Salpat	73.4
6	Gushal	31	23	Margaraon	75.8
7	Tandi	31	24	R.F. Khurail	78.1
8	Ruding*	38.1	25	R.F. Rhumas*	82.2
9	Lingar*	39.6	26	Kurched*	84.9
10	Rapay*	44.3	27	D.P.F. Dhanwani*	88.8
11	Tibok*	47.9	28	D.P.F. Tehtlo	94.1
12	Nalda	50.4	29	Kund Bara*	96
13	Thirot	56	30	Purthi*	118
14	Haruka*	62.1	31	Ajog*	119
15	Kishori*	64	32	Chhau*	119.5
16	Shanur*	65.2	33	Sach*	130.8
17	Triloknath*	66.2	34	Phindru	134

Note: * indicate few buildings, which are affected close to the river channel near the mentioned settlement.

Figure 33 shows close view of partly affected settlements and other infrastructure at Sissu (Left) and Tandi (Right) in both scenarios 7 and 8. The pink coloured flood inundation extent is the additional extent due to PMP over the inundation extent of scenarios 1 and 2 at the respective locations.

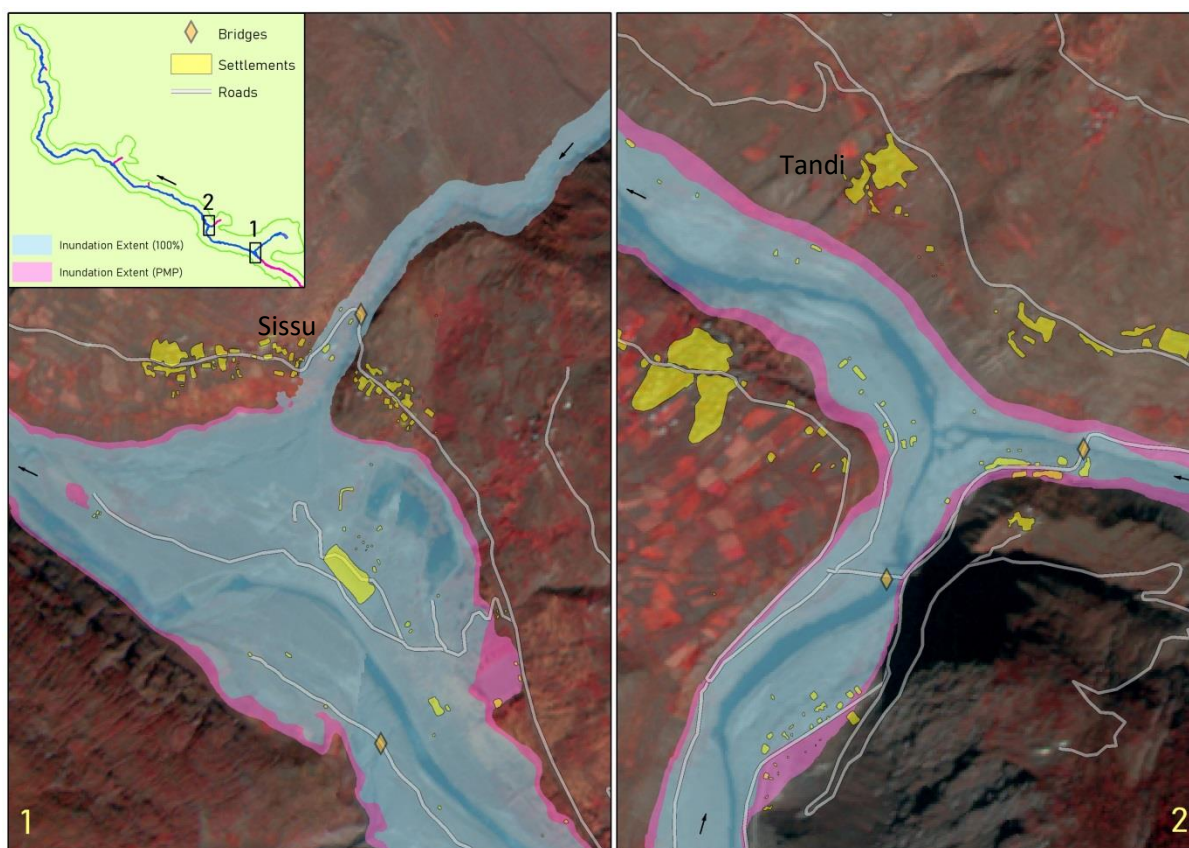


Figure 33: Map showing Close View of part of flood inundation for Scenarios - 7 and 8

5.2. GLOF Risk Assessment

The GLOF risk maps are generated for all the 8 scenarios as per procedure described under methodology section. The risk due to GLOF is categorised in Low, Moderate and High zones. An important point to note in the GAPHAZ (2017) technical document is that extreme scenarios like scenarios 7 and 8 are not assessed separately for hazard due to their extremely low frequency of occurrence. The inundation extents of these scenarios exceeding the maximum inundation extents of the other scenarios (1 and 2) mark zones of residual hazard. Therefore, the zones of residual risk are considered as the additional inundation zones caused due to PMP, and the risk for scenarios 7 and 8 are not assessed separately.

The results of GLOF scenarios of 1 and 2 (100% of lake volume release) and 7 and 8 (100% of lake volume release with PMP) are discussed here and results of other scenarios are provided in annexure 3. The additional risk due to PMP in scenarios 7 and 8 are shown as residual risk in the risk maps of scenarios 1 and 2 respectively.

5.2.1. GLOF Scenarios 1&7 (100% release & PMP)

The GLOF risk map for scenarios 1 and 7 are shown in figure 34. The GLOF risk map for scenario 1 consists of three categories of risk zones namely high, moderate and low whereas scenario 7 includes all three categories of scenario 1 and residual risk zone (residual risk is due to PMP). The total area under GLOF scenarios 1 and 7 are 2,248 ha and 6,150 ha respectively. The area under high, moderate and low risk zones of GLOF

scenario 1 are 401 ha, 1,018 ha and 829 ha respectively. The additional area under risk due to PMP is the residual risk zone extent of 3,902 ha. The area under the high risk zone will be most affected area with no time (less than 2 hours) for warning in case of GLOF event occurrence. Table 18 gives details of flood inundation area, number of settlements, agricultural land, number of bridges and length of road network affected exclusively under various categories of GLOF risk zones. As already mentioned in the previous section all the settlements are partly affected. The total number of settlements, agricultural land, bridges, and road length affected in scenario 1 are 32, 94.3 ha, 41 and 37.5 km respectively. Figures 35 and 36 show close view of affected infrastructure (settlements, bridges, road network, etc) and agriculture land by GLOF inundation extent near Sissu respectively. Annexure 4 provides close view of GLOF risk maps at important locations along the Chenab river reach.

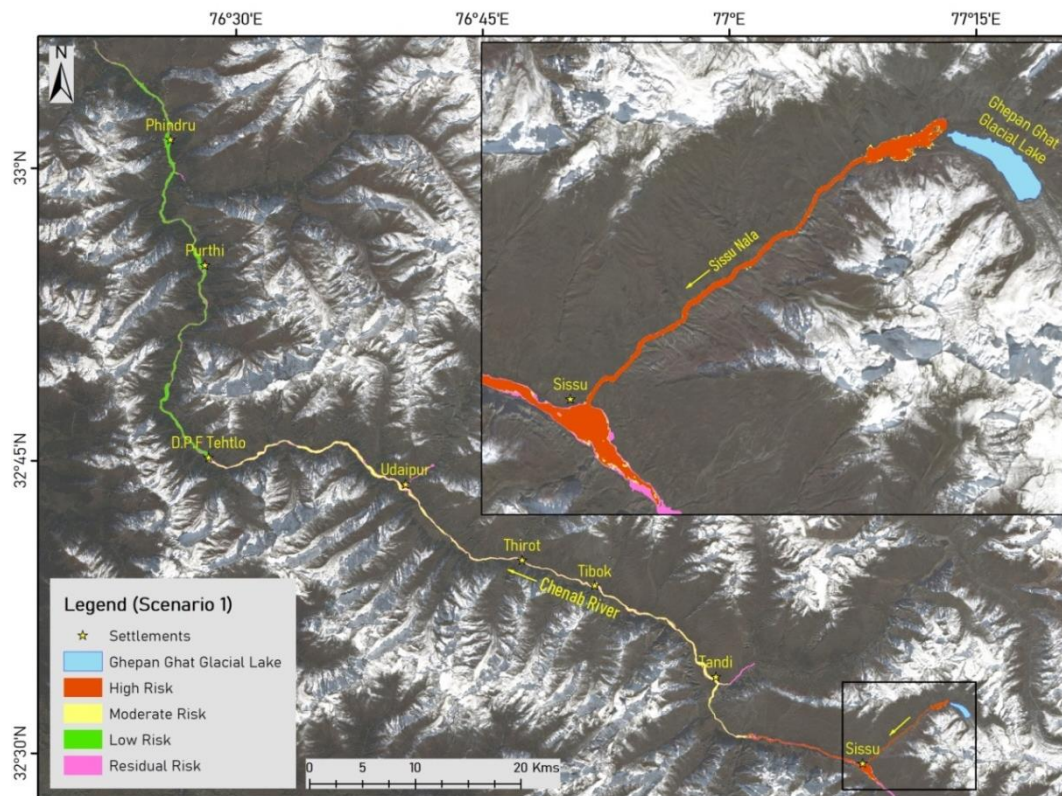


Figure 34: GLOF Risk Map for the Study Area (Scenario-1 and 7)

Table 18: Zone wise details of Infrastructure affected in GLOF Scenarios 1 and 7

Scenario		Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Road (km)
7	1	High	401	3	15.8	4	6.7
		Moderate	1,018	24	46.2	24	17.5
		Low	829	5	32.3	13	13.3
		Residual	3,902	2	110.4	16	69.4
Total			6,150	34	204.7	57	106.9

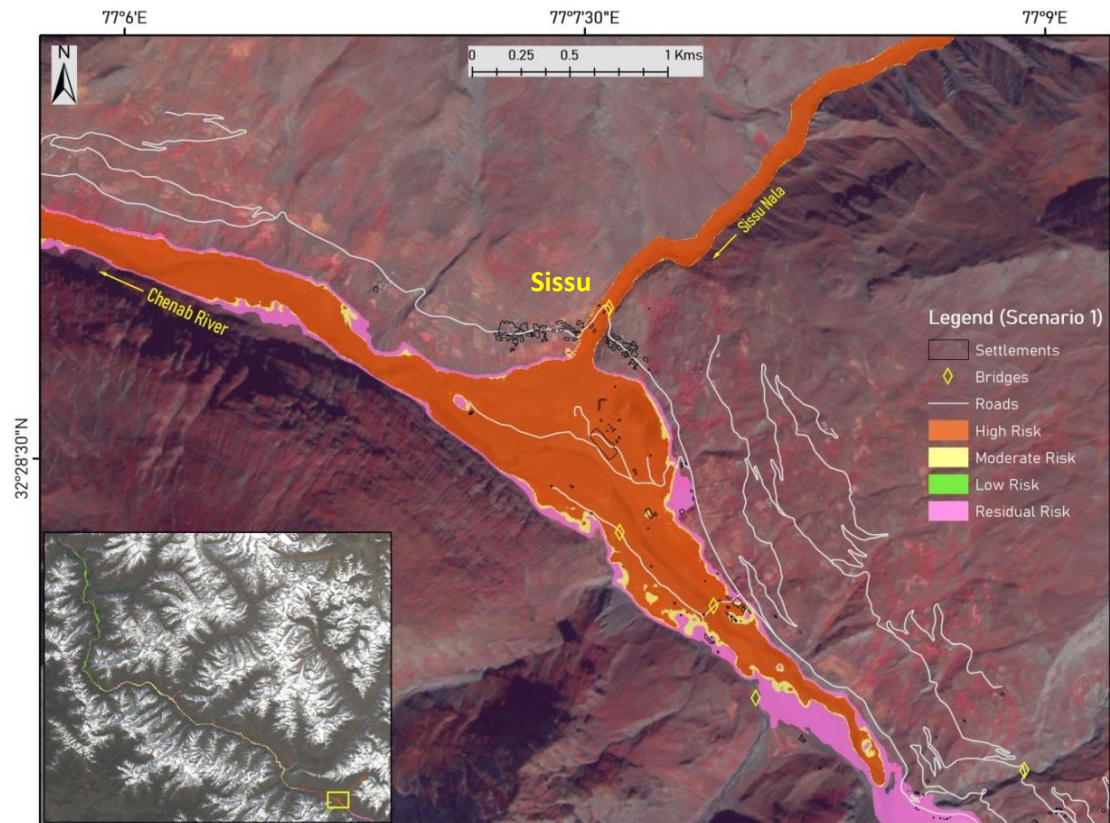


Figure 35: GLOF Risk Map showing Affected Infrastructure near Sissu (Scenario-1 and 7)

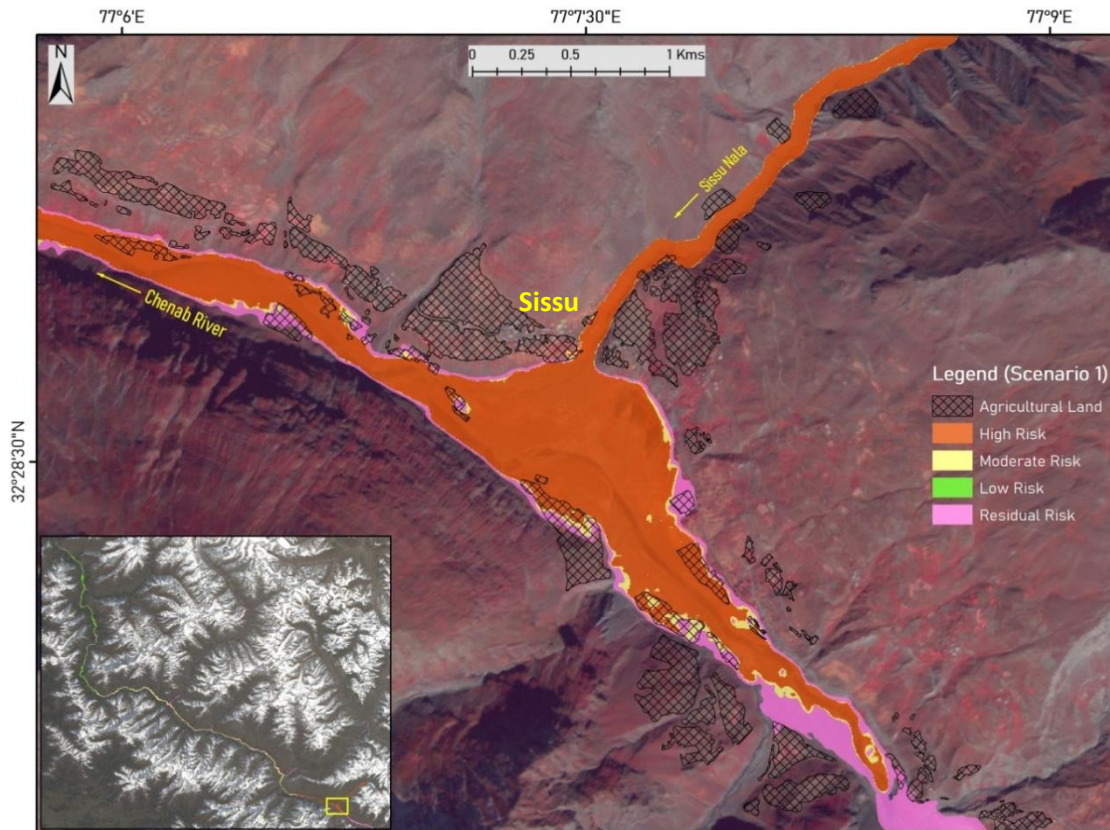


Figure 36: GLOF Risk Map showing Affected Agricultural Land near Sissu (Scenario-1 and 7)

5.2.2. GLOF Scenarios 2&8 (100% release & PMP)

The GLOF risk map for scenarios 2 and 8 are shown in figure 37. The GLOF risk map for scenario 2 consists of three categories of risk zones namely high, moderate and low whereas scenario 8 includes all three categories of scenario 2 and residual risk zone (residual risk is due to PMP). The total area under GLOF scenarios 2 and 8 are 2,245 ha and 6,125 ha respectively. The area under high, moderate and low risk zones of GLOF scenario 2 are 413 ha, 1,007 ha and 825 ha respectively. The additional area under risk due to PMP is the residual risk zone extent of 3,880 ha. The area under the high risk zone will be most affected area with no time (less than 2 hours) for warning in case of GLOF event occurrence. Table 18 gives details of flood inundation area, number of settlements, agricultural land, number of bridges and length of road network affected exclusively under various categories of GLOF risk zones. All the settlements are partly affected. The total number of settlements, agricultural land, bridges, and road length affected in scenario 2 are 32, 93.9 ha, 41 and 37.4 km respectively. Figures 38 and 39 show close view of affected infrastructure (settlements, bridges, road network, etc) and agriculture land by GLOF inundation extent near Sissu respectively.

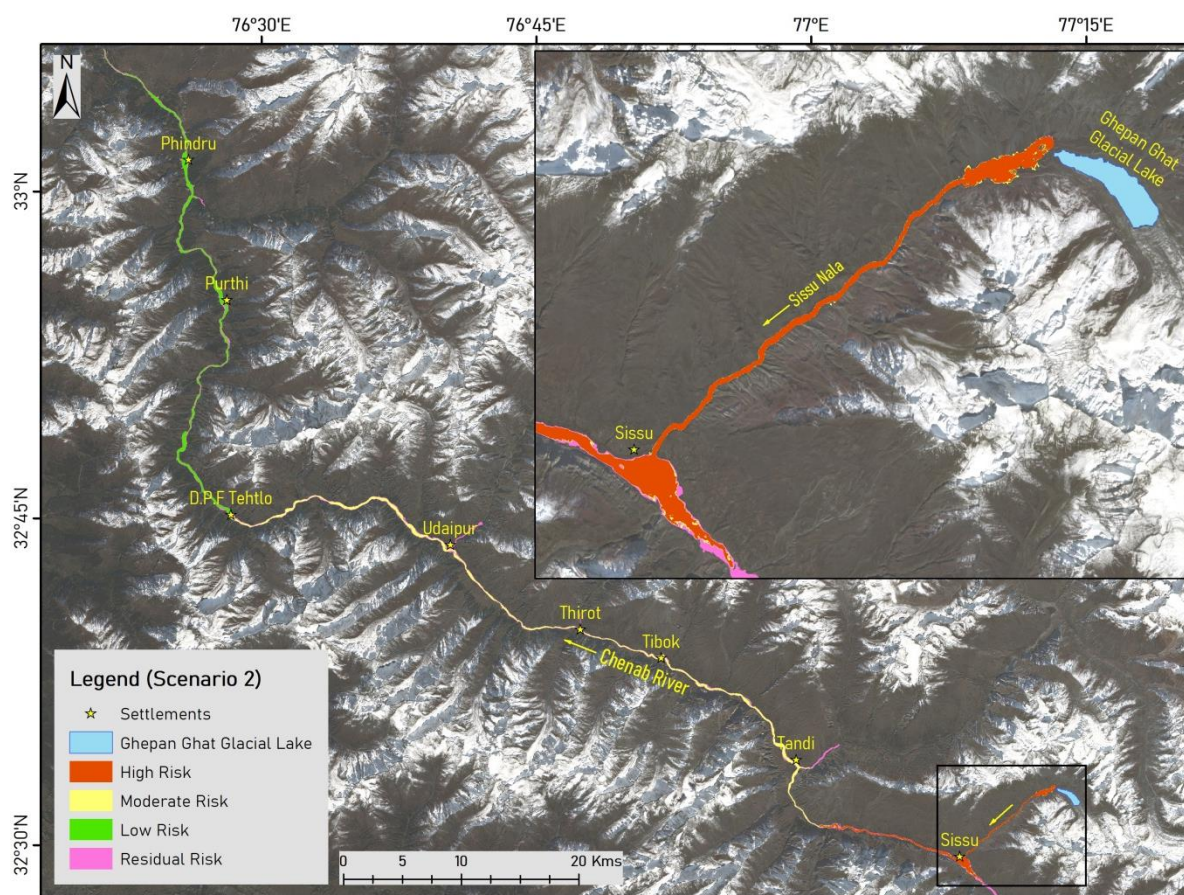


Figure 37: GLOF Risk Map for the Study Area (Scenario-2 and 8)

Table 19: Zone wise details of Infrastructure affected in GLOF Scenarios 2 and 8

Scenario		Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Roads (km)
8	2	High	413	3	15.8	4	7.0
		Moderate	1,007	24	45.9	24	17.3
		Low	825	5	32.2	13	13.1
		Residual	3,880	2	110.4	16	69.2
Total			6,125	34	204.3	57	106.6

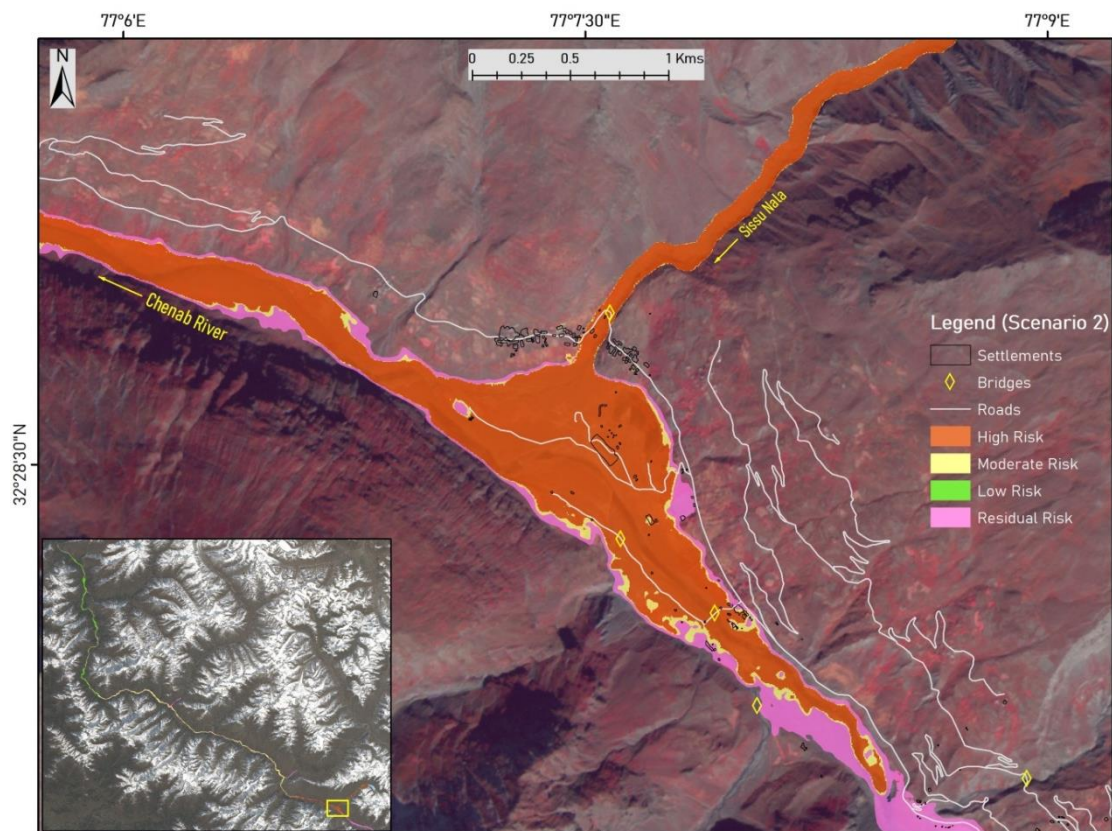


Figure 38: GLOF Risk Map showing Affected Infrastructure near Sissu (Scenario-2 and 8)

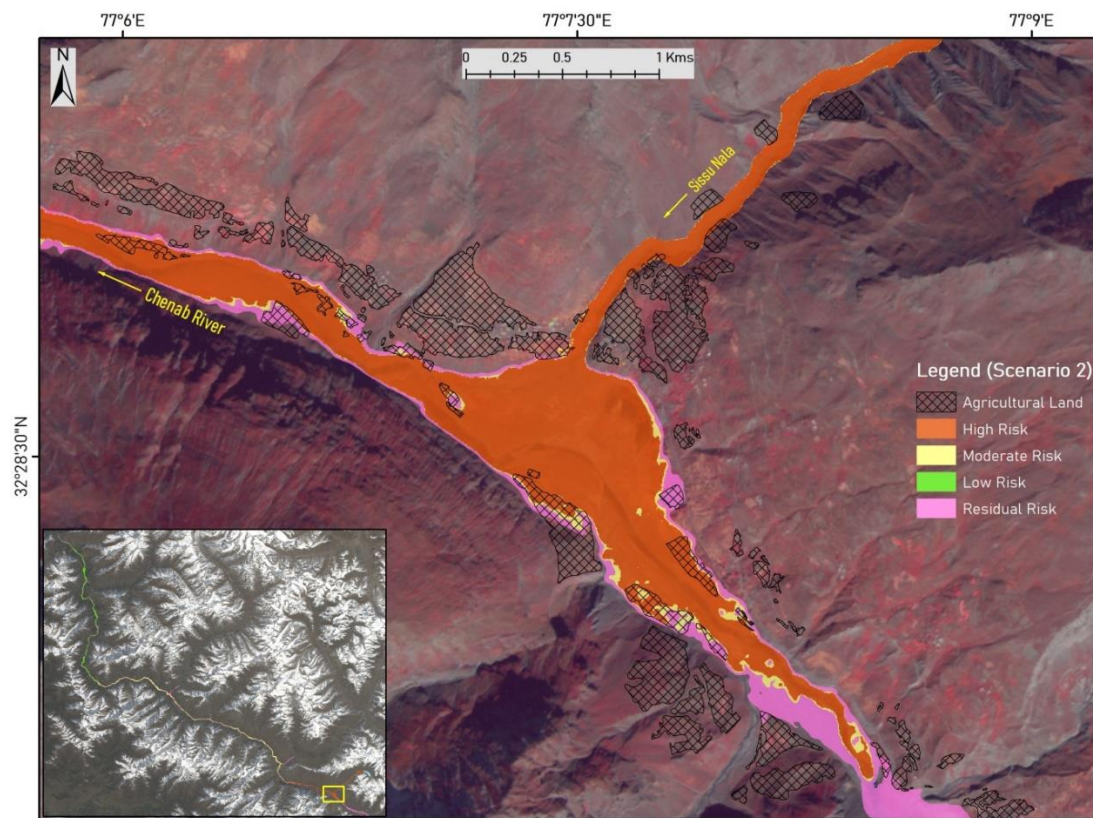


Figure 39: GLOF Risk Map showing Affected Agricultural Land near Sissu (Scenario-2 & 8)

5.3. Limitations

The limitations of this study are listed below:

1. Due to the lack of Gopang Ghat glacial lake bathymetric information, the volume of the glacial lake was estimated using Huggel's formula, which may lead to different peak discharges and different flood inundation extents than the actual values.
2. Errors in the Digital Terrain Model, especially in the channel regions will affect the hydrodynamics of the flood wave. Although the major errors were corrected manually using cross sections in HEC-RAS, but few minor terrain errors may have still been neglected due to practical reasons.
3. Manning's n values adopted in the study are based on landcover data. The channel regions are manually corrected for accurate 'n' values.
4. The moraine geometry was estimated using remotely sensed data, mainly from the Digital Terrain Model. Also, the condition of the moraine dam was assumed to be poor, which may not represent the actual case.
5. Dam breach parameters are estimated using Froehlich's regression equations rather than in-situ geotechnical observation-based data. There are uncertainties associated with regression-based dam breach parameters as described by Wahl (2004) and Sattar et al. (2021) with equations (xxii) and (xxiii):

$$LL = P \times (10^{-e-2Se}) \quad \text{..(xxii)}$$

$$UL = P \times (10^{-e+2Se}) \quad \text{..(xxiii)}$$

where, LL and UL are the lower and upper uncertainty limits of dam breach parameters respectively, P is the predicted dam breach parameter, e and 2Se are the mean prediction error and width of the uncertainty band respectively. For average breach width, e and 2Se are 0.01 and ± 0.39 , for breach formation time, e and 2Se are -0.22 and ± 0.64 , and for peak discharge, e and 2Se are -0.04 and ± 0.32 respectively.

6. The dam break modelling in HEC-RAS does not include estimation of water surface profiles along with sediment transport modelling.

6. Conclusions

National Remote Sensing Centre (NRSC), Hyderabad is carrying out hydrological studies using satellite data and geo-spatial techniques under National Hydrology Project. As part of this project, a detailed glacial lake inventory, prioritization of glacial lakes, Glacial Lake Outburst Flood (GLOF) inundation simulation and GLOF risk assessment for selected lakes are taken up for entire catchment of Indian Himalayan Rivers covering Indus, Ganga, and Brahmaputra River basins. Ghepang Ghat lake is one of the five prioritized glacial lakes identified in Indus river basin.

The Ghepang Ghat Glacial Lake is located at an elevation of 4,068 m a.m.s.l. in the state of Himachal Pradesh, India. A high resolution Digital Terrain Model of Tandem-X with a spatial resolution of 5 m was used in the study to simulate GLOF inundations of various scenarios. A series of 2D hydrodynamic dam-breach simulations in HEC-RAS software are developed for 8 different failure modes (overtopping and piping), different volumes of water released in case of a failure of the lake moraine (100%, 75%, and 50%), and under different weather conditions (clear-weather and Probable Maximum Precipitation). The worst-case scenario (scenario 8) was the one with a 100% discharge of the lake water under piping failure due to PMP occurrence over the catchment area of glacial lake. The GLOF peak hydrograph of 9,673 cumecs propagated from the moraine dam to the nearest settlement of Sissu in just 21 minutes where it was estimated as 9,450 cumecs. The narrow and steep V-shaped valley from the downstream of glacial lake to Sissu village has resulted in high flood depths of around 20 m along with velocities of approximately 12 m/s during the peak of the flood wave near the village. The simulated GLOF peak of flood hydrographs for 100%, 75% and 50% of lake water releases scenarios (scenario 1, 3 and 5) yielded 9,378 cumecs, 6,628 cumecs and 3,127 cumecs near Sissu village for overtopping failure. GLOF hazard maps are prepared by integrating flood depth and flood velocity for different scenarios.

High resolution satellite images (spatial resolution of 0.5 m) are used for mapping of settlements, agriculture lands, road network, road bridges, hydropower projects and other public utilities along the river reach for identifying the elements of exposure due to the various Ghepang Ghat lake GLOF scenarios. The total number of settlements, agricultural land, bridges, and road length inundated in the worst-case scenario (scenario 8) are 34, 204 ha, 57 and 106 km respectively. All the 34 settlements are partially flooded by the GLOF inundation extent.

GLOF risk maps are prepared by integrating flood hazard (flood depth X flood velocity) and flood wave arrival time, which was classified, into zones of high, medium, and low risk. The combination of flood hazard and flood wave arrival time for flood risk mapping presents a unique approach to flood risk assessment. Zones of high risk are defined as those regions where flood severity was either medium or high, and the flood wave arrival time was within 2 hours since the start of the breach. Consequently, Sissu village and nearby areas falls under the high-risk zone, and as we move further downstream, the risk reduces to medium near Ghondhla at distance of 21 km from lake for scenarios 1 & 2, 7 & 8. The medium risk zone extends for a distance of 94 km along the river reach from lake covering the settlements of Gushal, Tandi Udaipur and Phindru.

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Annexure 1: Lateral Inflow Hydrographs due to PMP at Eight Locations

The following eight figures show the lateral inflow hydrographs generated due to PMP at various locations in the catchment area of Ghepang Ghat glacial lake and its downstream along Chenab river reach (refer Figure 15).

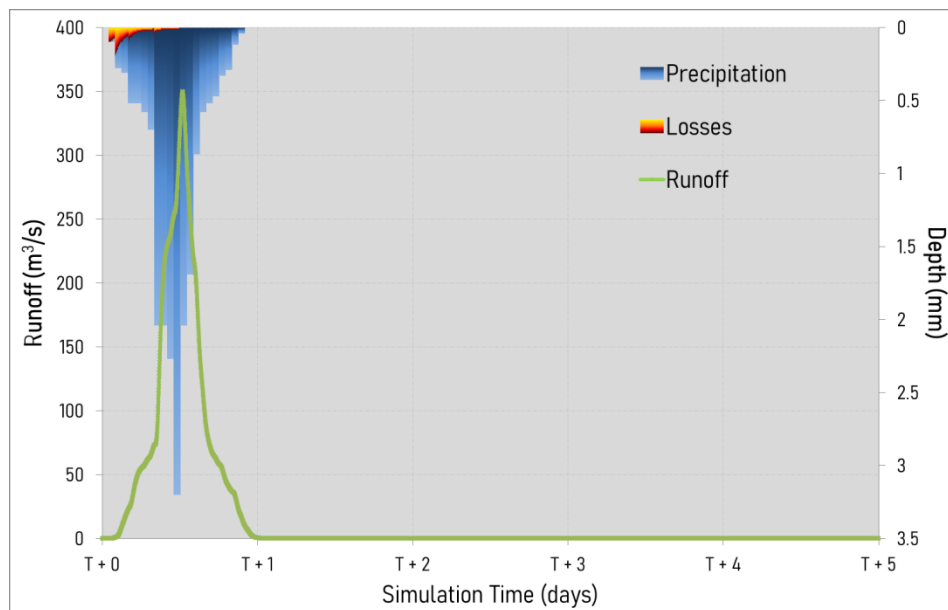


Figure 40: Lateral Inflow Hydrograph due to PMP at Inlet Point 1

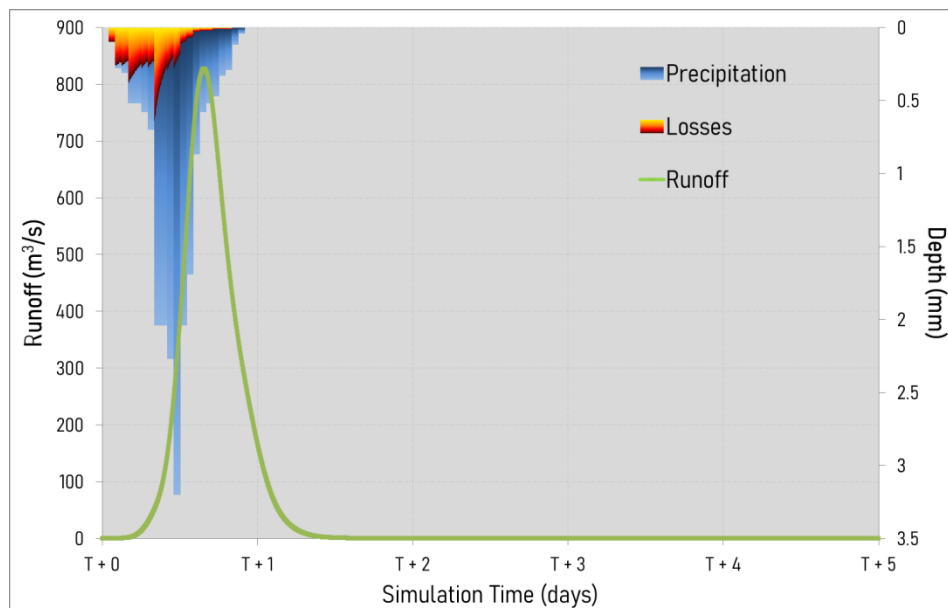


Figure 41: Lateral Inflow Hydrograph due to PMP at Inlet Point 2

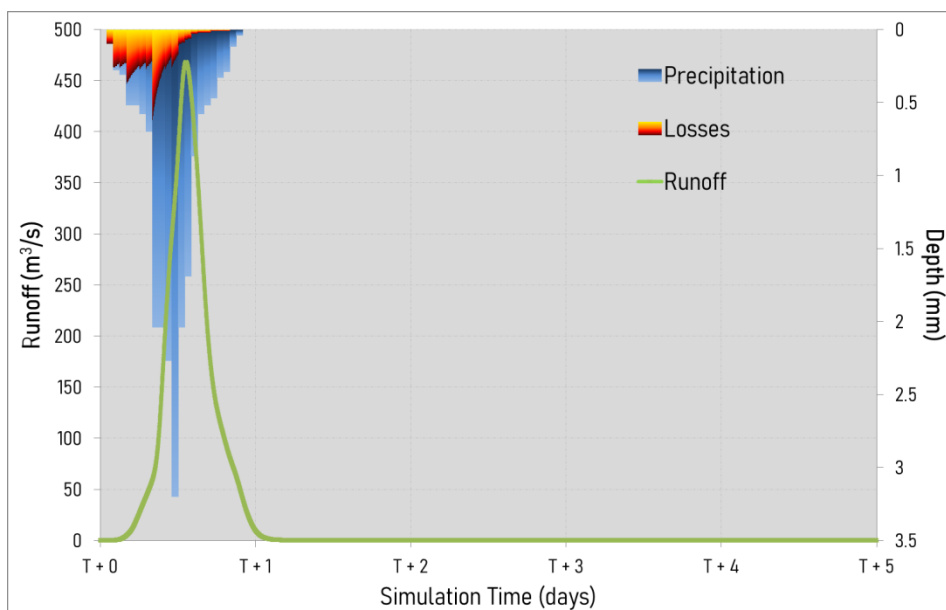


Figure 42: Lateral Inflow Hydrograph due to PMP at Inlet Point 3

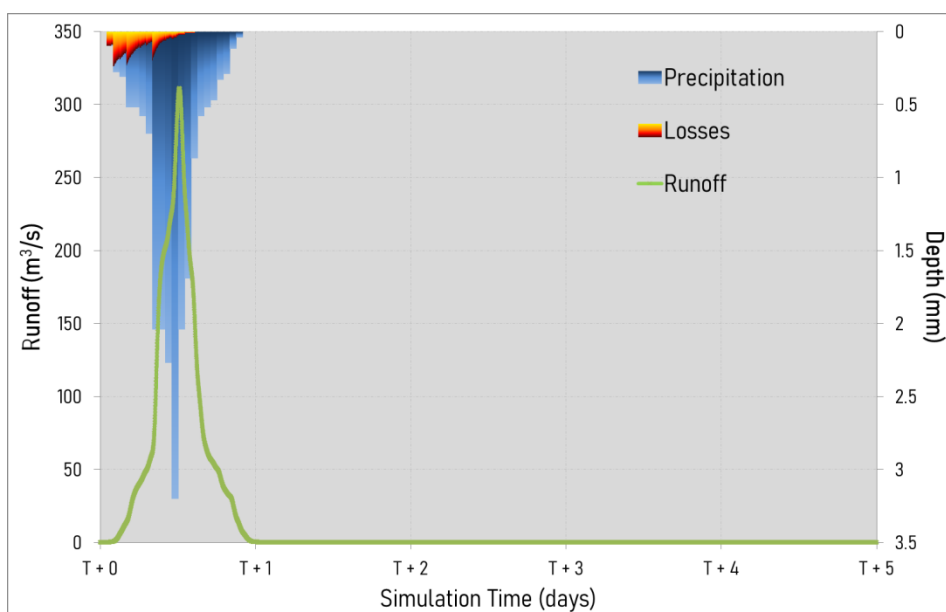


Figure 43: Lateral Inflow Hydrograph due to PMP at Inlet Point 4

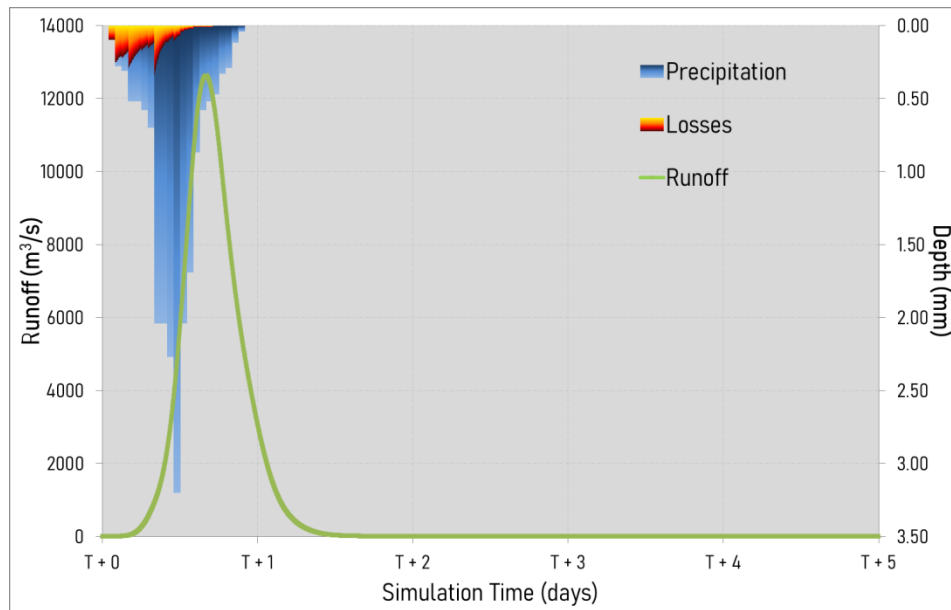


Figure 44: Lateral Inflow Hydrograph due to PMP at Inlet Point 5

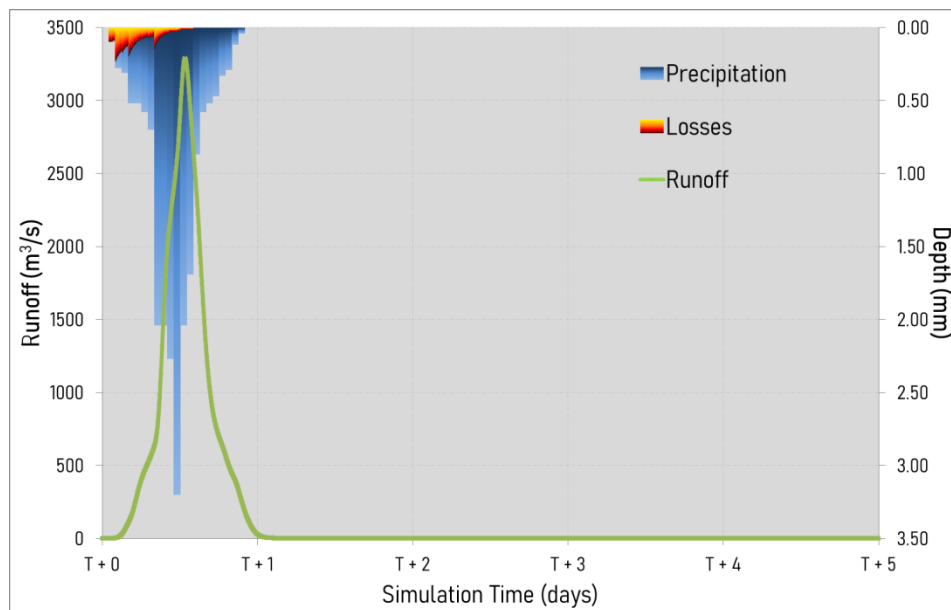


Figure 45: Lateral Inflow Hydrograph due to PMP at Inlet Point 6

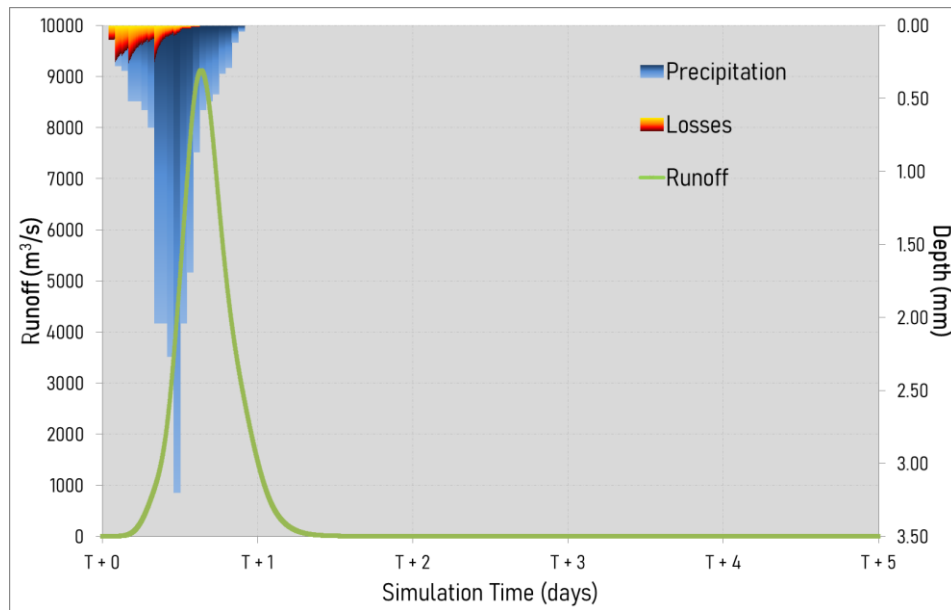


Figure 46: Lateral Inflow Hydrograph due to PMP at Inlet Point 7

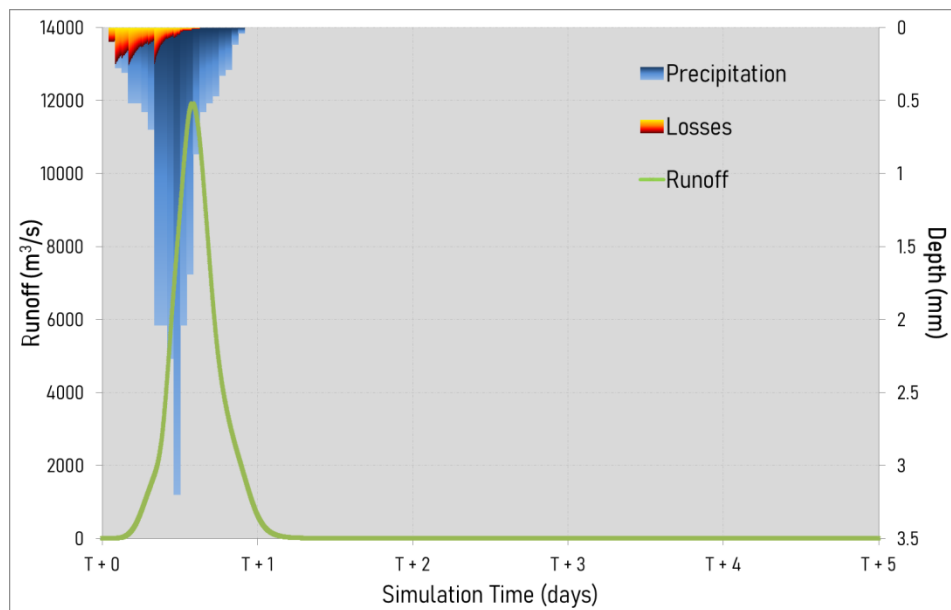


Figure 47: Lateral Inflow Hydrograph due to PMP at Inlet Point 8

Annexure 2: Results of GLOF Scenarios of 3 to 6

1. GLOF Scenarios 3 & 4 (75% release)

The GLOF scenarios 3 and 4 are simulated for 75% of lake volume release (26.31 MCM) in two failure modes (scenario 3 for overtopping and scenario 4 for piping). Figure 48 shows GLOF hydrograph downstream of the lake for scenario 3 (overtopping failure mode). The flood hydrograph reached its peak of 6,729 cumecs in 1 hour 7 minutes after the initiation of breach in the lake. Figure 49 shows GLOF hydrographs downstream of the lake at various locations on the river reach for scenario 3. The peak of the flood hydrograph is attenuated from 6,729 cumecs to 203 cumecs over river reach length of 134 km at Phindru.

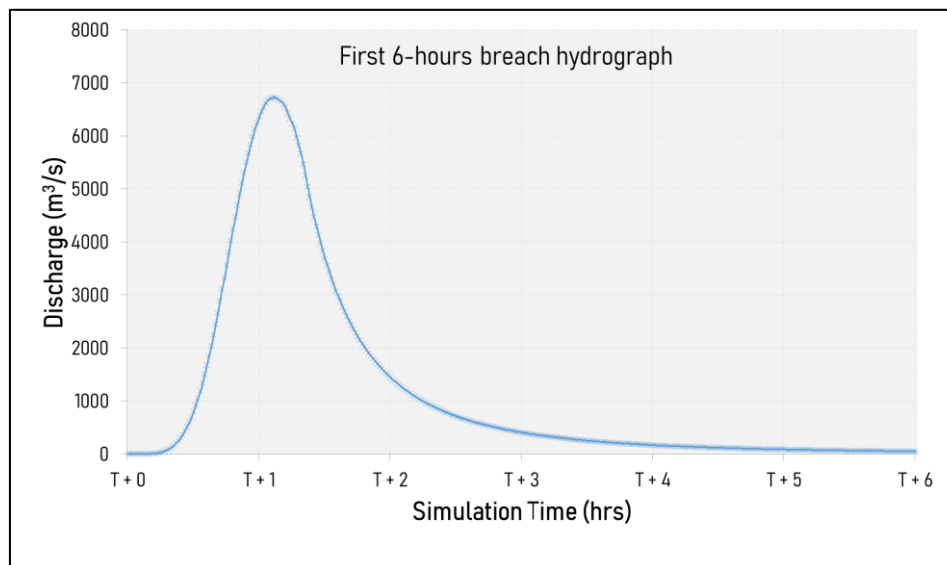


Figure 48: GLOF hydrograph for Scenario-3 (75% volume discharge - Overtopping failure)

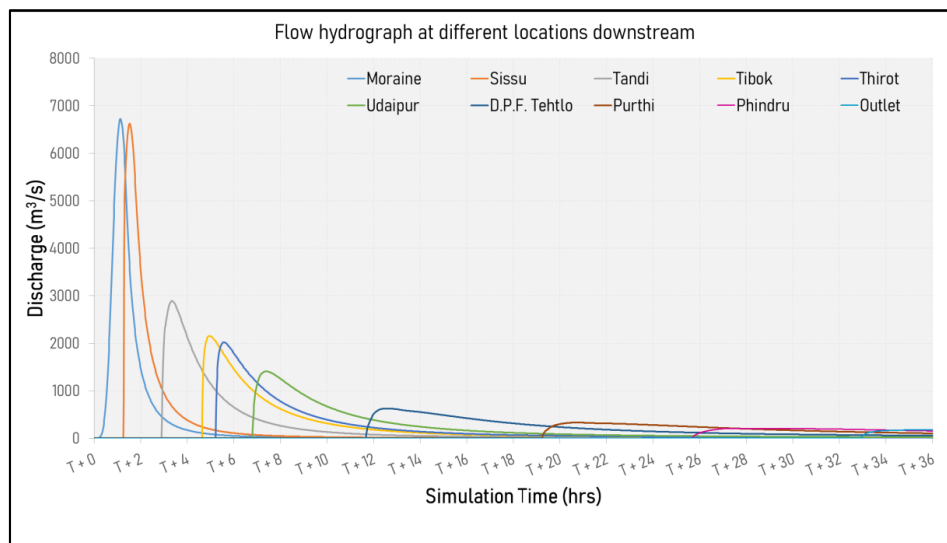


Figure 49: GLOF hydrographs at Different Downstream Locations for scenario-3

Figure 50 shows GLOF hydrograph downstream of the lake for scenario 4 (piping failure mode). The flood hydrograph reached its peak of 6,858 cumecs in 59 minutes after the initiation of breach in the lake. Figure 51 shows GLOF hydrographs downstream of the lake at various locations on the river reach for scenario 4. The peak of the flood hydrograph is attenuated from 6,858 cumecs to 201 cumecs over river reach length of 134 km at Phindru.

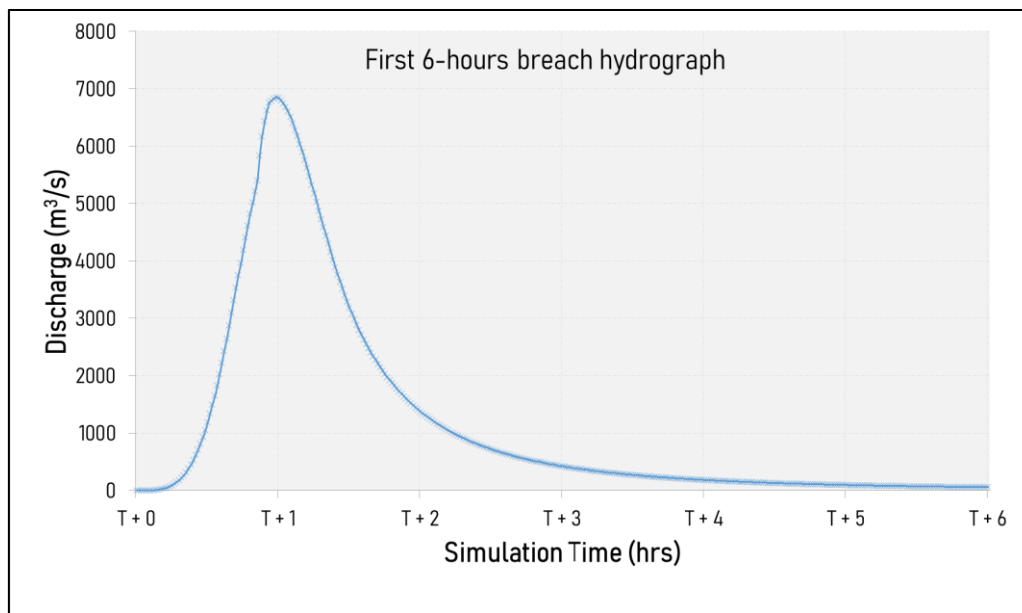


Figure 50: GLOF hydrograph for Scenario-4 (100% volume discharge - Piping failure)

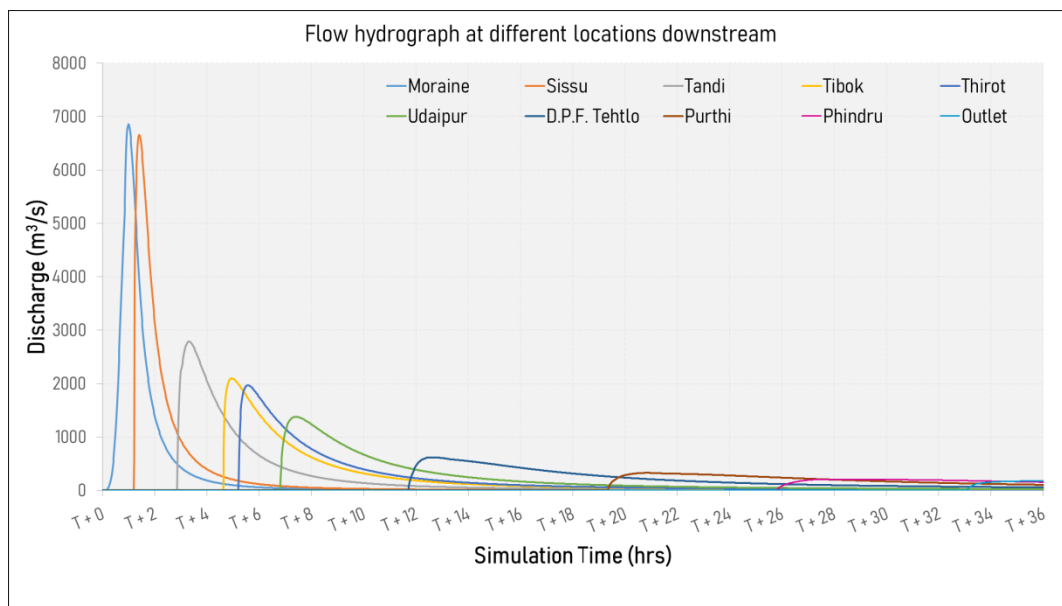


Figure 51: GLOF hydrographs at Different Downstream Locations for scenario-4

Table 21 describes the flood wave characteristics of GLOF scenario 3. After the breach of lake, the flood wave reaches nearest village of Sissu located at a distance of 11 km with peak discharge of 6,628 cumecs (maximum depth:18.6 m; maximum velocity:7.6 m/s) and as the flood wave traverses further downstream gets attenuated.

Table 20: Flood Wave Characteristics of GLOF Scenario 3

Location	Distance from Lake (km)	Time to peak	Peak Discharge (m ³ /s)	Max Depth (m)	Max Velocity (m/s)
Sissu	11	1 hr 30 mins	6,628	18.6	7.6
Tandi	31	3 hrs 20 mins	2,889	8.8	2.9
Tibok	47.9	4 hrs 57 mins	2,152	7.5	4.7
Thirot	56	5 hrs 33 mins	2,018	10.4	5.2
Udaipur	71	7 hrs 22 mins	1,406	5.5	2.5
D.P.F. Tehtlo	94.1	12 hrs 33 mins	625	5.2	2.2
Purthi	118	20 hrs 43 mins	330	3.2	0.8
Phindru	134	27 hrs 29 mins	203	2.2	0.6

Table 22 describes the flood wave characteristics of GLOF scenario 4. After the breach of lake, the flood wave reaches nearest village of Sissu located at a distance of 11 km with peak discharge of 6,658 cumecs (maximum depth:18.6 m; maximum velocity:7.6 m/s) and as the flood wave traverses further downstream gets attenuated.

Table 21: Flood Wave Characteristics of GLOF Scenario 4

Location	Distance from Lake (km)	Time to peak	Peak Discharge (m ³ /s)	Max Depth (m)	Max Velocity (m/s)
Sissu	11	1 hr 24 mins	6,658	18.6	7.6
Tandi	31	3 hrs 18 mins	2,788	8.6	2.8
Tibok	47.9	4 hrs 56 mins	2,095	7.4	4.7
Thirot	56	5 hrs 33 mins	1,968	10.3	5.1
Udaipur	71	7 hrs 24 mins	1,377	5.5	2.4
D.P.F. Tehtlo	94.1	12 hrs 33 mins	616	5.2	2.2
Purthi	118	20 hrs 50 mins	326	3.1	0.8
Phindru	134	27 hrs 33 mins	201	2.2	0.6

Figure 52 shows the map of flood inundation extent along with major settlements affected due to the flood for GLOF scenario 3. The inset images show flood depth and flood velocity near Sissu village along with GLOF affected settlements, roads, bridges and other infrastructure.

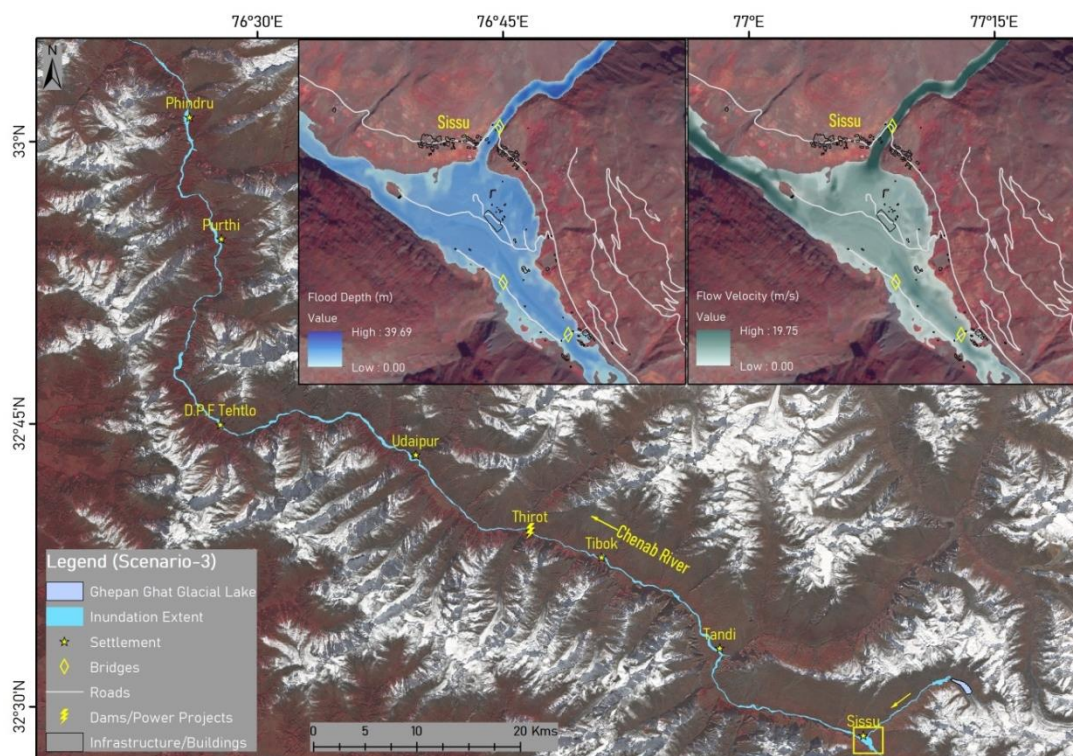


Figure 52: Map of Flood Inundation Extent for GLOF Scenario-3

Figure 53 shows the map of flood inundation extent along with major settlements affected due to the flood for GLOF scenario 4. The inset images show flood depth and flood velocity near Sissu village along with GLOF affected settlements, roads, bridges and other infrastructure.

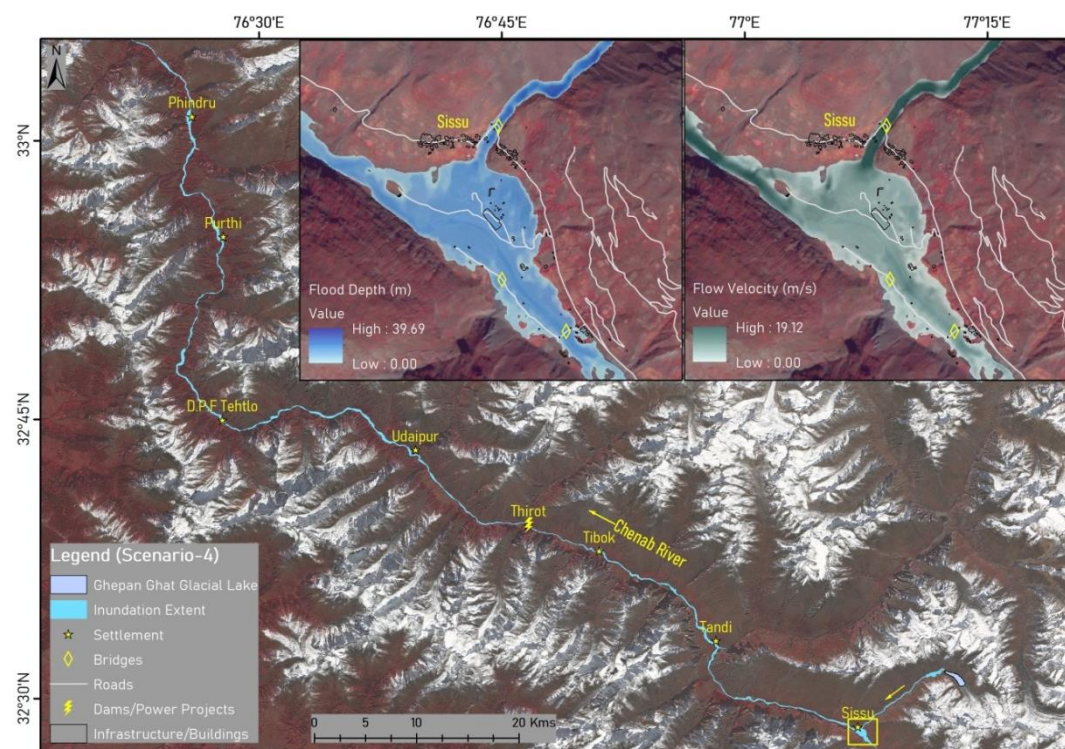


Figure 53: Map showing extent of inundation for Scenario-4

Table 23 provides number of settlements, extent of agriculture land, number of bridges, length of road network and public utilities affected by scenarios 3 and 4. Table 24 provides names of settlements affected by scenarios 3 and 4. All the settlements (30) are partly affected by the GLOF inundation. The two settlements (Shipting and Ruding) affected in scenario 1 & 2 are not affected in scenario 3 & 4.

Table 22: Infrastructure affected in GLOF Scenarios 3 and 4

Scenario	No. of Affected Settlements	Area of Agricultural Land Affected (ha)	No. of Bridges Affected	Length of Roads affected (km)	No. of Public Utilities affected	Inundated Area (ha)
Scenario-3	30	83.0	41	34.6	3	2,134
Scenario-4	30	82.2	41	34.4	3	2,127

Table 23: Names of Settlements affected in GLOF Scenarios 3 and 4

S. No.	Settlement Name	Distance from lake (km)
1	Sissu	11
2	Ghondhla*	21.2
3	Dalang*	22.7
4	Bha-Garang	30.5
5	Gushal	31
6	Tandi	31
7	Lingar*	39.6
8	Rapay*	44.3
9	Tibok*	47.9
10	Nalda	50.4
11	Thirot	56
12	Kishori*	64
13	Shanur*	65.2
14	Triloknath*	66.2
15	D.P.F. Udaipur	66.9

S. No.	Settlement Name	Distance from lake (km)
16	D.P.F. Bardang*	68.6
17	Lobar	70.4
18	Udaipur	71
19	Salpat	73.4
20	Margaraon	75.8
21	R.F. Khurail	78.1
22	R.F. Rhumas*	82.2
23	Kurched*	84.9
24	D.P.F. Dhanwani*	88.8
25	D.P.F. Tehtlo	94.1
26	Purthi*	118
27	Ajog*	119
28	Chhau*	119.5
29	Sach*	130.8
30	Phindru	134

Note: * indicate few buildings, which are affected close to the river channel near the mentioned settlement.

2. GLOF Scenarios 5 & 6 (50% release)

The GLOF scenarios 5 and 6 are simulated for 50% of lake volume release (17.54 MCM) in two failure modes (scenario 5 for overtopping and scenario 6 for piping). Figure 54 shows GLOF hydrograph downstream of the lake for scenario 5 (overtopping failure mode). The flood hydrograph reached its peak of 3,167 cumecs in 1 hour 35 minutes after the initiation of breach in the lake. Figure 55 shows GLOF hydrographs downstream of the lake

at various locations on the river reach for scenario 5. The peak of the flood hydrograph is attenuated from 3,167 cumecs to 78 cumecs over river reach length of 134 km at Phindru.

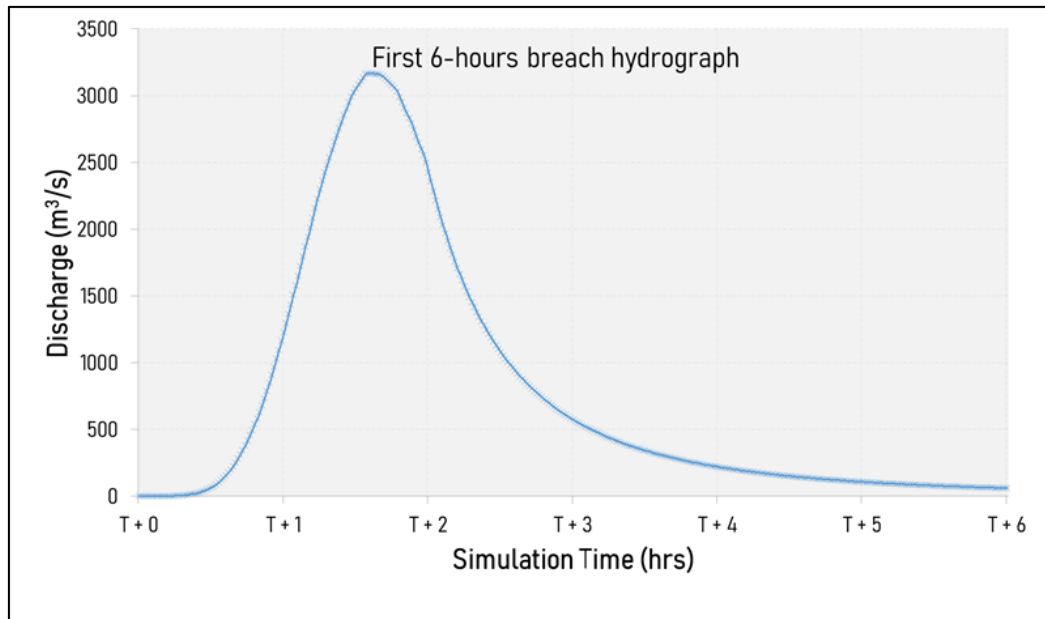


Figure 54: GLOF hydrograph for Scenario-5 (50% volume discharge - Overtopping failure)

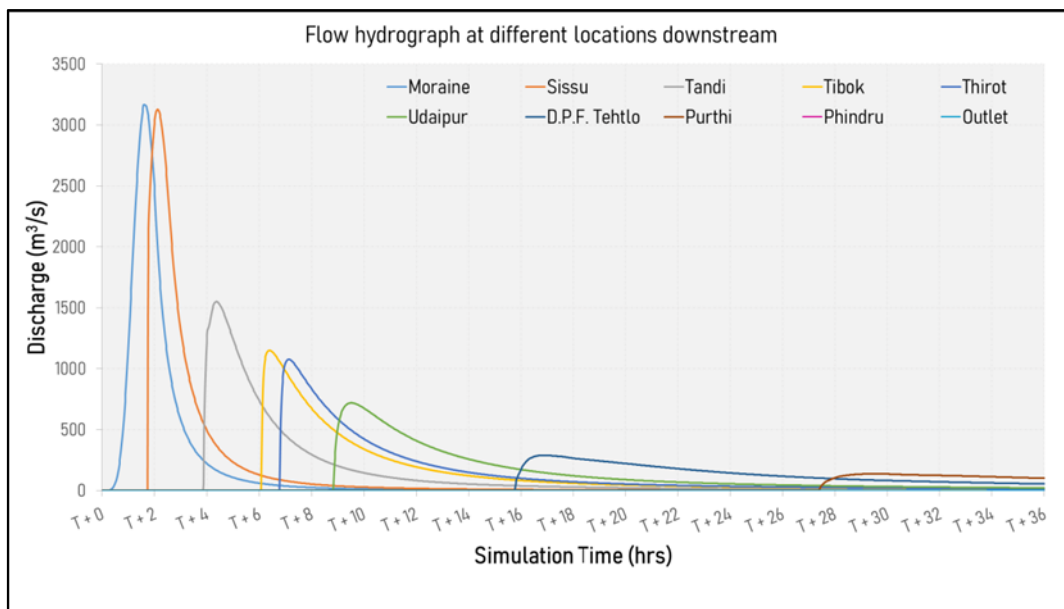


Figure 55: GLOF hydrographs at Different Downstream Locations for scenario-5

Figure 56 shows GLOF hydrograph downstream of the lake for scenario 6 (piping failure mode). The flood hydrograph reached its peak of 3,434 cumecs in 1 hour 22 minutes after the initiation of breach in the lake. Figure 57 shows GLOF hydrographs downstream of the

lake at various locations on the river reach for scenario 6. The peak of the flood hydrograph is attenuated from 3,434 cumecs to 77 cumecs over river reach length of 134 km at Phindru.

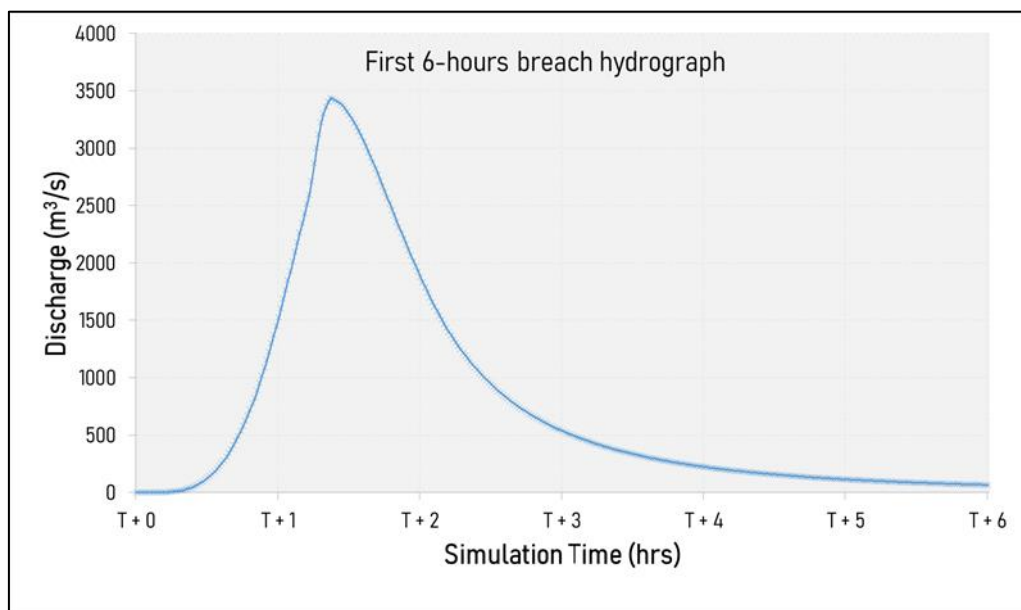


Figure 56: GLOF hydrograph for Scenario-6 (100% volume discharge - Piping failure)

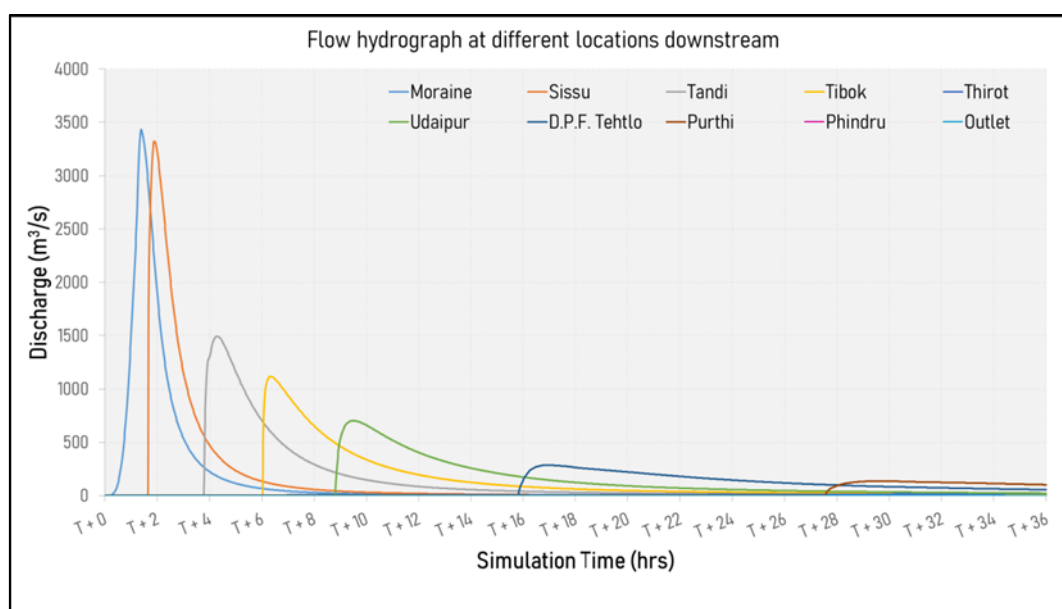


Figure 57: GLOF hydrographs at Different Downstream Locations for scenario-6

Table 24 describes the flood wave characteristics of GLOF scenario 5. After the breach of lake, the flood wave reaches nearest village of Sissu located at a distance of 11 km with

peak discharge of 3,127 cumecs (maximum depth:13.7 m; maximum velocity:5.6 m/s) and as the flood wave traverses further downstream gets attenuated.

Table 24: Flood Wave Characteristics of GLOF Scenario 5

Location	Distance from Lake (km)	Time to peak	Peak Discharge (m ³ /s)	Max Depth (m)	Max Velocity (m/s)
Sissu	11	2 hrs 6 mins	3,127	13.7	5.6
Tandi	31	4 hrs 22 mins	1,550	6.5	2.1
Tibok	47.9	6 hrs 23 mins	1,150	5.5	4.1
Thirot	56	7 hrs 7 mins	1,077	7.5	4.1
Udaipur	71	9 hrs 31 mins	718	4.3	2
D.P.F. Tehtlo	94.1	16 hrs 51 mins	289	3.6	1.5
Purthi	118	29 hrs 33 mins	137	2	0.5
Phindru	134	40 hrs	78	1.5	0.4

Table 25 describes the flood wave characteristics of GLOF scenario 6. After the breach of lake, the flood wave reaches nearest village of Sissu located at a distance of 11 km with peak discharge of 3,324 cumecs (maximum depth:14.0 m; maximum velocity:5.8 m/s) and as the flood wave traverses further downstream gets attenuated.

Table 25: Flood Wave Characteristics of GLOF Scenario 6

Location	Distance from Lake (km)	Time to peak	Peak Discharge (m ³ /s)	Max Depth (m)	Max Velocity (m/s)
Sissu	11	1 hr 53 mins	3,324	14	5.8
Tandi	31	4 hrs 17 mins	1,494	6.4	2.1
Tibok	47.9	6 hrs 20 mins	1,116	5.4	4
Thirot	56	7 hrs 5 mins	1,060	7.4	4.1
Udaipur	71	9 hrs 30 mins	702	4.3	1.9
D.P.F. Tehtlo	94.1	16 hrs 54 mins	284	3.6	1.5
Purthi	118	29 hrs 42 mins	136	2	0.5
Phindru	134	40 hrs 15 mins	77	1.5	0.4

Figure 58 shows the map of flood inundation extent along with major settlements affected due to the flood for GLOF scenario 5. The inset images show flood depth and flood velocity near Sissu village along with GLOF affected settlements, roads, bridges and other infrastructure.

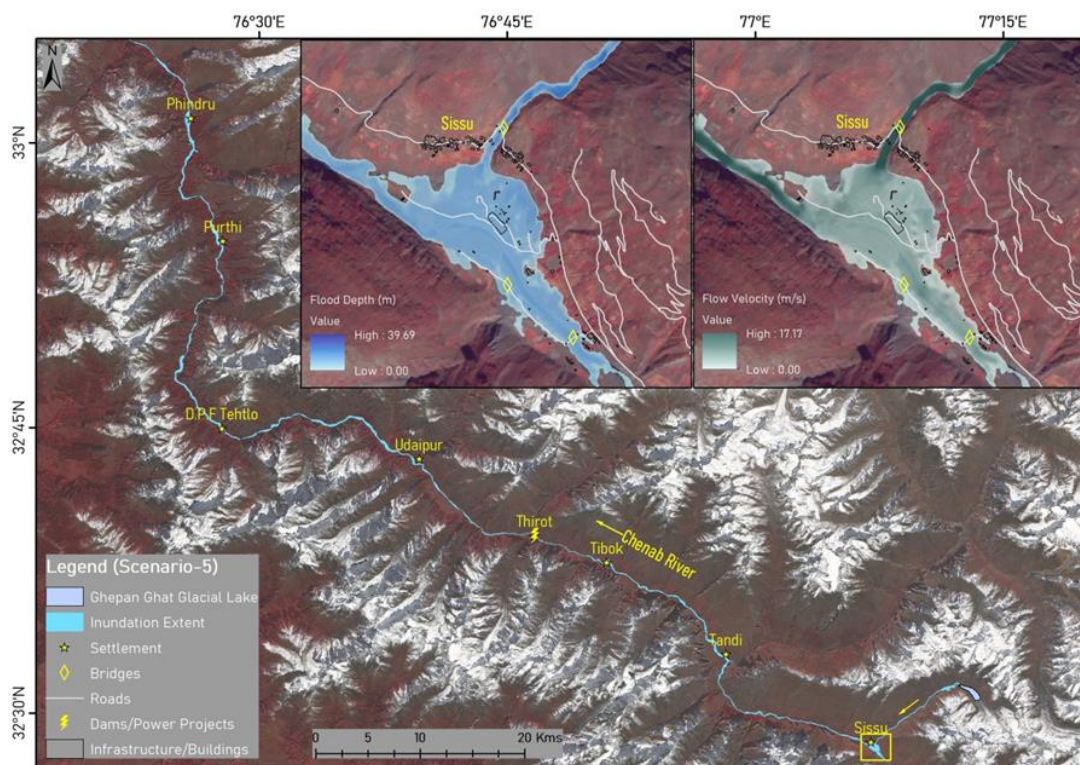


Figure 58: Map of Flood Inundation Extent for GLOF Scenario-5

Figure 59 shows the map of flood inundation extent along with major settlements affected due to the flood for GLOF scenario 6. The inset images show flood depth and flood velocity near Sissu village along with GLOF affected settlements, roads, bridges and other infrastructure.

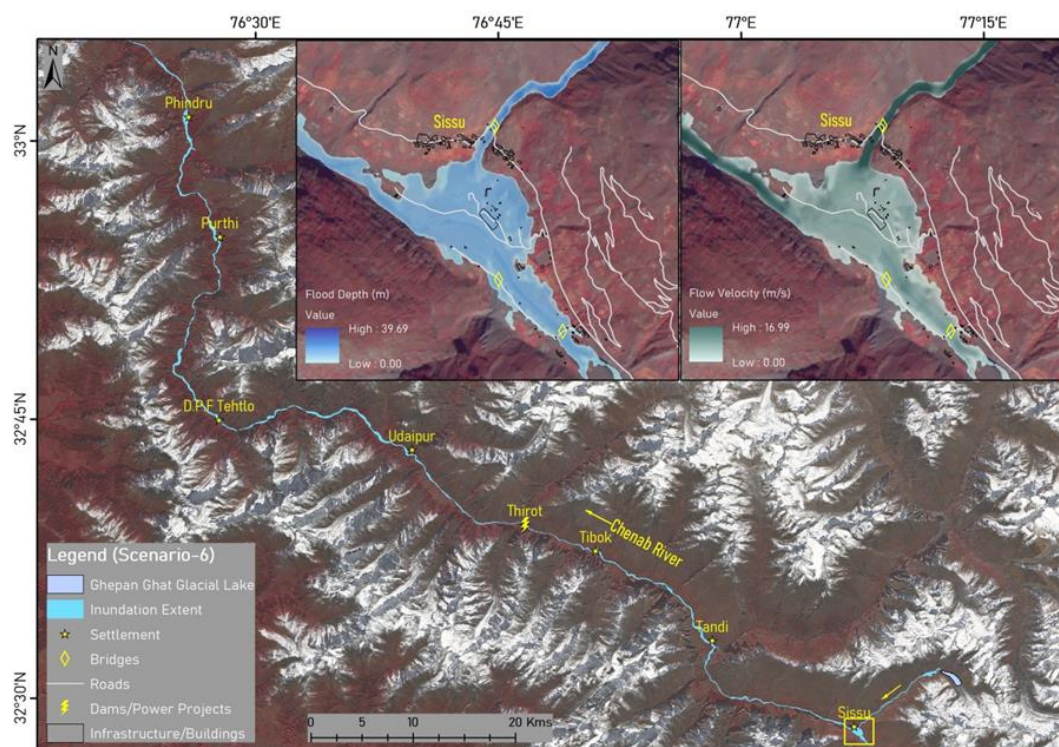


Figure 59: Map showing extent of inundation for Scenario-6

Table 26 provides number of settlements, extent of agriculture land, number of bridges, length of road network and public utilities affected by scenarios 5 and 6. Table 27 provides names of settlements affected by scenarios 5 and 6. All the settlements (29) are partly affected by the GLOF inundation. The settlement (D.P.F. Bardang) affected in scenario 3 & 4 is not affected in scenario 5 & 6.

Table 26: Infrastructure affected in GLOF Scenarios 5 and 6

Scenario	No. of Affected Settlements	Area of Agricultural Land Affected (ha)	No. of Bridges Affected	Length of Roads affected (km)	No. of Public Utilities affected	Inundated Area (ha)
Scenario-5	29	69.8	39	31.1	2	1,972.0
Scenario-6	29	69.3	39	31.0	2	1,968.5

Table 27: Names of Settlements affected in GLOF Scenarios 5 and 6

S. No.	Settlement Name	Distance from lake (km)
1	Sissu	11
2	Ghondhla*	21.2
3	Dalang*	22.7
4	Bha-Garang	30.5
5	Gushal	31
6	Tandi	31
7	Lingar*	39.6
8	Rapay*	44.3
9	Tibok*	47.9
10	Nalda	50.4
11	Thirot	56
12	Kishori*	64
13	Shanur*	65.2
14	Triloknath*	66.2
15	D.P.F. Udaipur	66.9
16	Lobar	70.4

S. No.	Settlement Name	Distance from lake (km)
17	Udaipur	71
18	Salpat	73.4
19	Margaraon	75.8
20	R.F. Khurail	78.1
21	R.F. Rhumas*	82.2
22	Kurched*	84.9
23	D.P.F. Dhanwani*	88.8
24	D.P.F. Tehtlo	94.1
25	Purthi*	118
26	Ajog*	119
27	Chhau*	119.5
28	Sach*	130.8
29	Phindru	134

Note: * indicate few buildings, which are affected close to the river channel near the mentioned settlement.

Annexure 3: Results of GLOF Risk Assessment for Scenarios of 3 to 6

The results of Ghepan ghat glacial lake GLOF risk assessment for the scenarios 3 to 6 are described here.

1. GLOF Risk for Scenario 3 (75% release-Overtopping failure mode)

The GLOF risk map for scenario 3 is shown in figure 60. The area under high, moderate and low risk zones of GLOF scenario 3 are 300 ha, 919 ha and 915 ha respectively. The area under the high risk zone will be most affected area with no time (less than 2 hours) for warning in case of GLOF event occurrence. Table 28 gives details of flood inundation area, number of settlements, agricultural land, number of bridges and length of road network affected exclusively under various categories of GLOF risk zones. As already mentioned in the previous section all the settlements are partly affected. The total number of settlements, agricultural land, bridges, and road length affected in scenario 1 are 30, 83 ha, 41 and 34.6 km respectively. Figures 61 and 62 show close view of affected infrastructure (settlements, bridges, road network, etc) and agriculture land by GLOF inundation extent near Sissu respectively.

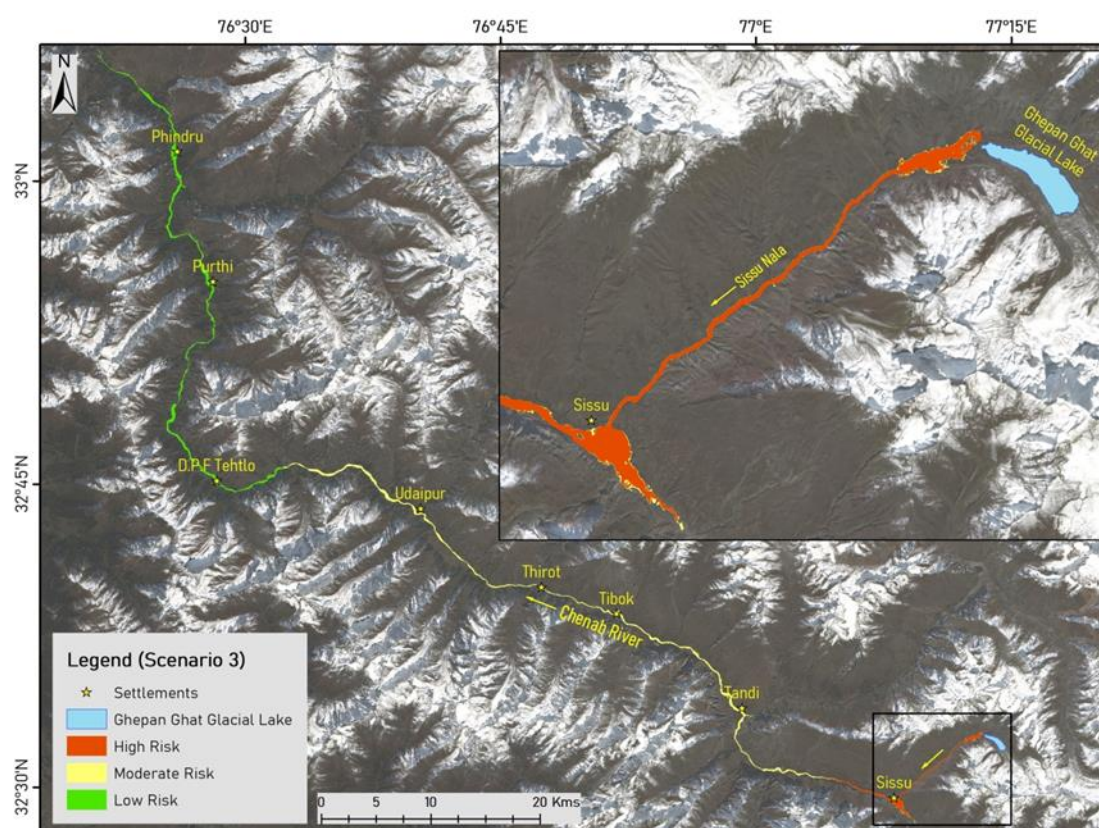


Figure 60: GLOF Risk Map for the Study Area (Scenario-3)

Table 28: Zone wise details of Infrastructure affected in GLOF Scenario 3

Scenario	Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Road (km)
3	High	300	1	9.7	3	3.4
	Moderate	919	22	41.3	25	15.2
	Low	915	7	32	13	16.0
Total		2,134	30	83	41	34.6

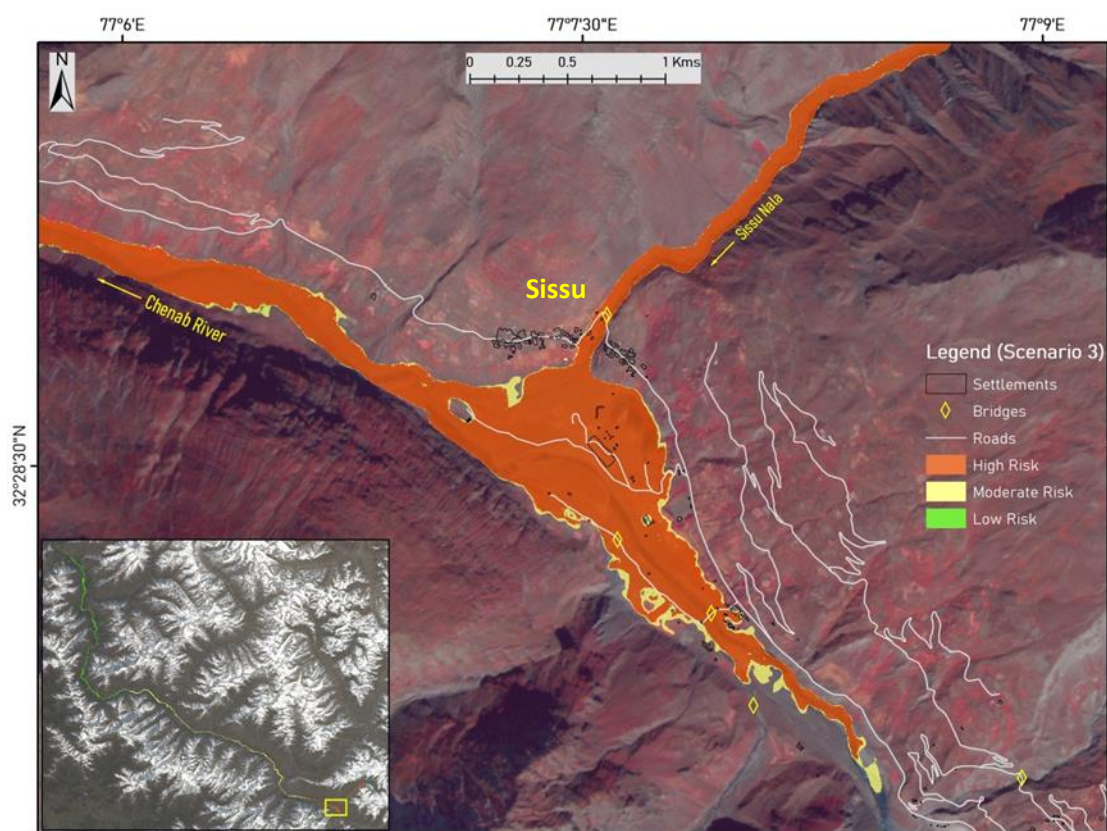


Figure 61: GLOF Risk Map showing Affected Infrastructure near Sissu (Scenario-3)

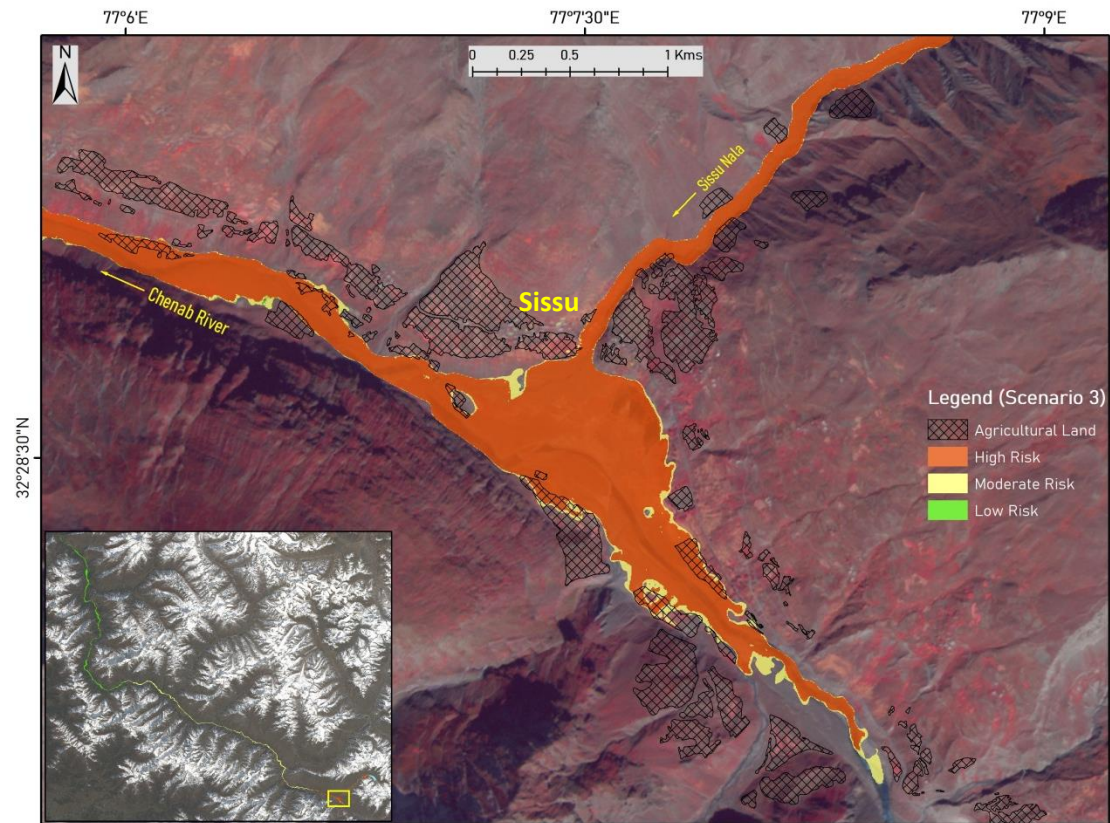


Figure 62: GLOF Risk Map showing Affected Agricultural Land near Sissu (Scenario-3)

2. GLOF Risk for Scenario 4 (75% release- Piping failure mode)

The GLOF risk map for scenario 4 is shown in figure 63. The area under high, moderate and low risk zones of GLOF scenario 3 are 305 ha, 906 ha and 917 ha respectively. The area under the high risk zone will be most affected area with no time (less than 2 hours) for warning in case of GLOF event occurrence. Table 29 gives details of flood inundation area, number of settlements, agricultural land, number of bridges and length of road network affected exclusively under various categories of GLOF risk zones. As already mentioned in the previous section all the settlements are partly affected. The total number of settlements, agricultural land, bridges, and road length affected in scenario 1 are 32, 94.3 ha, 41 and 37.5 km respectively. Figures 35 and 36 show close view of affected infrastructure (settlements, bridges, road network, etc) and agriculture land by GLOF inundation extent near Sissu respectively.

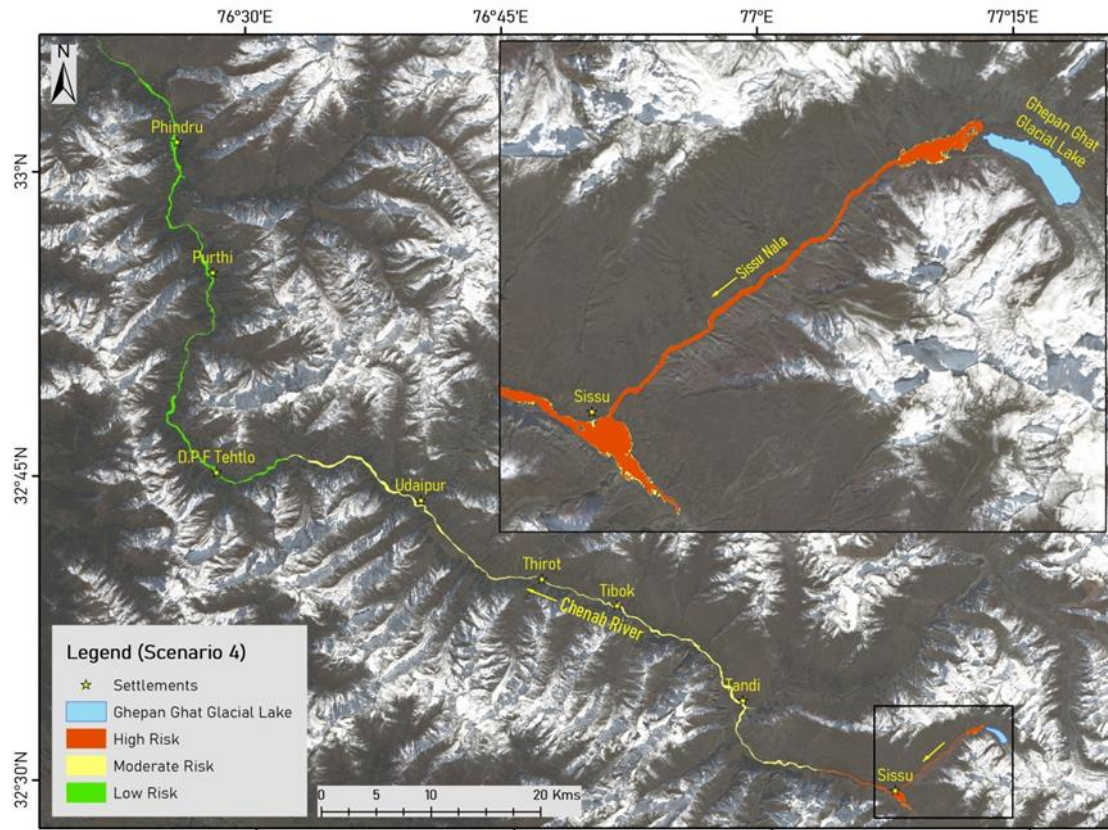


Figure 63: GLOF Risk Map for the Study Area (Scenario-4)

Table 29: Zone wise details of Infrastructure affected in GLOF Scenario 4

Scenario	Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Road (km)
4	High	305	1	9.9	3	3.4
	Moderate	906	22	40.3	25	15.1
	Low	917	7	32	13	15.9
Total		2,128	30	82.2	41	34.4

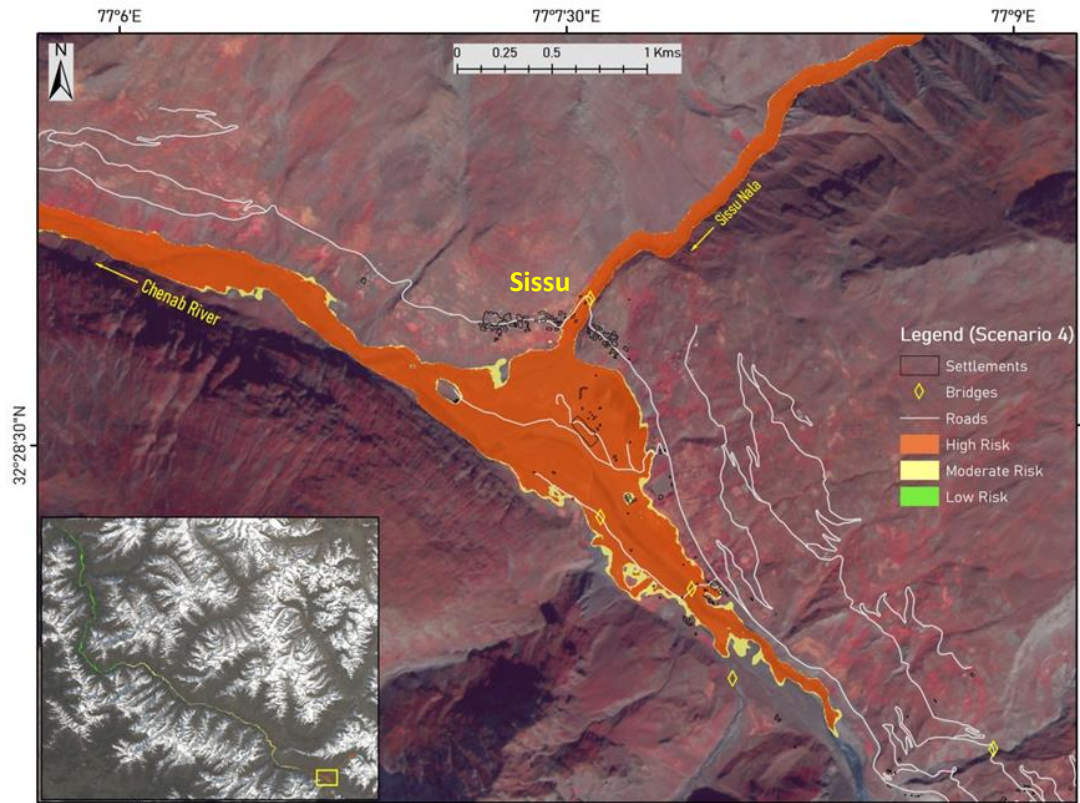


Figure 64: GLOF Risk Map showing Affected Infrastructure near Sissu (Scenario-4)

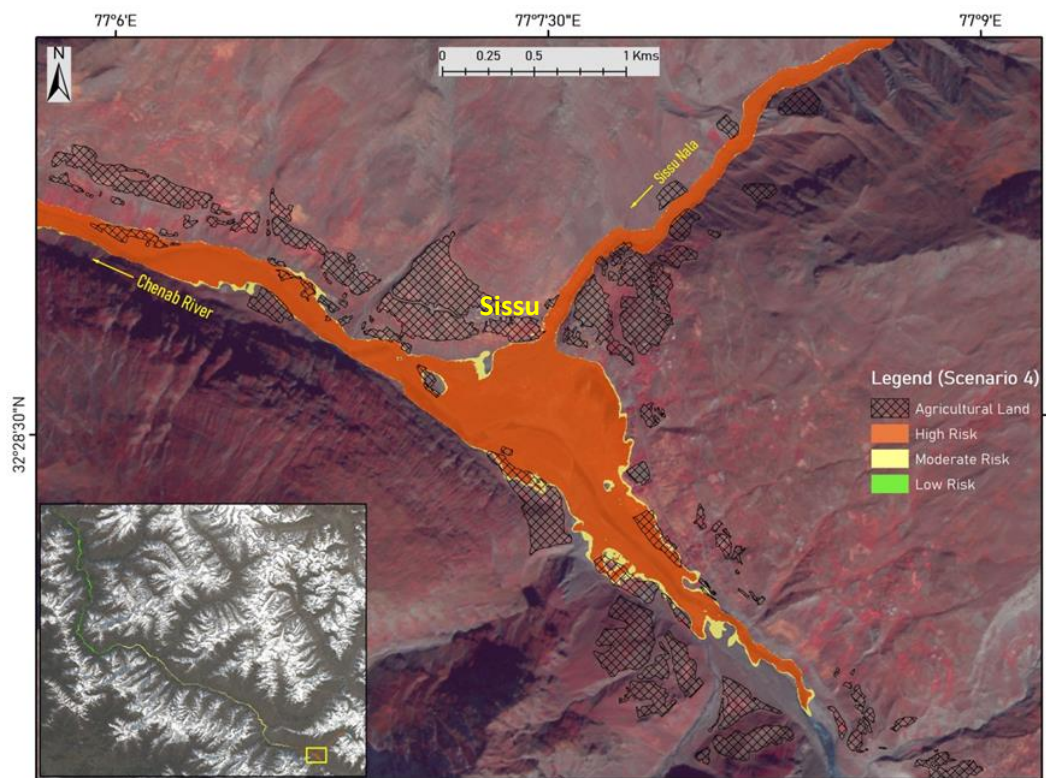


Figure 65: GLOF Risk Map showing Affected Agricultural Land near Sissu (Scenario-4)

3. GLOF Risk for Scenario 5 (50% release- Overtopping failure mode)

The GLOF risk map for scenario 5 is shown in figure 66. The area under high, moderate and low risk zones of GLOF scenario 3 are 167 ha, 736 ha and 1,069 ha respectively. The area under the high risk zone will be most affected area with no time (less than 2 hours) for warning in case of GLOF event occurrence. Table 30 gives details of flood inundation area, number of settlements, agricultural land, number of bridges and length of road network affected exclusively under various categories of GLOF risk zones. As already mentioned in the previous section all the settlements are partly affected. The total number of settlements, agricultural land, bridges, and road length affected in scenario 1 are 29, 69.8 ha, 39 and 31.1 km respectively. Figures 67 and 68 show close view of affected infrastructure (settlements, bridges, road network, etc) and agriculture land by GLOF inundation extent near Sissu respectively.

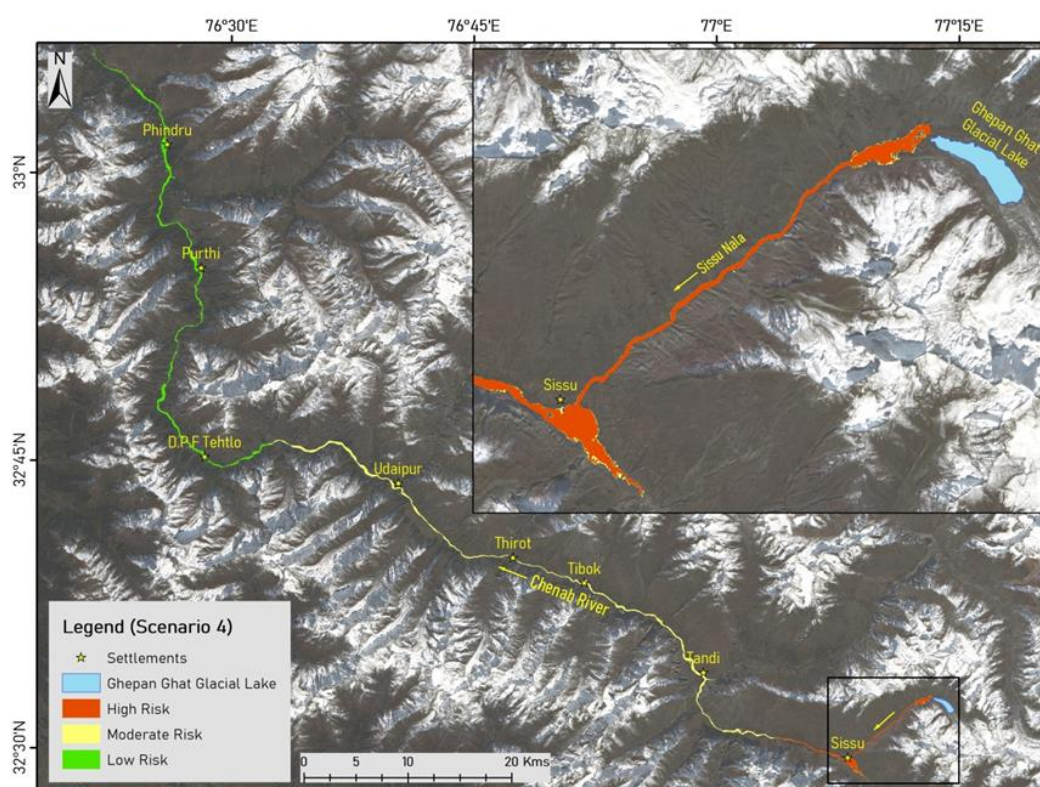


Figure 66: GLOF Risk Map for the Study Area (Scenario-5)

Table 30: Zone wise details of Infrastructure affected in GLOF Scenario 5

Scenario	Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Road (km)
5	High	167	1	1.0	2	2.2
	Moderate	736	17	31.7	22	8.2
	Low	1,069	11	37.1	15	20.7
Total		1,972	29	69.8	39	31.1

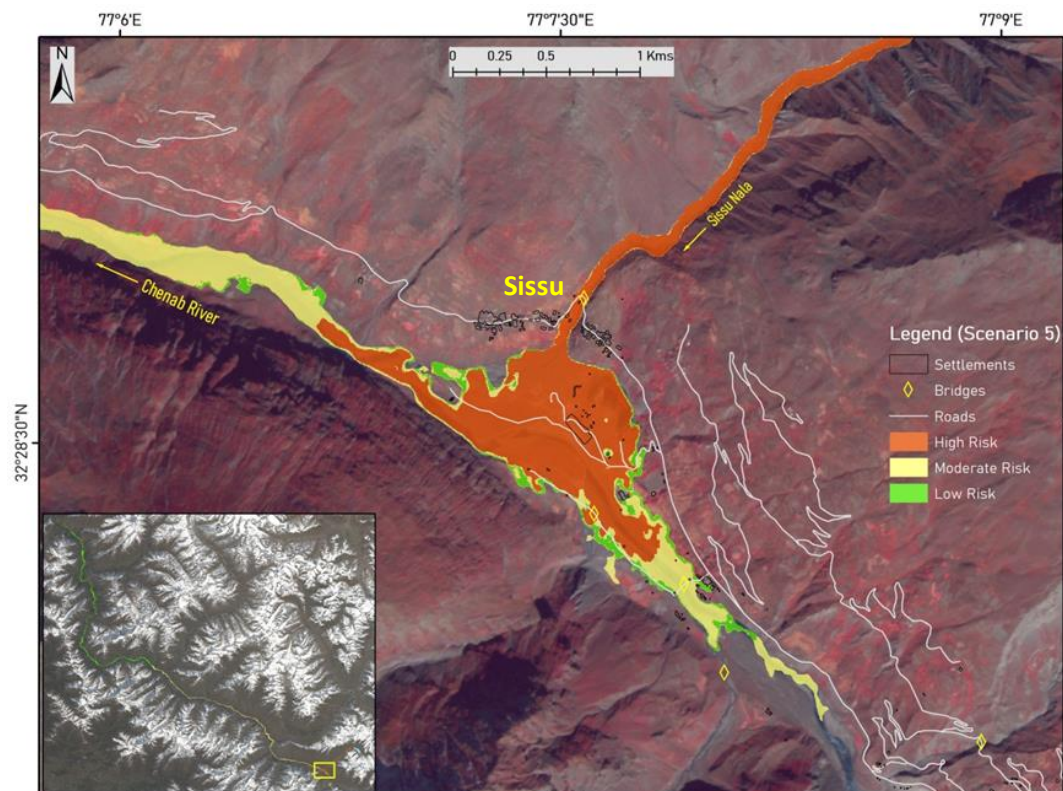


Figure 67: GLOF Risk Map showing Affected Infrastructure near Sissu (Scenario-5)

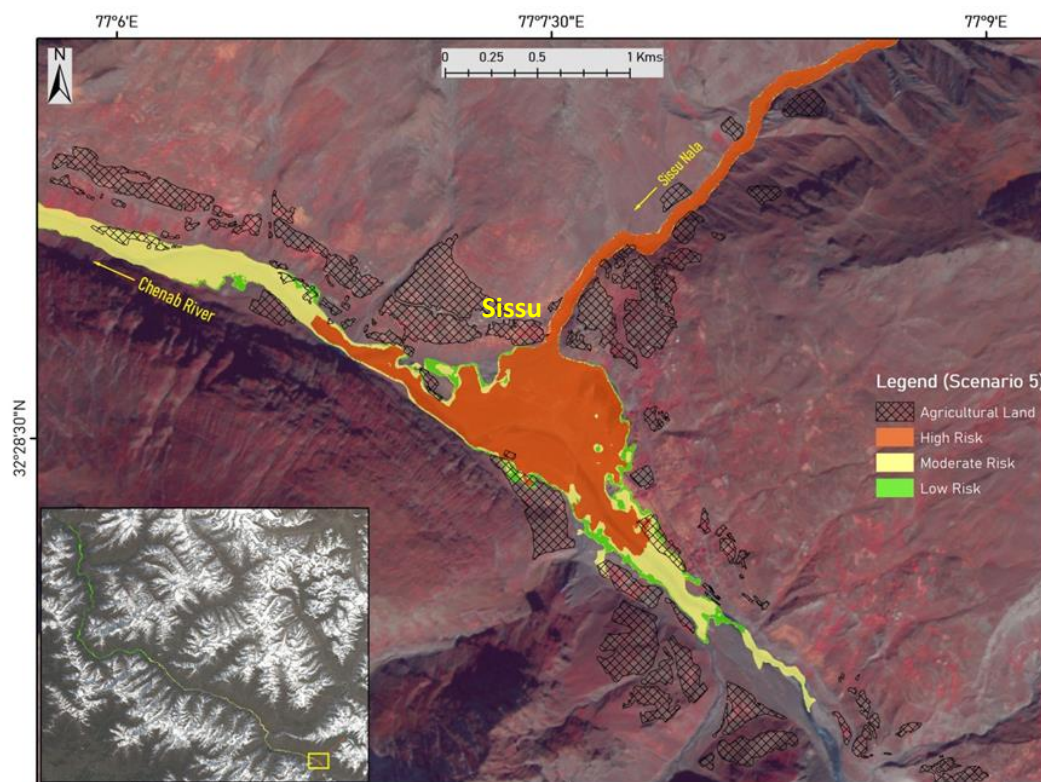


Figure 68: GLOF Risk Map showing Affected Agricultural Land near Sissu (Scenario-5)

4. GLOF Risk for Scenario 6 (50% release- Piping failure mode)

The GLOF risk map for scenario 6 is shown in figure 69. The area under high, moderate and low risk zones of GLOF scenario 3 are 183 ha, 718 ha and 1,067 ha respectively. The area under the high risk zone will be most affected area with no time (less than 2 hours) for warning in case of GLOF event occurrence. Table 31 gives details of flood inundation area, number of settlements, agricultural land, number of bridges and length of road network affected exclusively under various categories of GLOF risk zones. As already mentioned in the previous section all the settlements are partly affected. The total number of settlements, agricultural land, bridges, and road length affected in scenario 1 are 29, 69.3 ha, 39 and 31.0 km respectively. Figures 70 and 71 show close view of affected infrastructure (settlements, bridges, road network, etc) and agriculture land by GLOF inundation extent near Sissu respectively.

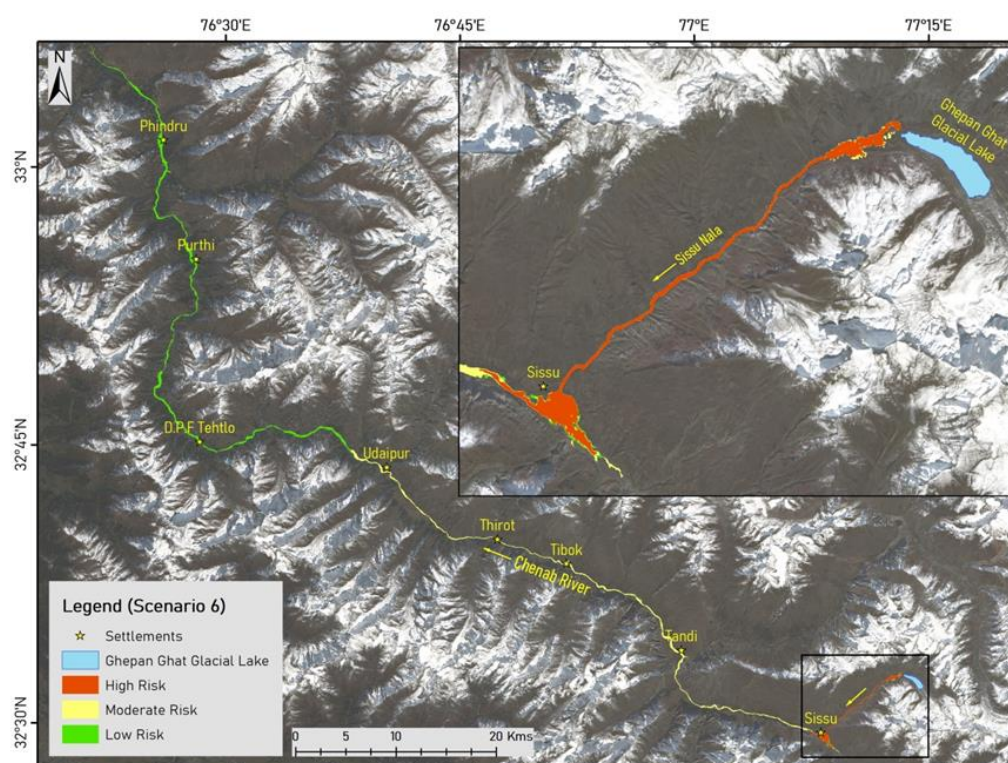


Figure 69: GLOF Risk Map for the Study Area (Scenario-6)

Table 31: Zone wise details of Infrastructure affected in GLOF Scenario 6

Scenario	Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Road (km)
6	High	183	1	2.3	2	2.4
	Moderate	718	17	30.2	22	7.9
	Low	1,067	11	36.8	15	20.7
Total		1,968	29	69.3	39	31.0

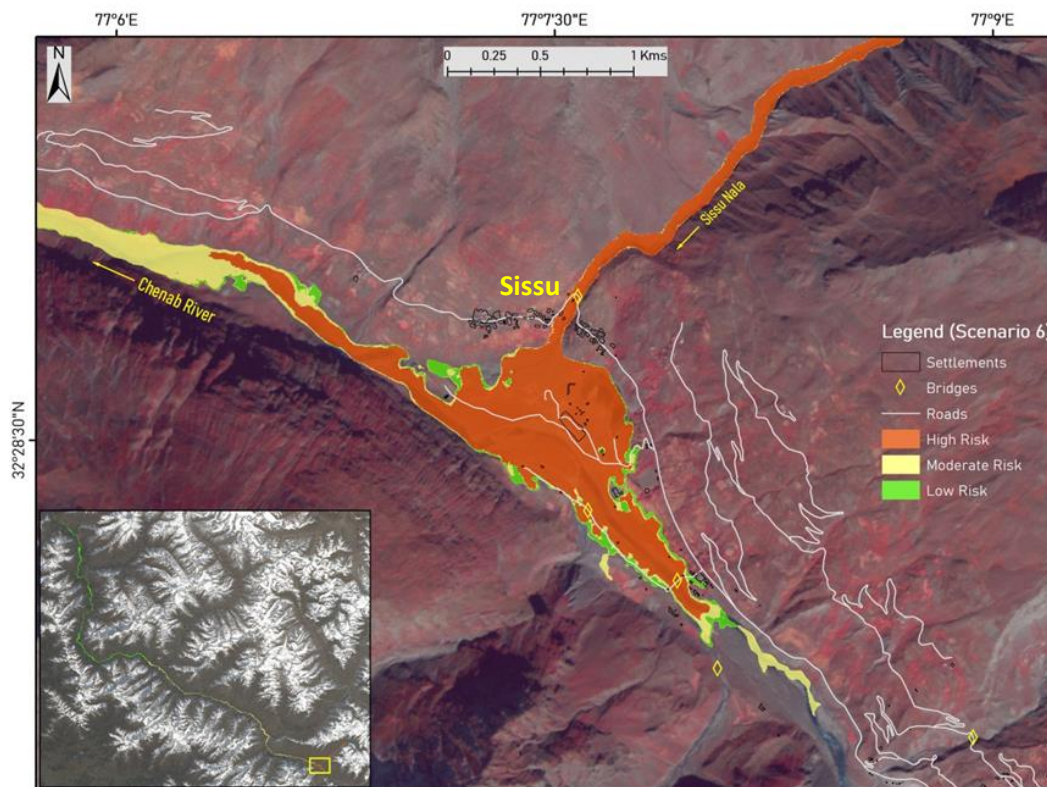


Figure 70: GLOF Risk Map showing Affected Infrastructure near Sissu (Scenario-6)

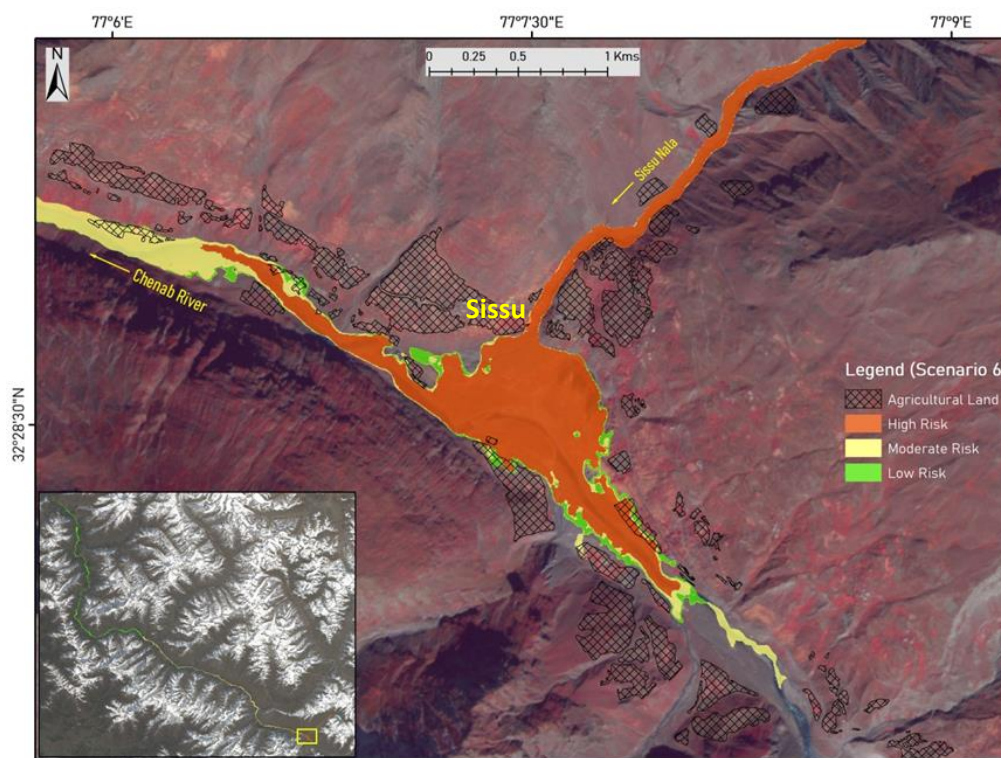
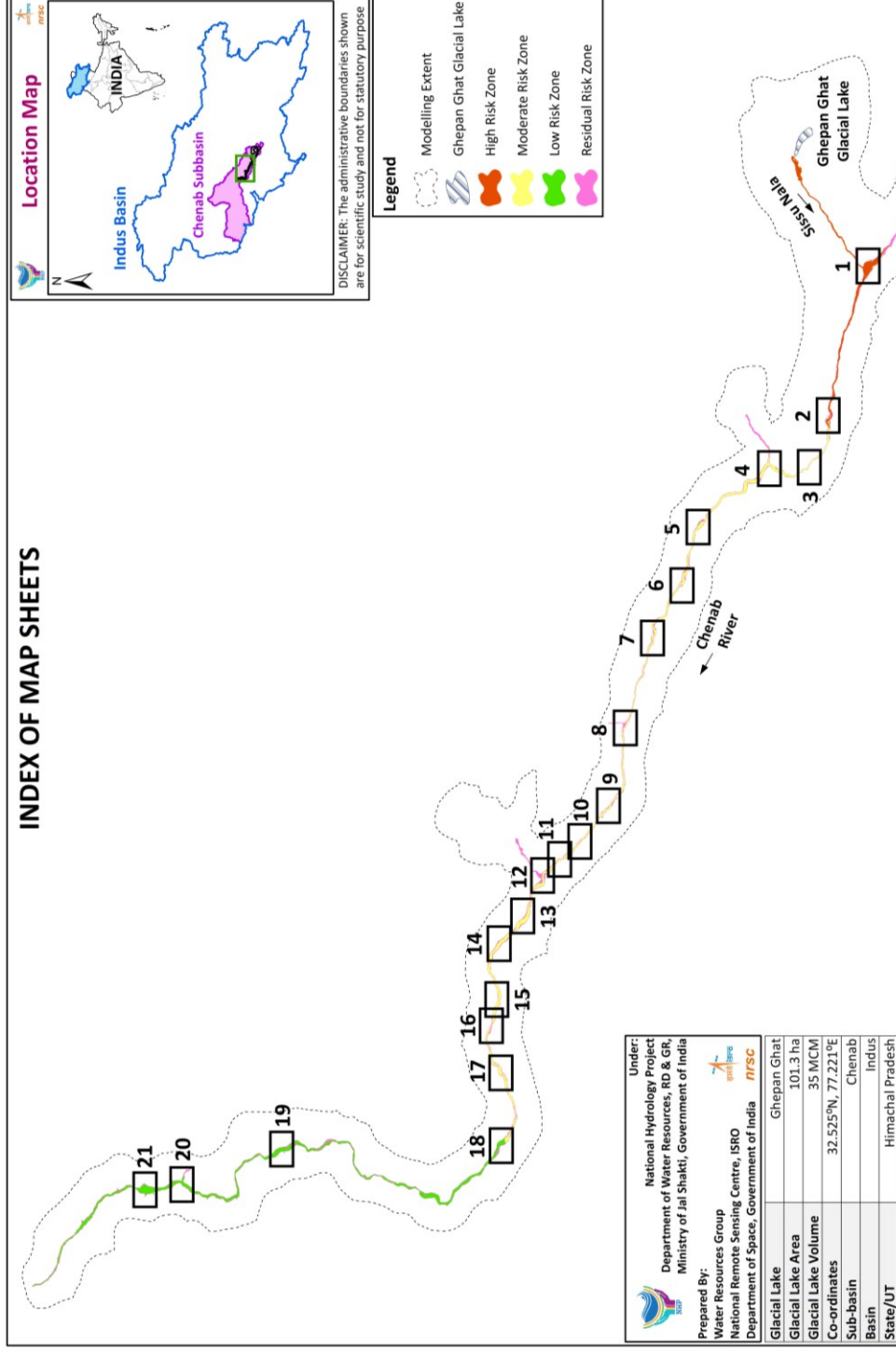


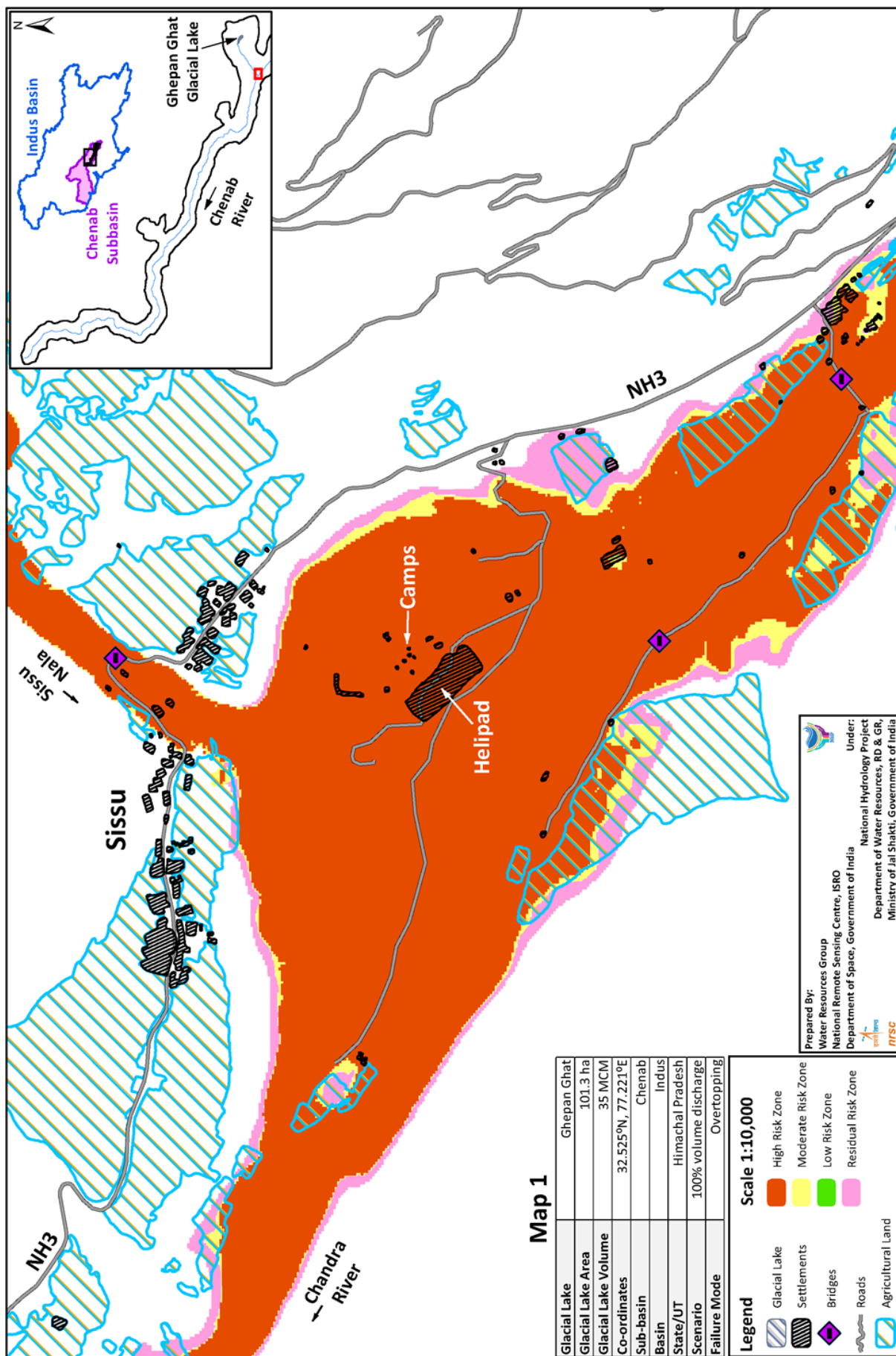
Figure 71: GLOF Risk Map showing Affected Agricultural Land near Sissu (Scenario-6)

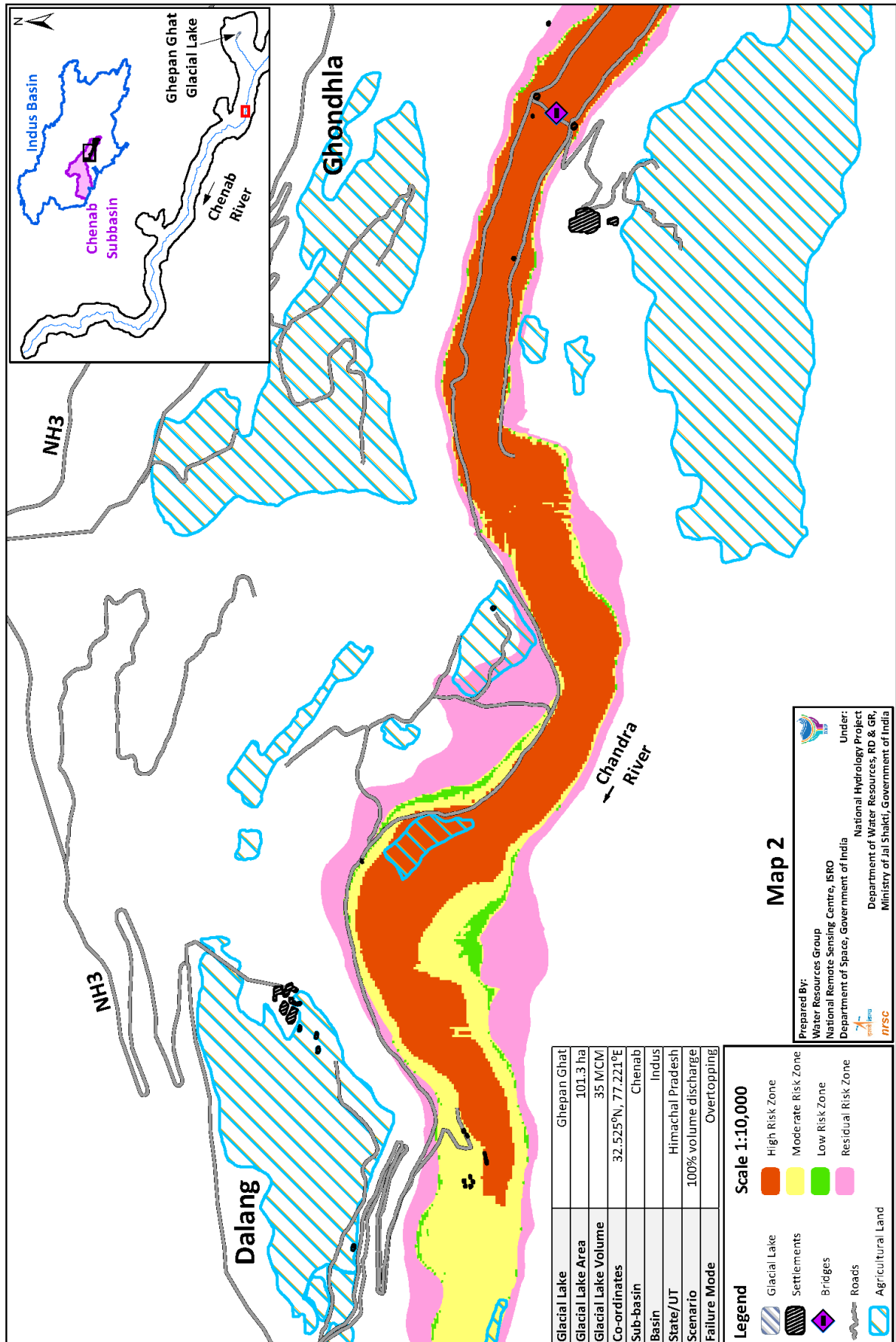


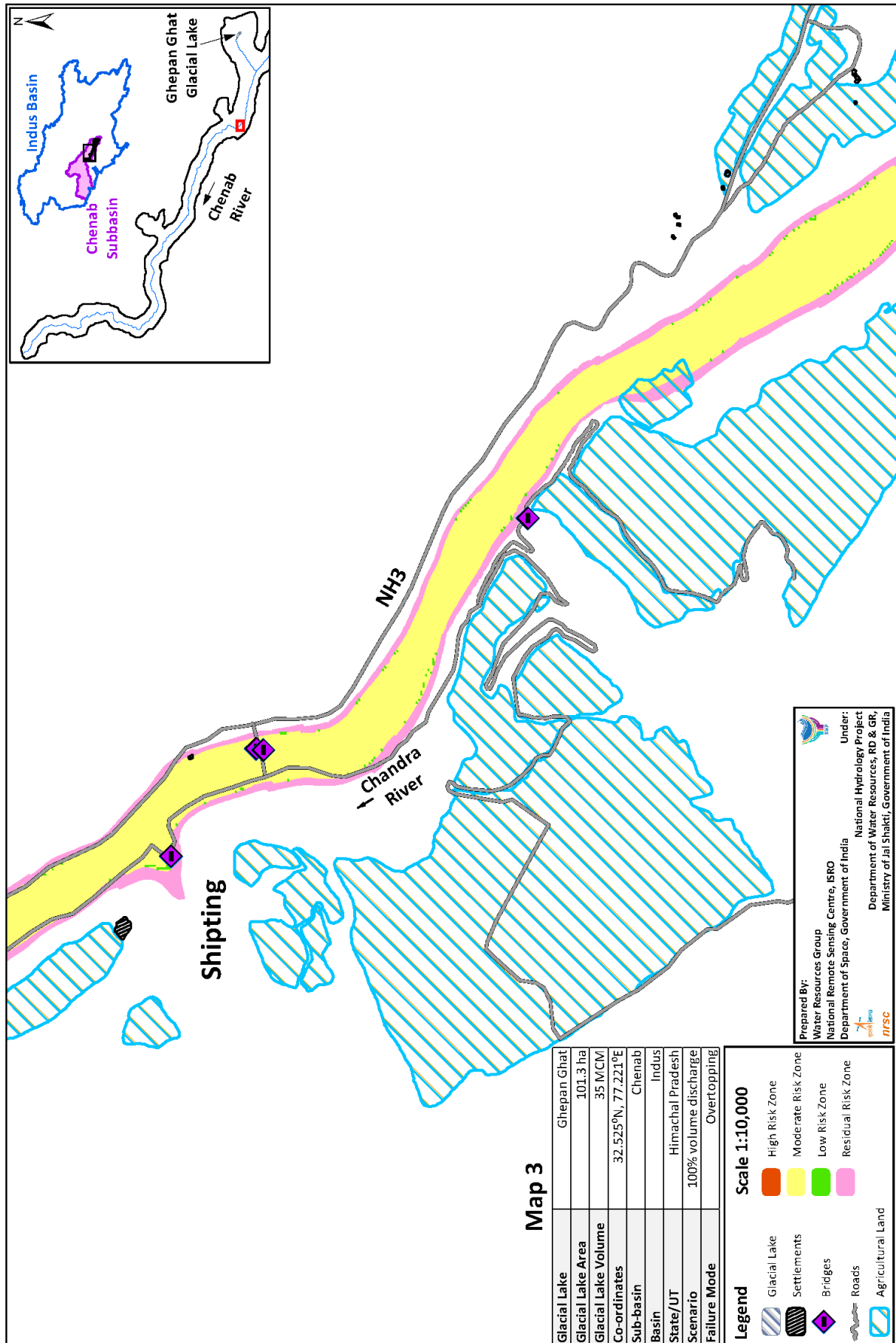
Annexure 4: GLOF Risk maps for Scenarios of 1 and 7

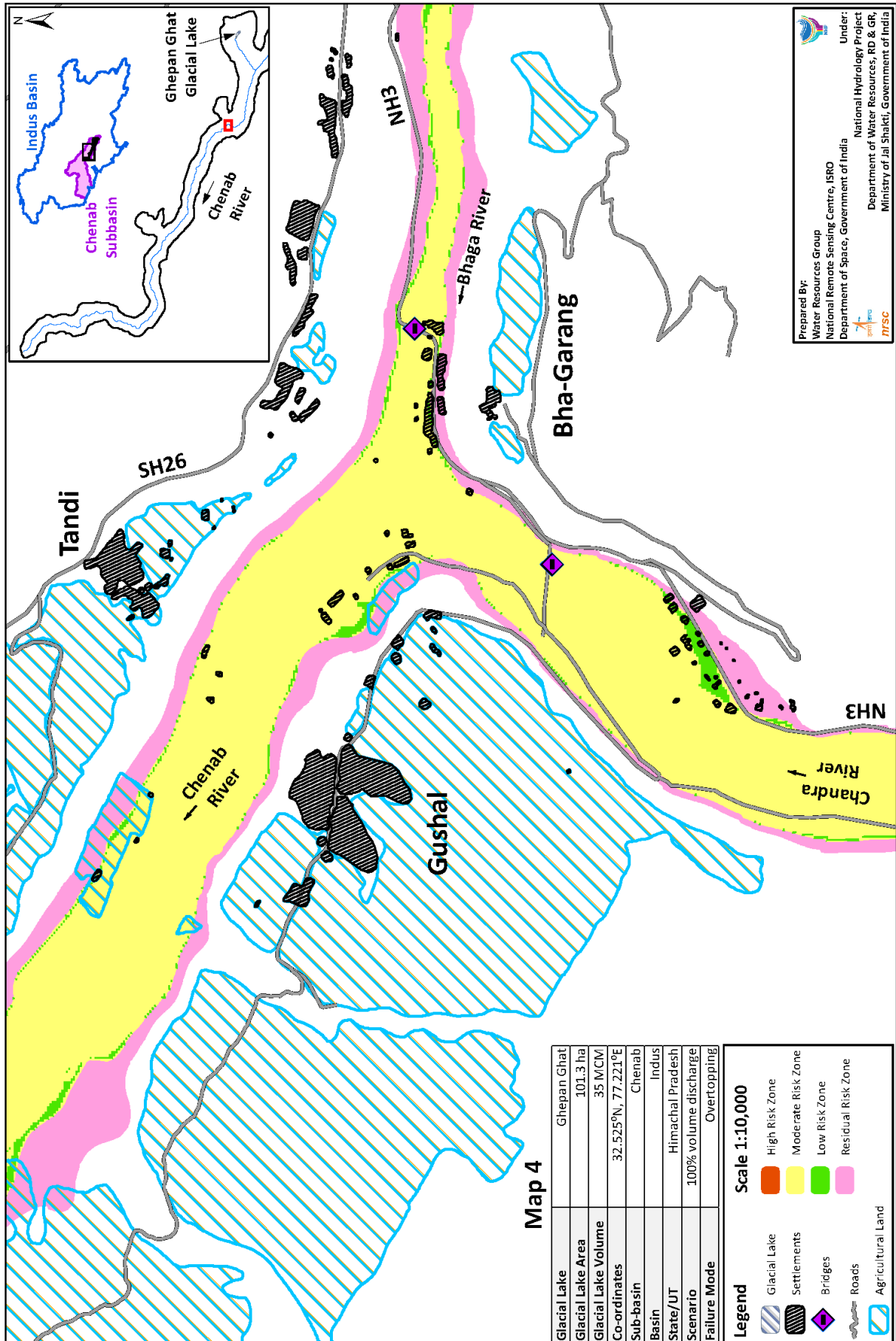
The Ghepang Ghat glacial lake GLOF risk zone maps of close view at important locations (21) along Chenab river reach for the scenarios 1 and 7 are given here.

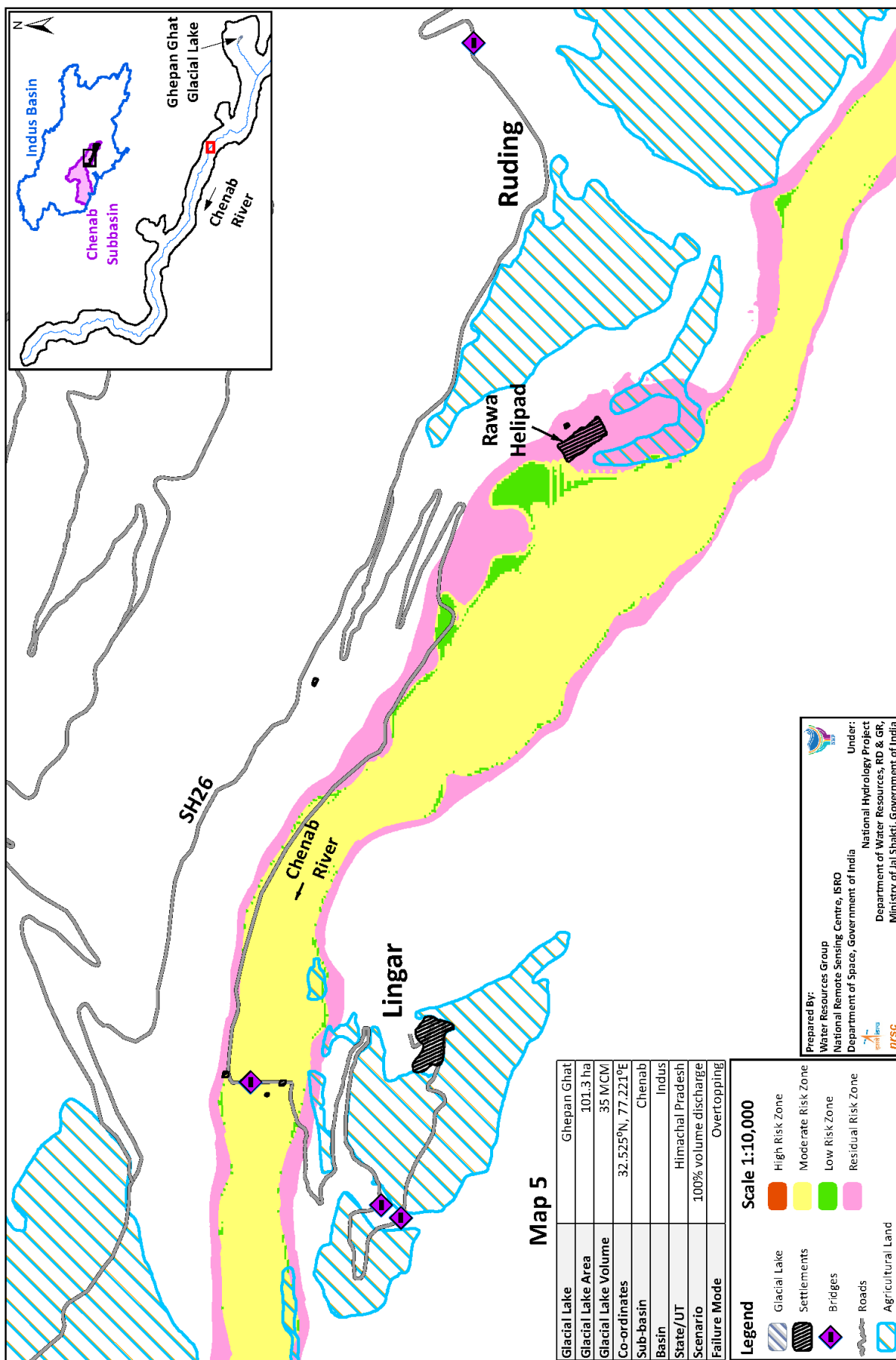


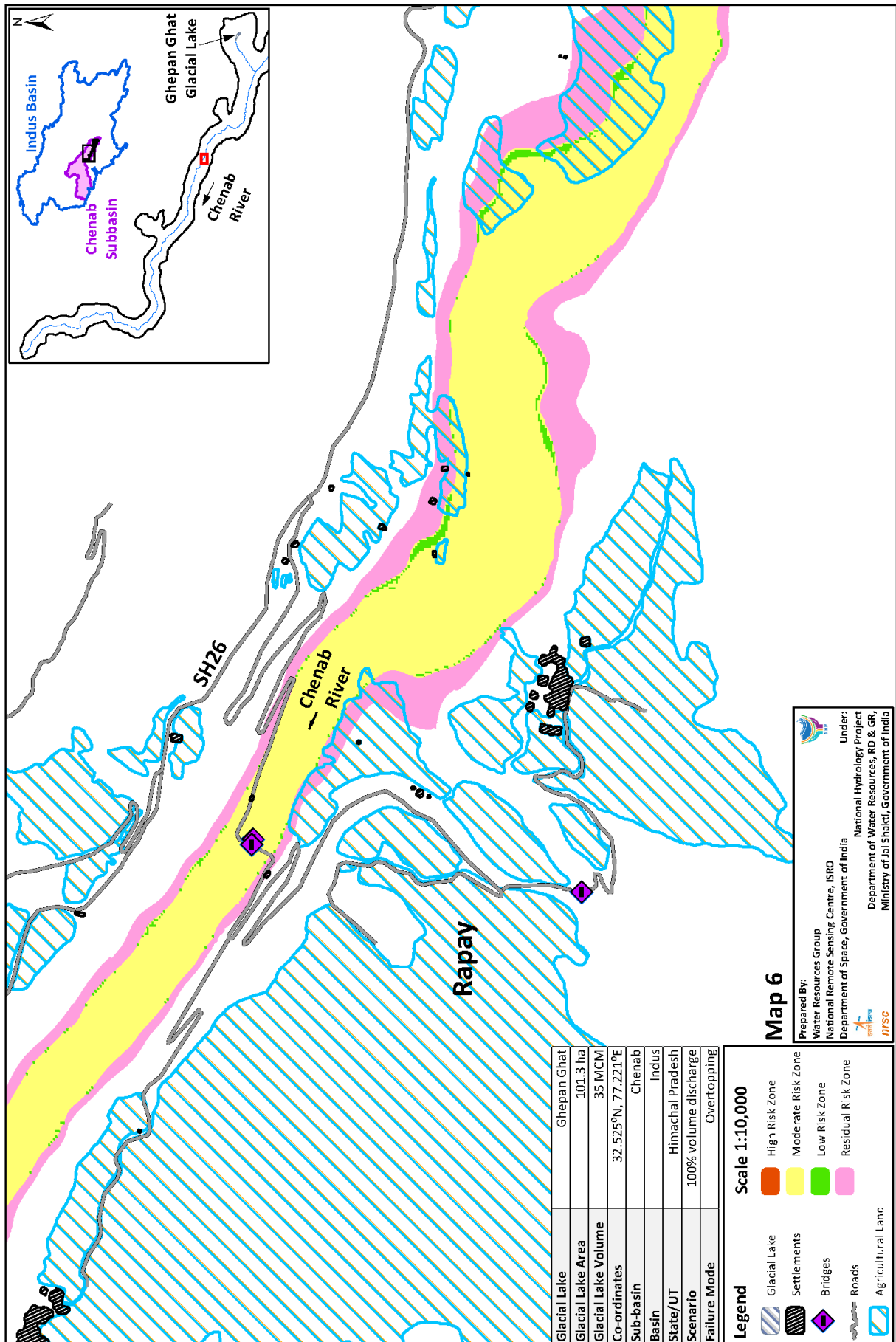


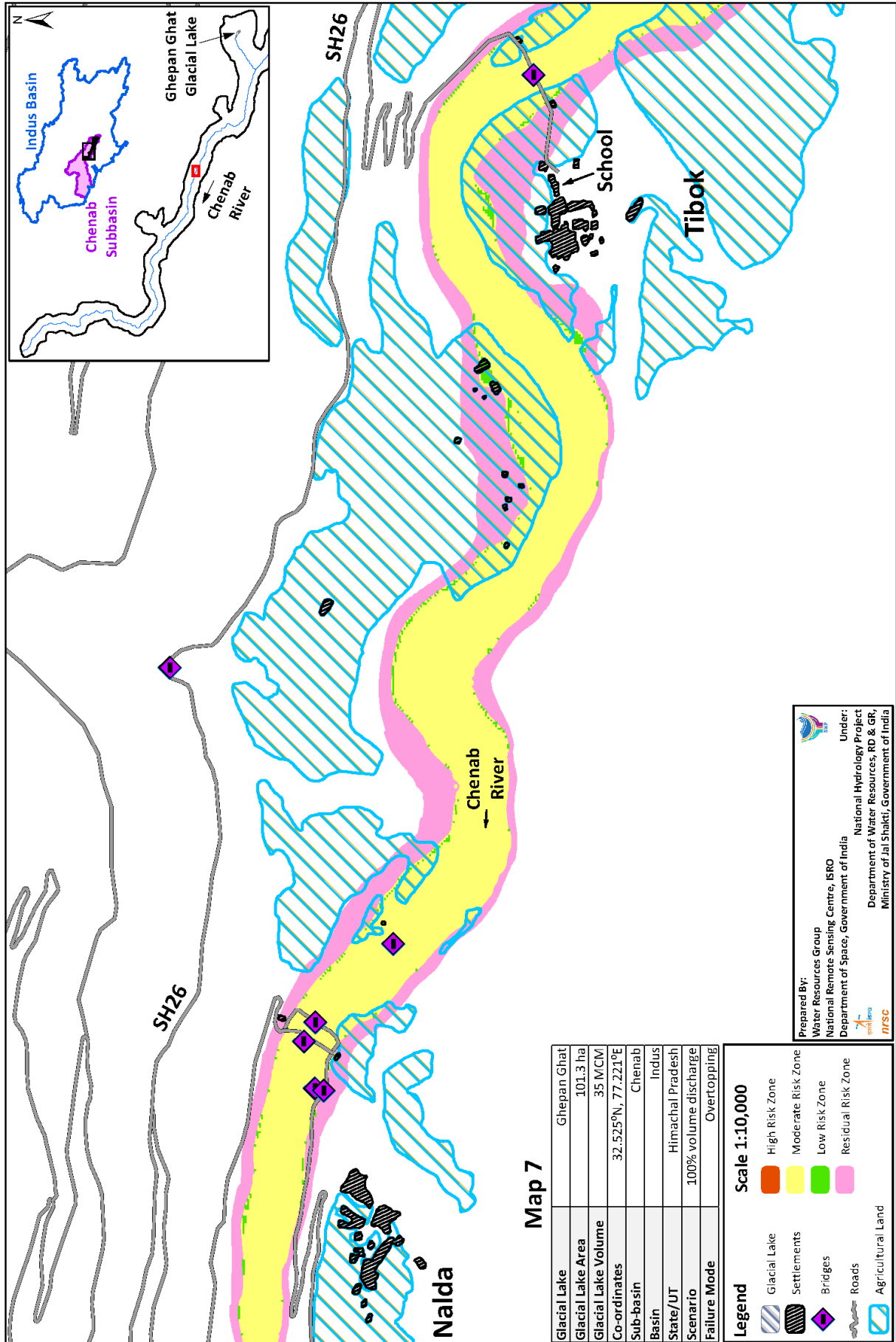


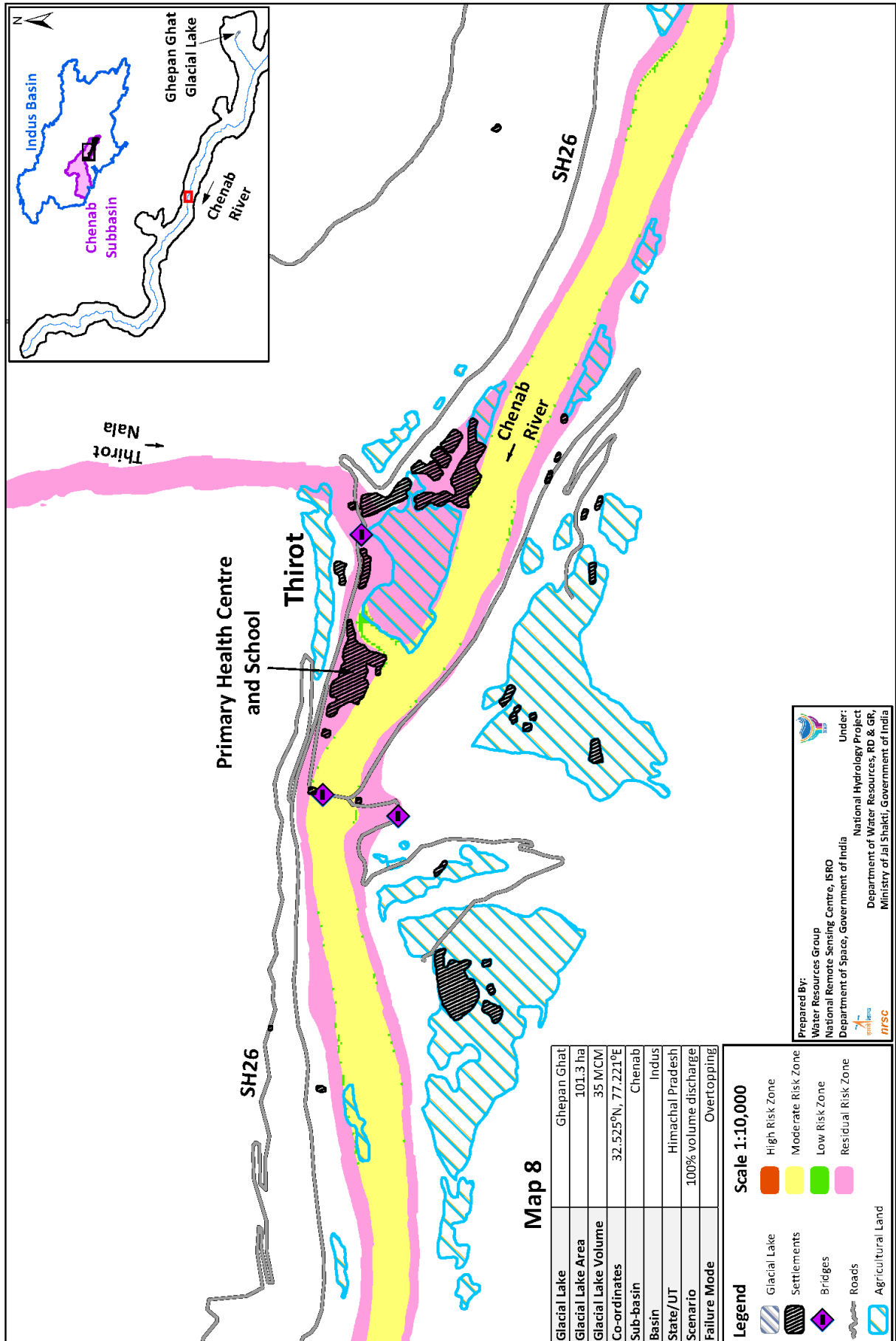


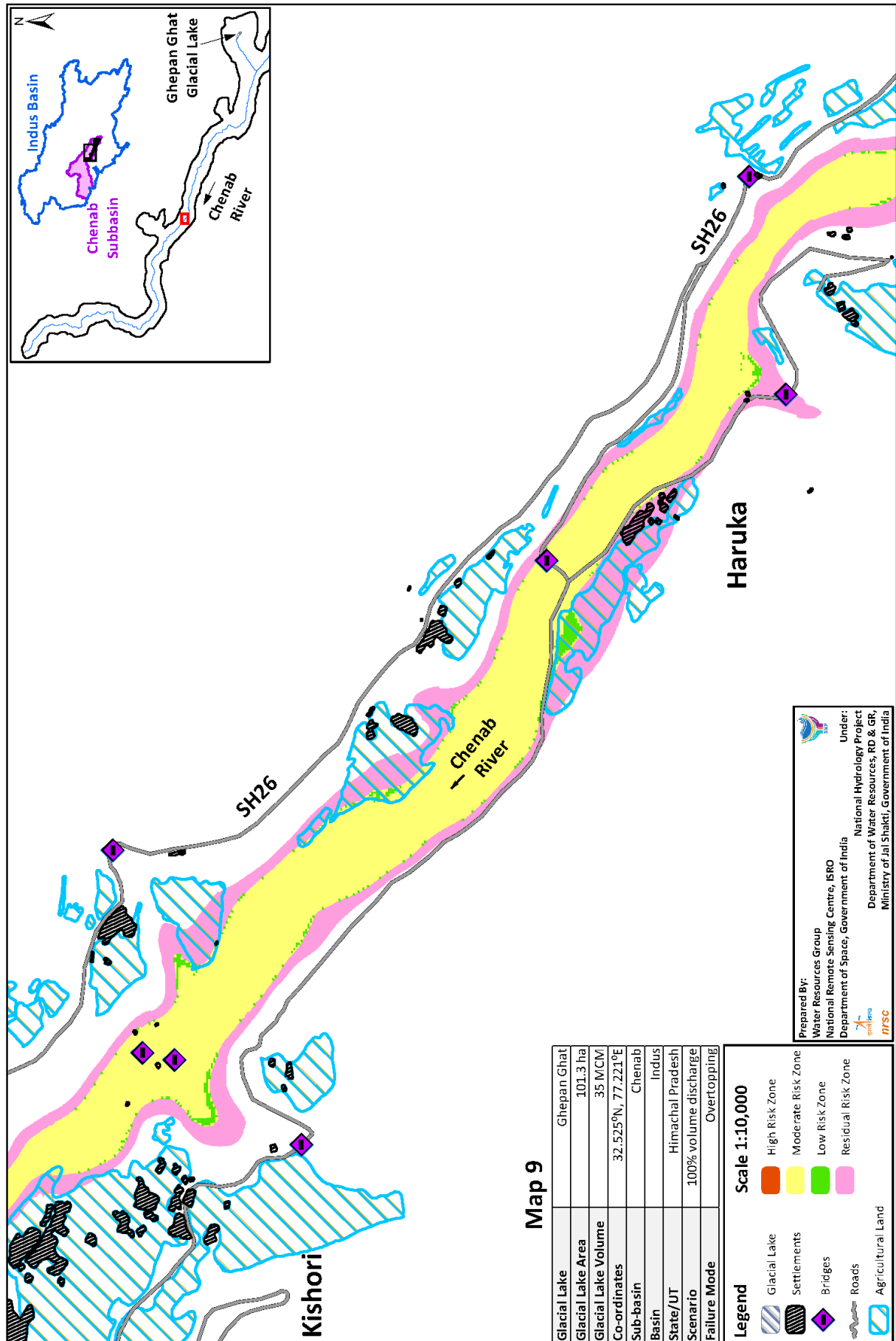


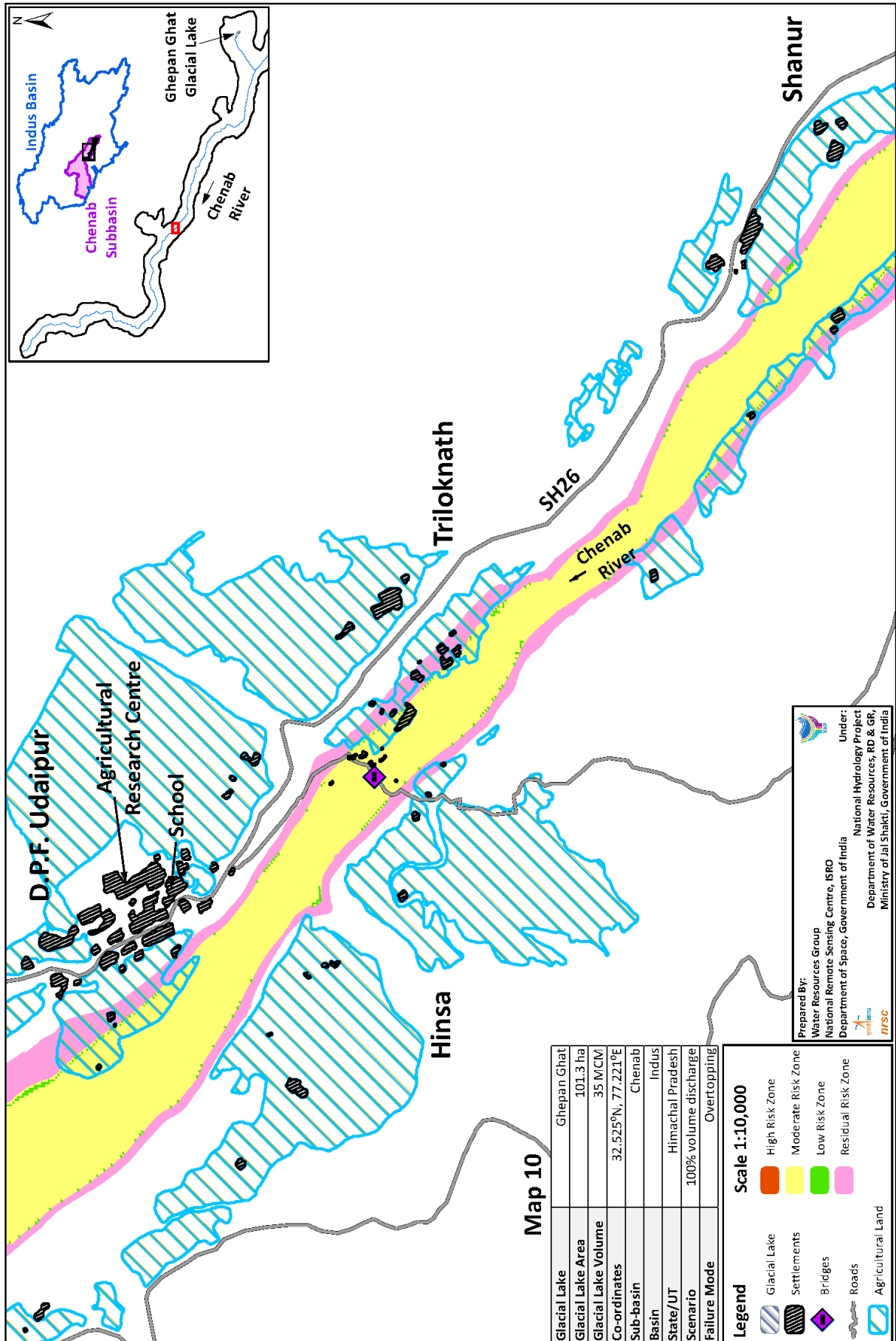


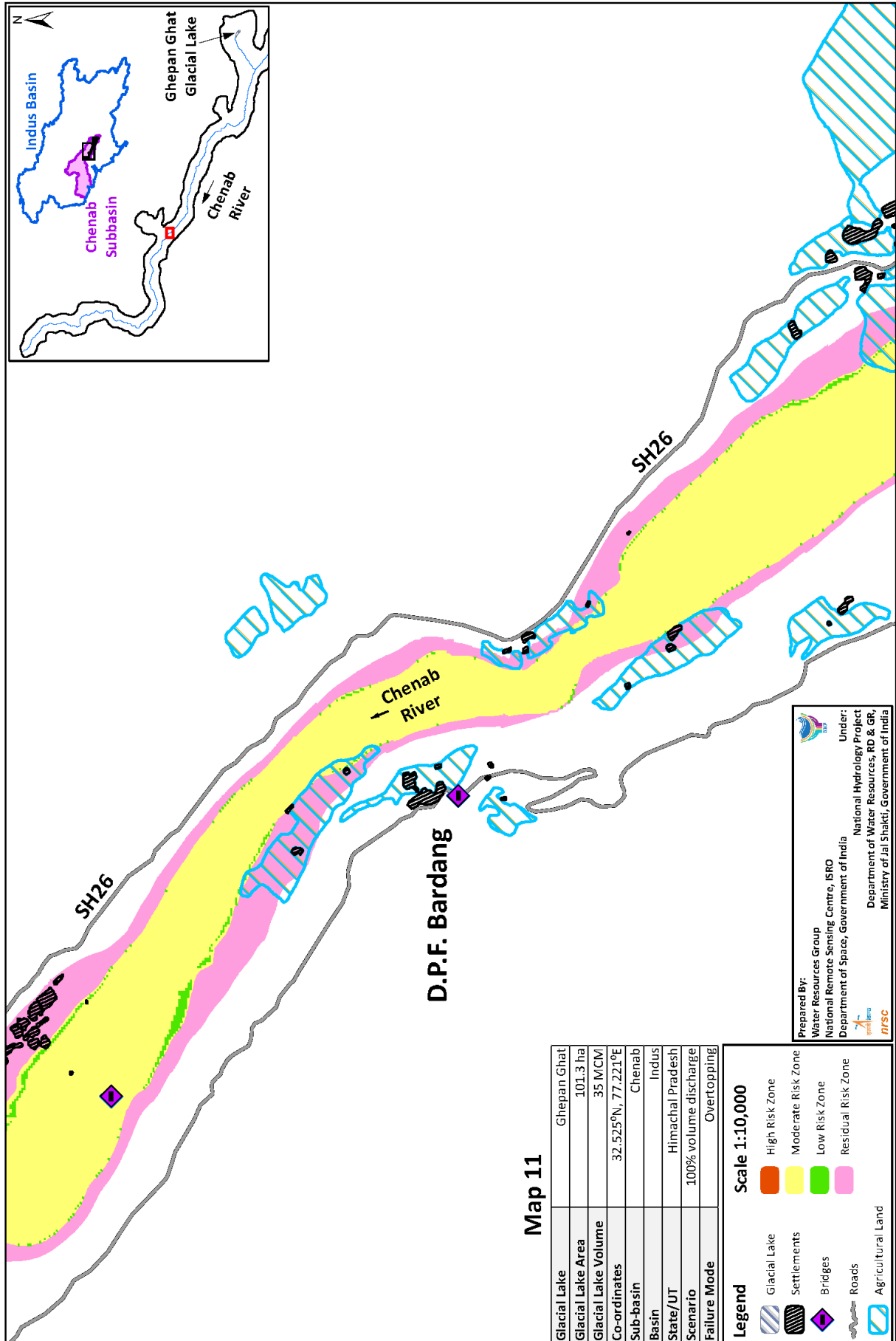


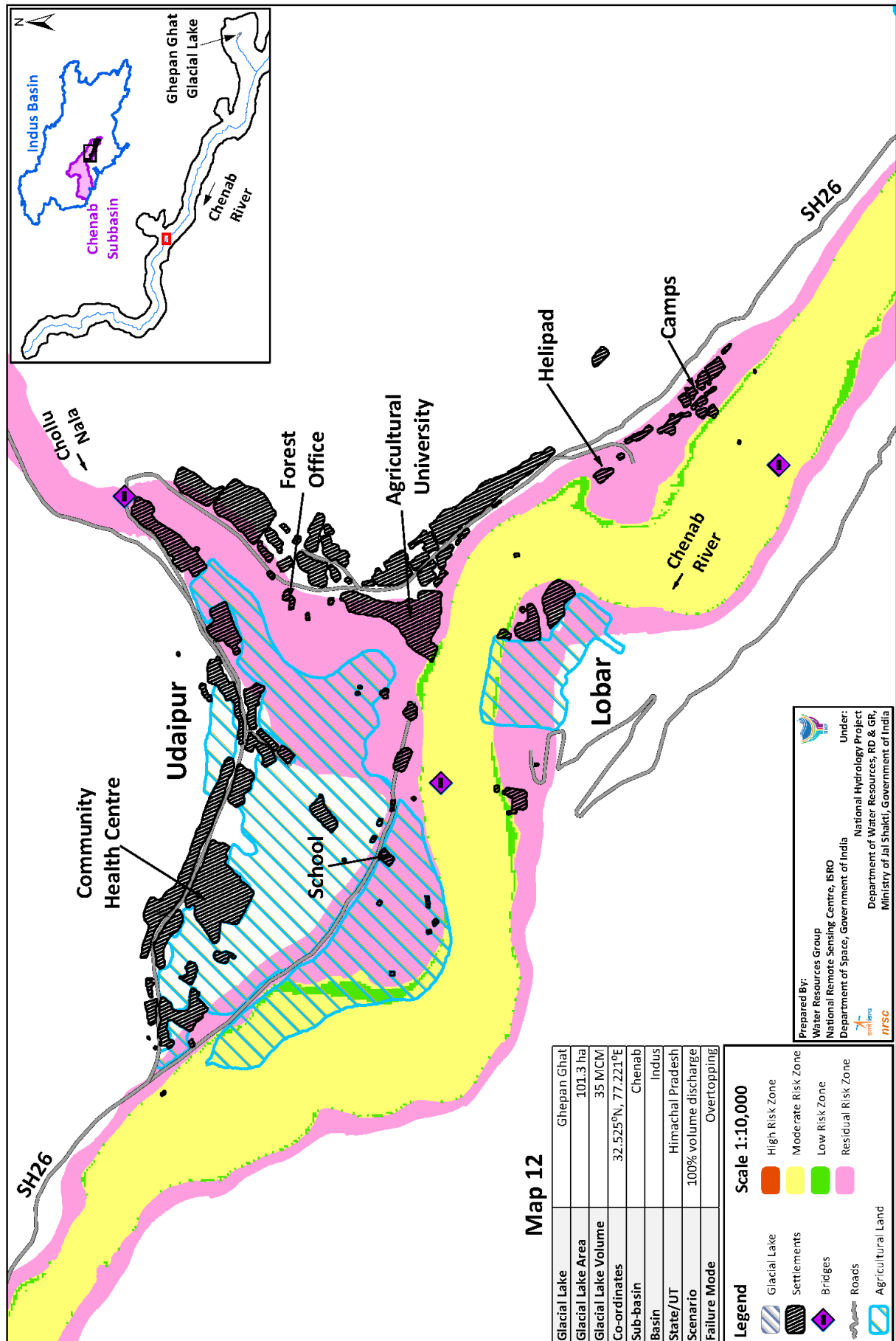


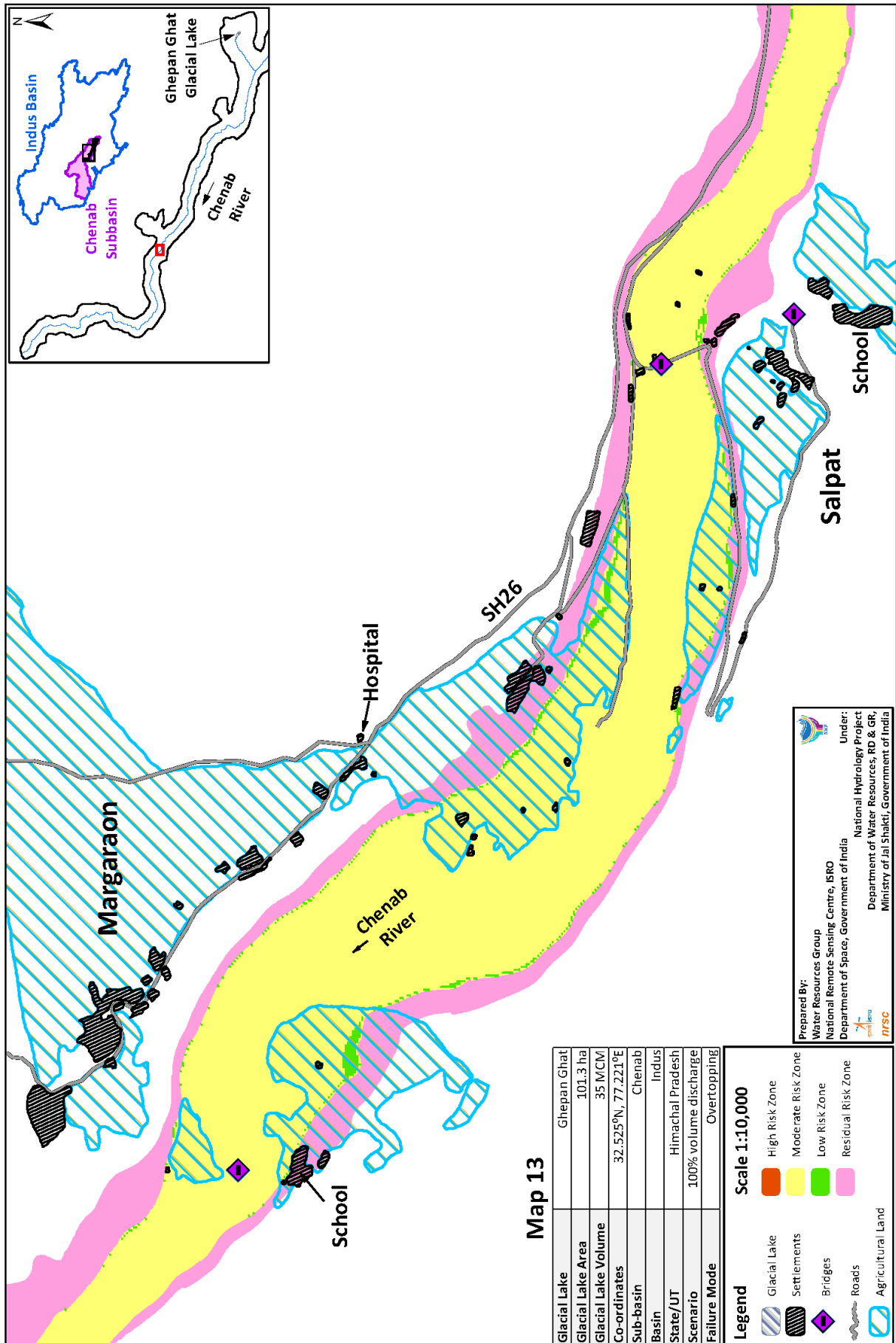


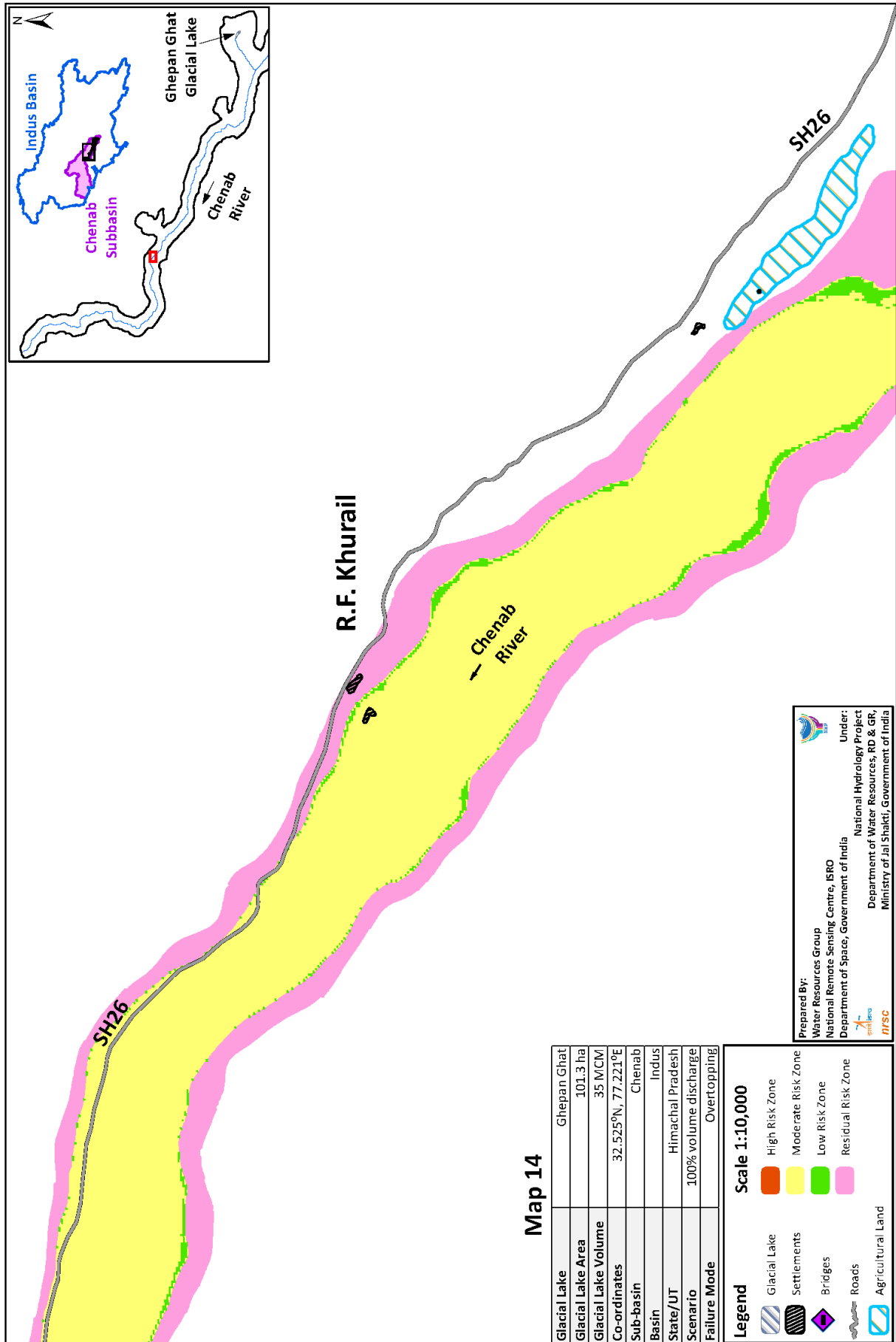


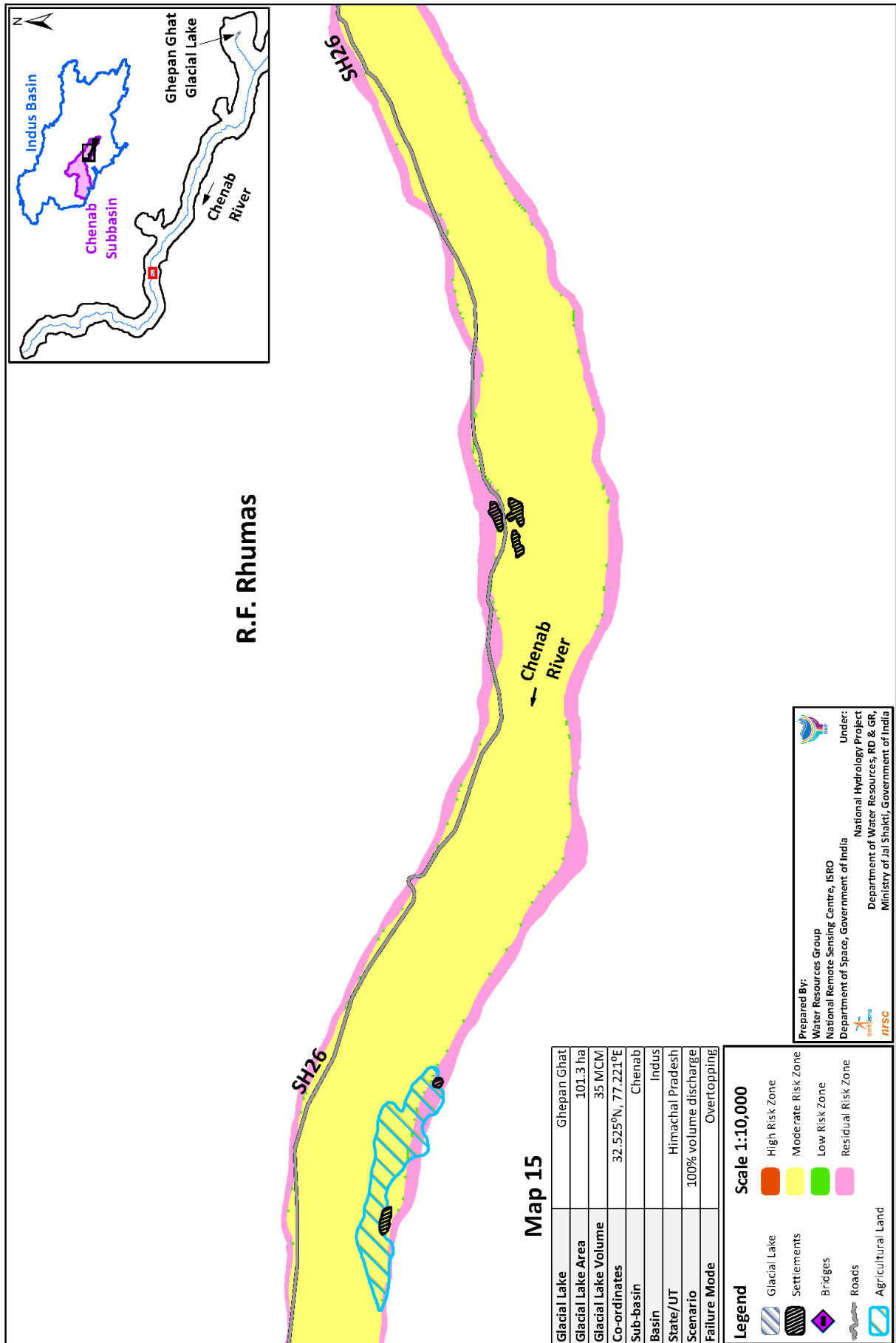


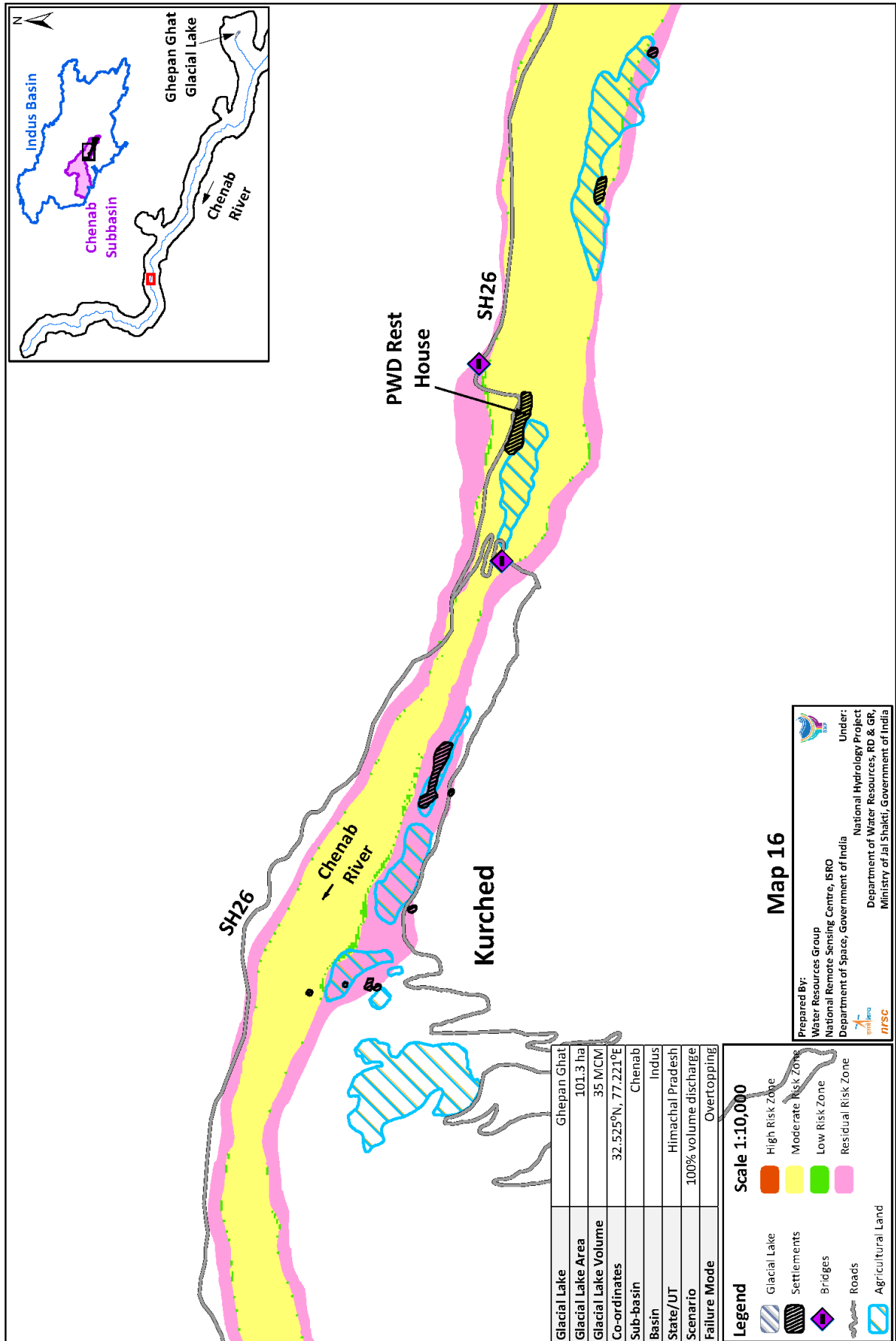


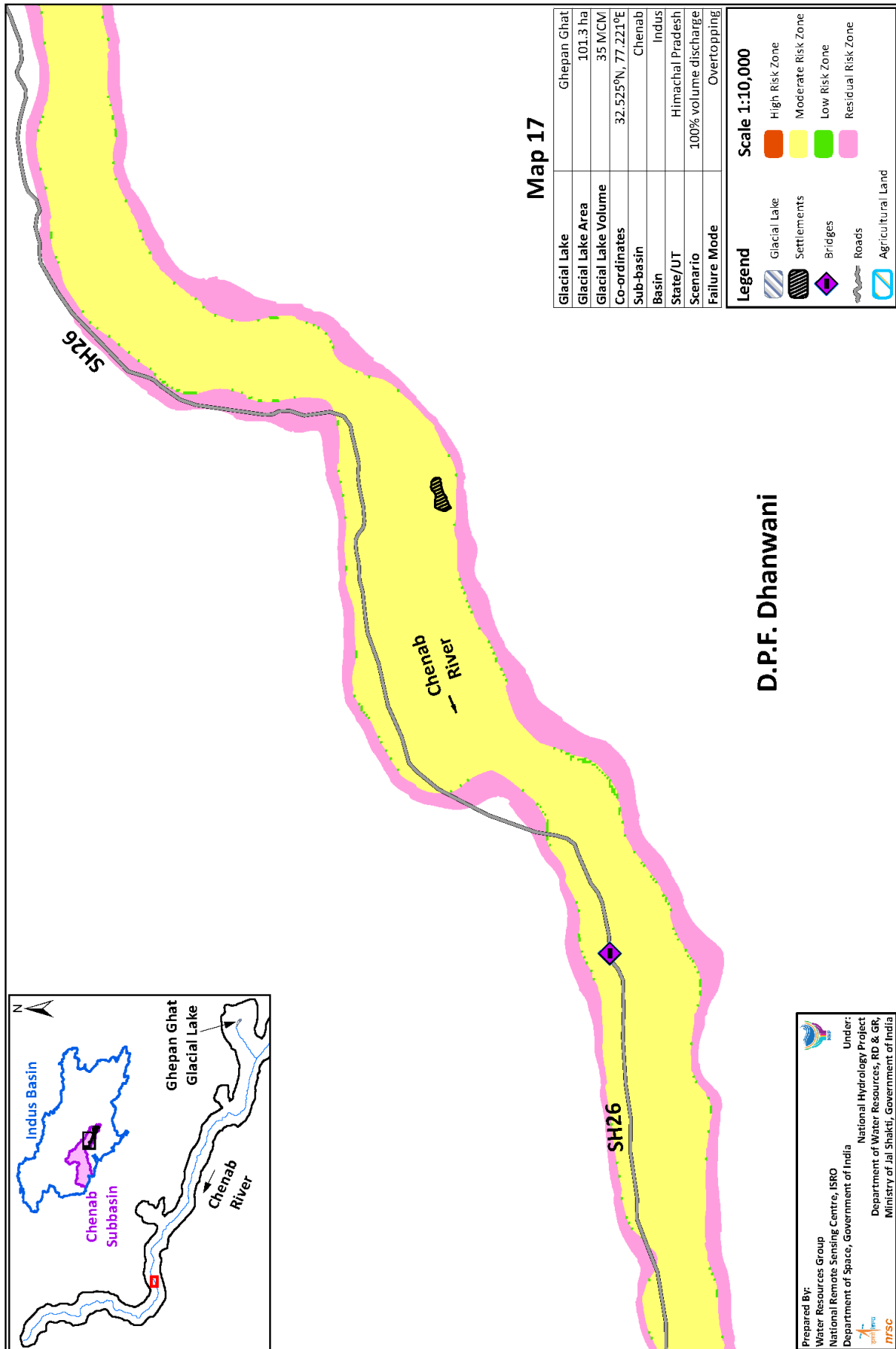


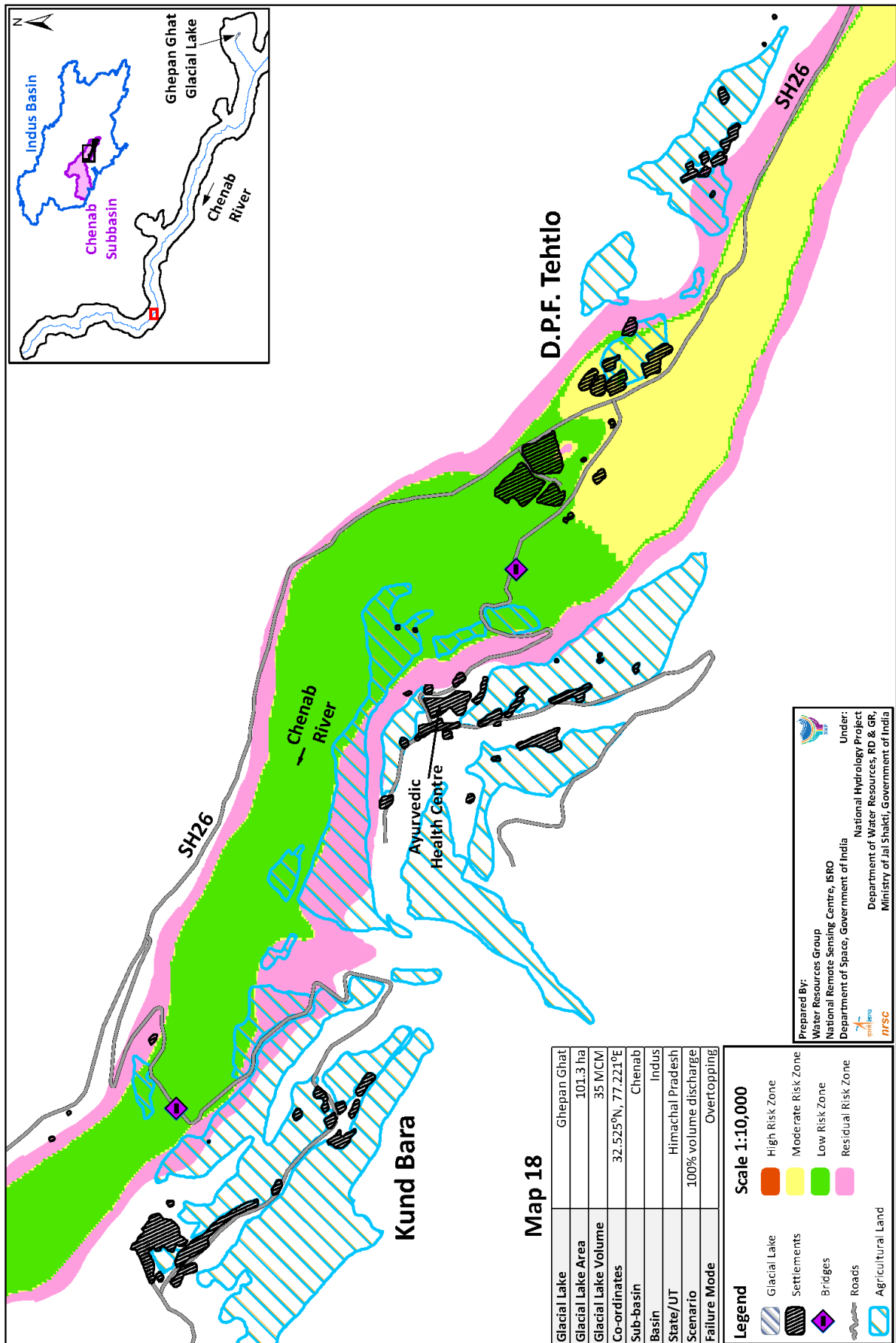


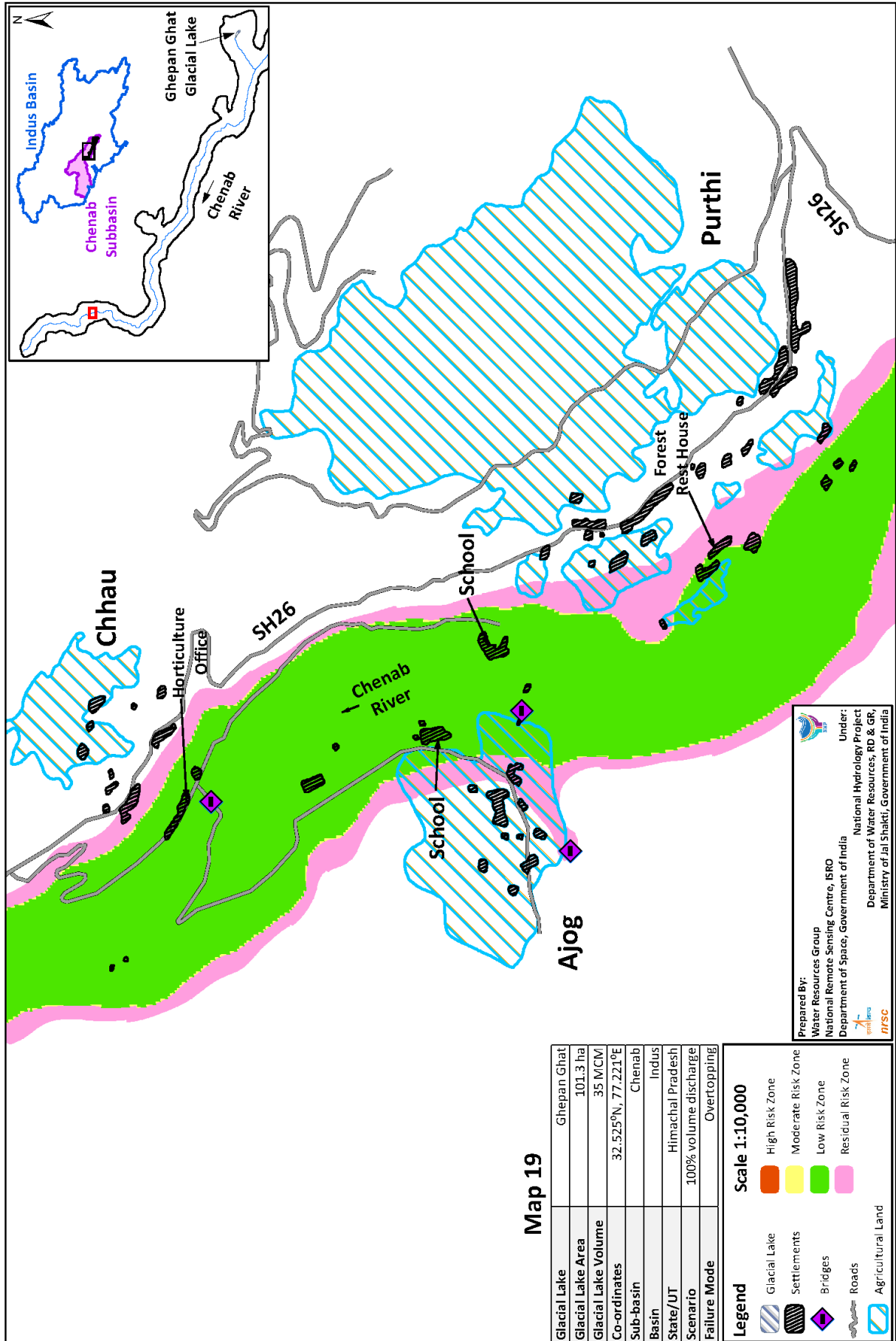


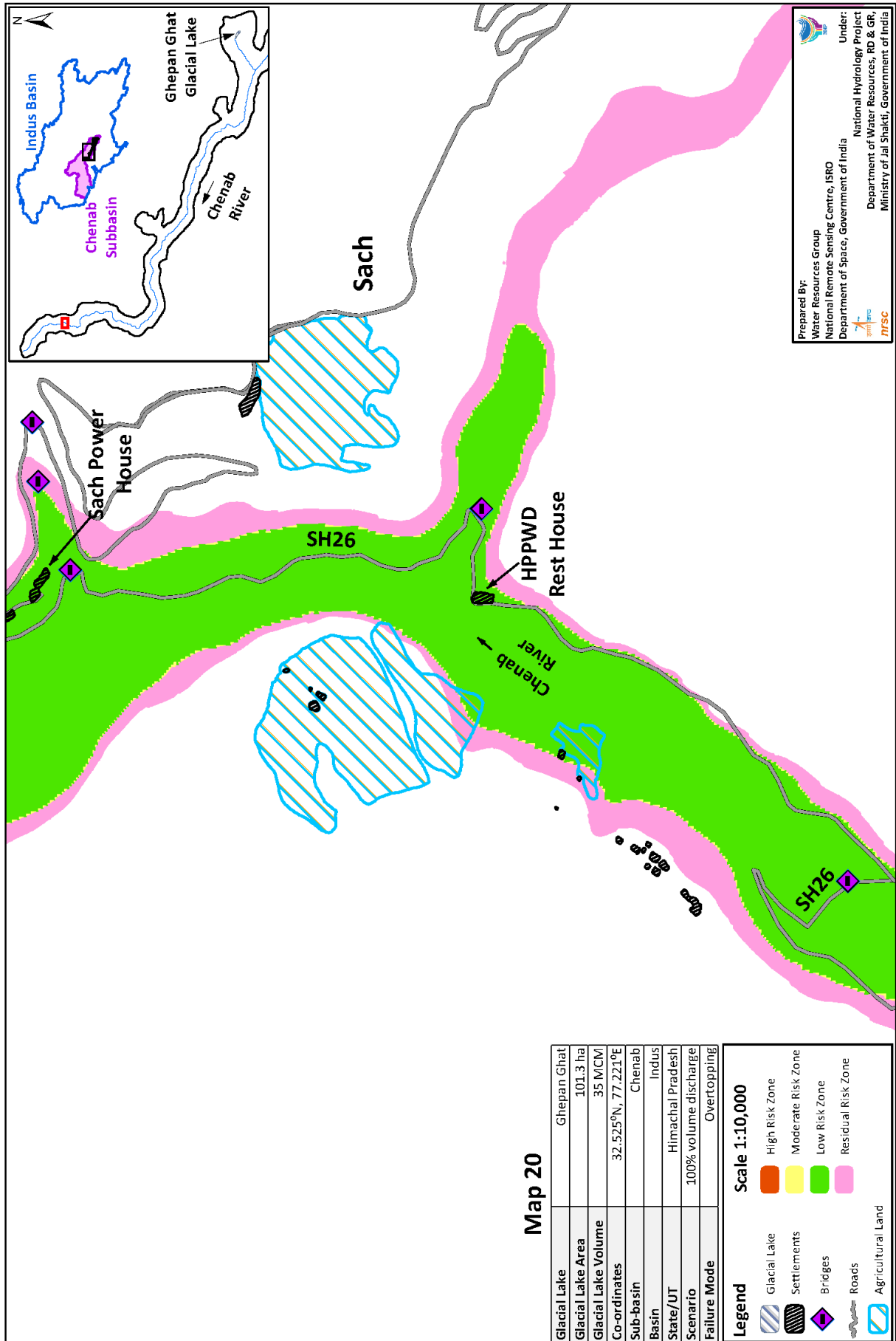


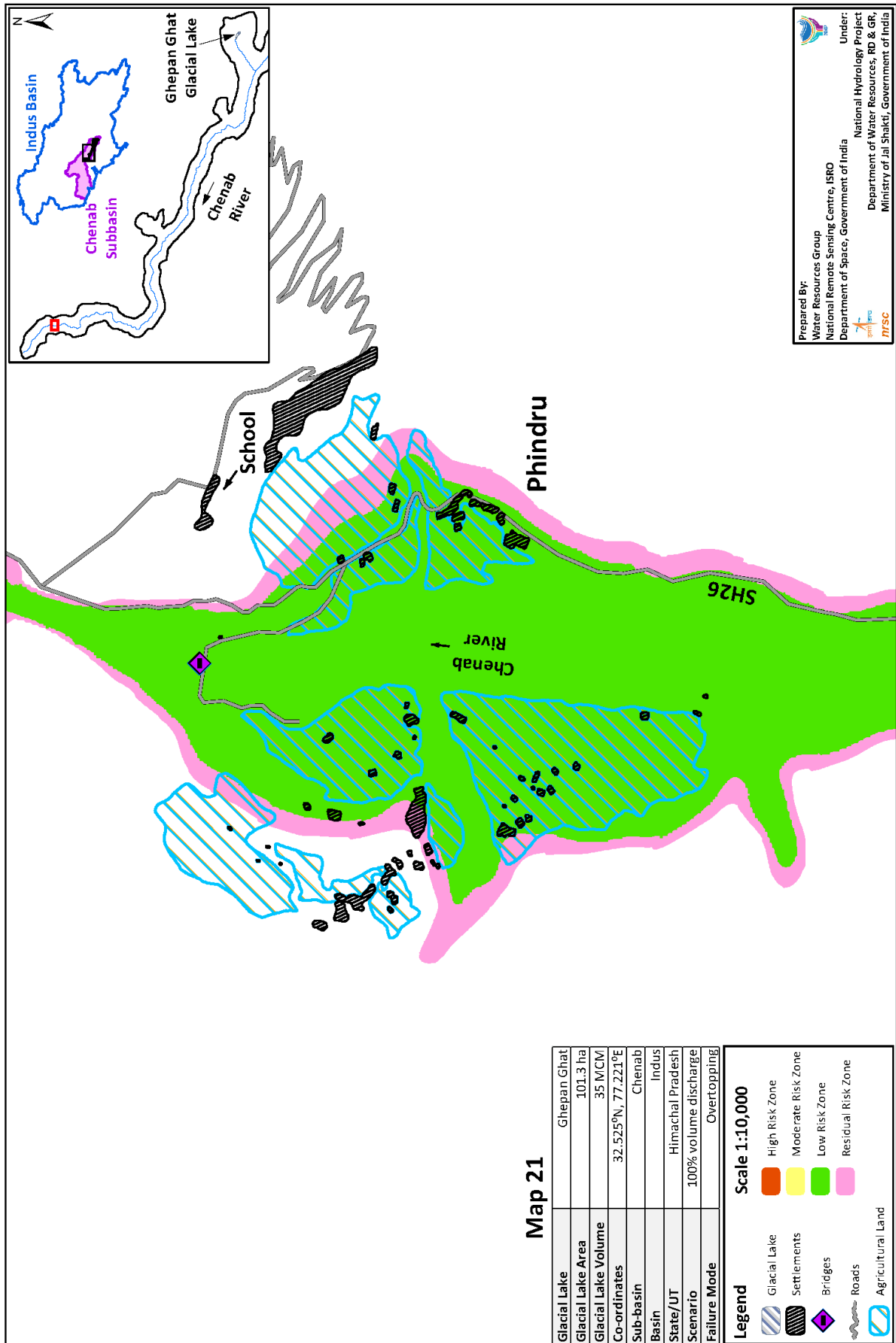


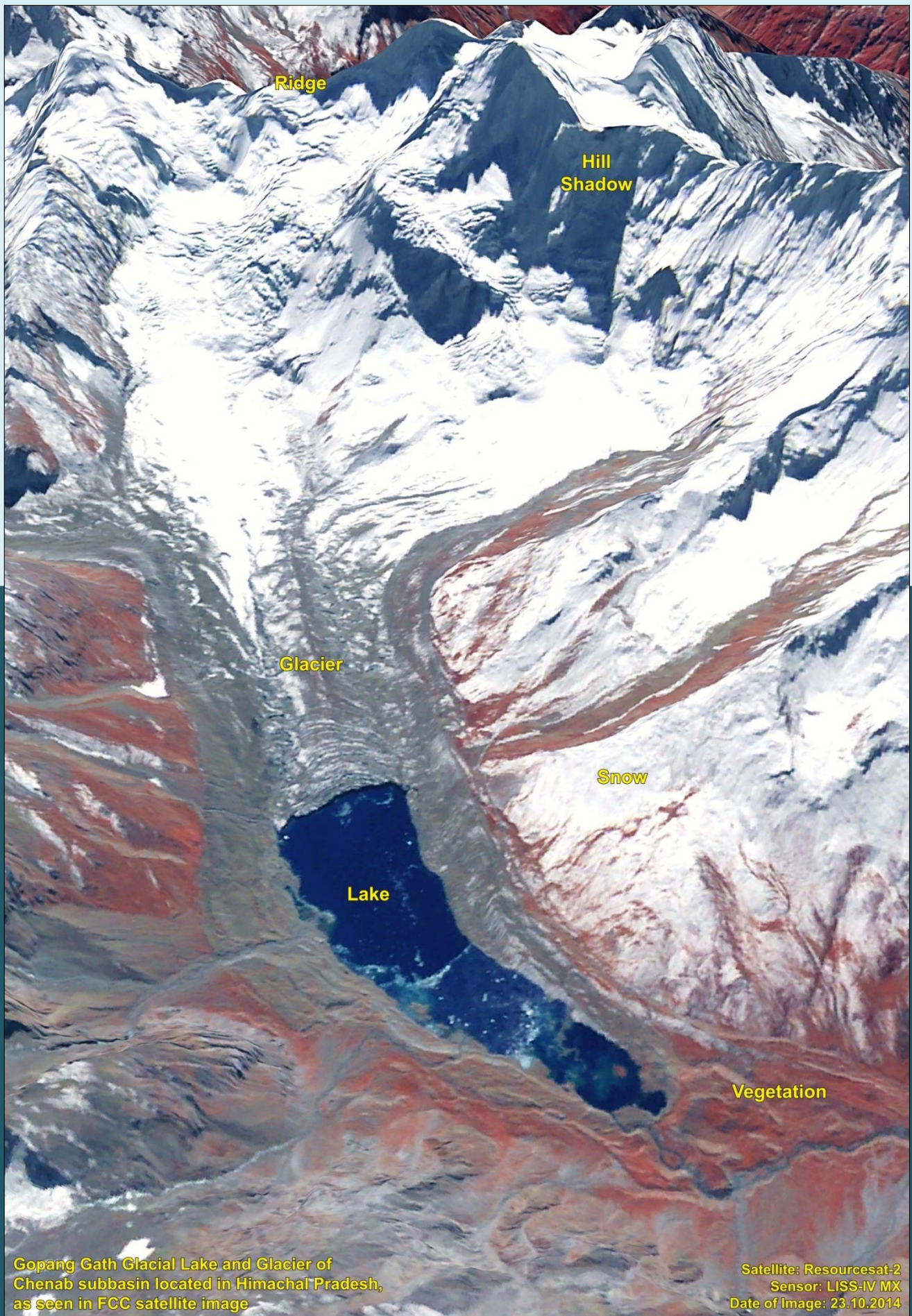












Gopang Gath Glacial Lake and Glacier of
Chenab subbasin located in Himachal Pradesh,
as seen in FCC satellite image

Satellite: Resourcesat-2
Sensor: LISS-IV MX
Date of Image: 23.10.2014