DETAILED REPORT

Study of Causes & Impacts of the Uttarakhand Disaster on 7th February 2021 in Raunthi Gadhera, Rishiganga & Dhauliganga Valley: Measures to Reduce Disaster Risks

April 2022

NATIONAL DISASTER MANAGEMENT AUTHORITY
MINISTRY OF HOME AFFAIRS
GOVERNMENT OF INDIA

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Abbreviations & Acronyms

BRO	:	Border Roads Organisation
CEA	:	Central Electricity Authority
CGRSM	:	Centre for Glacial Research, Studies and Management
CUMEC	:	Cubic Meter Per Second
CWC	:	Central Water Commission
DGRE	:	Defence Geoinformatics Research Establishment
DM	:	Disaster Management
DRDO	:	Defence Research & Development Organisation
DRR	:	Disaster Risk Reduction
DoS	:	Department of Space
DEM	:	Digital Elevation Model
DPR	:	Detailed Project Report
GLOF	:	Glacial Lake Outburst Floods
GoI	:	Government of India
G&D	:	Gauge & Discharge
GSI	:	Geological Survey of India
HEP	:	Hydro-Electric Power Project
IDS	:	Integrated Defence Staff
IMD	:	India Meteorological Department
ITBP	:	Indo-Tibetan Border Police
ISRO	:	Indian Space Research Organisation
LST	:	Land Surface Temperature
MCM	:	Million Cubic Meter (Million m^3)
MHA	:	Ministry of Home Affairs
MoD	:	Ministry of Defence
MoEFCC	:	Ministry of Environment, Forest & Climate Change
MoES	:	Ministry of Earth Science
MoJS	:	Ministry of Jal Shakti
MoM	:	Ministry of Mines
MoP	:	Ministry of Power
NCMC	:	National Crisis Management Committee (NCMC)
NCPOR	:	National Centre for Polar and Ocean Research
NCS	:	National Centre for Seismology
NDMA	:	National Disaster Management Authority (NDMA)
NDRF	:	National Disaster Response Force
NIDM	:	National Institute of Disaster Management
NIH-Roorkee	:	National Institute of Hydrology, Roorkee
NIM	:	Nehru Institute of Mountaineering
NRSC	:	National Remote Sensing Centre
NTPC	:	National Thermal Power Corporation Limited
NTRO	:	National Technical Research Organisation
USDMA	:	Uttarakhand State Disaster Management Authority
SDMA	:	State Disaster Management Authority
SDRF	:	State Disaster Response Force
SoI	:	Survey of India
THDCIL	:	Tehri Hydro Development Corporation India Limited
WIHG	:	Wadia Institute of Himalayan Geology

Executive Summary

On the morning of Sunday, 7th February 2021 at ~10:08:45 hours, a failure of huge rock mass along with dislodgement of a glacieret caused in an air blast and dust clouds in the higher reaches of Garhwal Himalaya (Nanda Devi Ranges). This event brought an unprecedented level of debris flow in the Raunthi Gadhera, Rishiganga, and Dhauliganga river valley in the Joshimath block of the Chamoli district. The displaced rock mass and glacieret ice moved downhill along the river valley at an extremely high speed, from a high altitude over the steep slopes. This event led to the formation of a landslide dam at the crash zone and a debris-dammed lake in the Rishiganga River. A bulk of debris also flowed into Raunthi Gadhera, Rishiganga and Dhauliganga rivers. Apart from damage to thebuildings, roads, bridges, and the Hydel projects at Raini and Tapovan, 204 people and about 186 livestock also lost their lives to this incident. Further, electricity, water, and connectivity to 13 villages were adversely affected but restored within a few weeks.

On the same day, at 16:30 hours, a high-level meeting on National Crisis Management Committee (NCMC) was held under the chairmanship of the Cabinet Secretary, GoI. In this meeting, all the concerned agencies were directed to work in close coordination and to extend all requisite assistance to the state. On 17th and 22nd February 2021, meetings were held under the chairmanship of Union Home Secretary, GoI to review the progress of search and rescue operations and decide the further course of action on the artificial lake formed in the Rishiganga river.

At the request of the Government of Uttarakhand, the Ministry of Home Affairs (MHA) requested National Disaster Management Authority (NDMA) to constitute an interdisciplinary joint study team of experts for understanding the event and suggesting the measures for disaster risk reduction. On 26th February 2021, based on the deliberation held in the meeting on 16th February 2021 with stakeholders, NDMA constituted a team of multi-disciplinary experts for a joint study to understand the causes and impacts of the event. The joint study team visited the incident site from 24th to 31st March 2021 and carried out a helicopter recce accompanied by afield survey. The joint study team was divided into an upstream team from the Raini up to rockfall source area and a downstream team focussed on the impact zone from Raini up to Central Water Commission (CWC) gauge station near Vishnuprayag, to find out the causes and impact of the event.

Satellite images and information provided by the Indian Space Research Organisation (ISRO) were used to study the source of rockfall with glacieret ice avalanche that caused the debris to flow in the downstream valley of Raunthi Gadhera, Rishiganga, and Dhauliganga River. A detailed geological, geomorphological and hydro-meteorological study was carried out for understanding the causes and impacts of the event. The joint study revealed that rockfall with glacieret ice avalanche is the primary slope failure which is controlled by three sets of joints that facilitated the inverted triangle type wedge failure of rock mass along with dislodgement of glacieret over it. The failed rock mass capped with ice descended from an altitude of 5474 m to 3732 m and travelled along a steep slope for about 2.9 km. The failed mass (rock and ice) with dislodged rocks from the travel path was pulverised and crashed onto the terminal moraine deposit. The pressure/ energy generated by the impact of this failure probably led to the melting of snow and ice besides pulverisation of crushing of rock mass. The melt water along with high snow melting due to the rise in temperature on that day descended further along the valley as debris flow in the downstream areas. The impact also created an air blast with debris flowed and uprooted trees in the downstream valley of Raunthi Gadhera, Rishiganga, and Dhauliganga valley. The hydel power projects of the Rishiganga hydro project (13 MW), NTPC hydropower project (520 MW), and BRO Bridge have washed away and damaged due to debris flow and caused loss of human lives. People trapped inside the HRT adit tunnel of NTPC hydel power project rescued by the National Disaster Response Force (NDRF), State Disaster Response Force (SDRF), ITBP, the Army, etc.

The joint study team of NDMA conducted pre and post field visit rounds of meetings with Expert institutions and other stakeholders on 16th February, 4th March, 15th March, 23rd March (in Dehradun), and 4th June 2021.

Cause of the Event

A major debris flow (initially termed as Glacial Outburst) was reported in the morning of 7th February 2021 (Sunday) at ~10:08:45 hours in Raunthi Gadhera, Rishiganga & Dhauliganga River valley. This created debris dammed lake at the confluence of the Raunthi Gadhera and Rishiganga river, followed by immense damage to the Rishiganga hydel power project, BRO bridge, Tapovan Hydro-electric project, and other infrastructure near Raini and Tapovan Villages. Different theories and assumptions (like glacier lake outburst flood, major avalanche, due to rockslide impact, or due to burst of possible underground glacier lake in the catchment, etc.) were proposed to explain the cause of the unprecedented and untimely debris flow.

Based on the helicopter-recce, field visits, and analysis of remote sensing data, the joint study team discussed the possible causes of the event and concluded the following:

- No geo-morphological evidence of Glacial Lake Outburst flood (GLOF) or sub-glacial flood was found during field survey or satellite image analysis.

Rockfall and Glacieret Ice Avalanche:

- The event started as **rock fall** and **Glacieret ice avalanche** caused by long-term and short-term geological, geomorphological, glaciological, cryospheric, and hydro-meteorological processes, followed by an extreme massive debris flow in the catchment of River Raunthi Gadhera, Rishiganga, and Dhauliganga.
  - **Geological processes:** Fragile rock type, structurally controlled Raunthi hill.
  - **Glaciological processes:** Hanging glacier, glacier erosion/plucking/change in glacier velocity due to summer accumulation.
  - **Cryospheric & Geomorphological processes:** Frost cracking, permafrost freezing, and thawing of water in the discontinuities in the sub-glacial rock strata and the overlying debris.
  - **Hydro-Meteorological & Climatological processes:** Short-term increase in monsoon rainfall, pre-winter snow cover reduction, summer snow cover increase, increase in land surface temperature (LST) since 2008, and atmospheric warming.
- A large mass of rock, nearly triangular with an approximate area of 0.32 km^2 capped with hanging glacier (area of 0.59 km^2) bounded on two sides by joints and one side with a foliation got detached on 7th February 2021.
- As per the available satellite data and Digital Elevation Model (DEM) analysis, the volume of the released mass was about ~29.3 MCM including rock and glacier mass. The maximum depth of the released mass is about 197 m with average thicknesses of rock and ice mass of about 130 m and 20m respectively. The volume of glacier ice may be about 13 MCM but further studies are needed to confirm this. High-

resolution post-event DEM field survey/ satellite data will enable better estimation of release mass dimensions and volume.

- The failure is wedge type and controlled by geological structures, decrease in strength, and friction along the failure plane due to various natural processes (glacier processes, permafrost thawing, snowmelt water percolation), increase in pore water pressure, and increase in external loads (snowfall, glacier mass redistribution due to glacier movement). Long-term freezing and thawing action may have facilitated the opening and widening of joints and cracks within the failure plane of the rock mass.
- The observed increase in precipitation and land surface temperature since 2008 which peaked in 2016 may also have contributed to the increase in snow/ ice melt in the release area and movement of the overlying glacier. The advancement of the central lobe of the hanging glacier next to the release area during 2005-2016 and its detachment in 2016 may be a precursor to the present event.

Dynamics of the Detached Mass and Debris Flow:

Based on the terrain information and field observations, the following deductions on the dynamics of the released mass have been made by the joint study team:

- The dislodged mass of rock and glacieret ice traveled about 2.9 km on a slope of 40 degree with a fall of approximately 1740m.
- Before reaching the valley, the released mass attained significantly high velocity.
- On hitting the valley at high velocities, the released rock-ice mass disintegrated into smaller and irregular-sized rock and ice blocks. This process also led to partial melting of the glacier ice.
- Due to high momentum, a part of the released mass climbed the opposite slope after hitting the bottom of the valley. This mass came down to the valley floor and climbed about 285m on the opposite slope. During this process of climbing, the moving mass created an air blast leading to snapping and uprooting of the trees upto 3.2 km downstream from the impact zone.
- Due to the considerable slope of the valley floor (20-25 degrees), the partially wet released mass moved down the valley. During this valley movement, the moving mass entrained the soil mass, moraine material, snow, ice, leftover avalanche debris of the 2016 event, the water of Raunthi Gadhera, etc. lying on the valley floor and banks of the flow channel. The narrow pre-event channel (Total area~0.697 km^2) widened significantly (~4.22 km^2) due to channel scouring and entrained woody debris. The frictional heating within the moving mass and at the interface with the ground leads to the melting of snow/ ice and the addition of water.
- The presence of convergent-divergent sections and curves along the flow path led to splashing of the moving mass on the side slopes upto significant heights.
- Significant unstable sediment deposits along the debris flow reach were observed during field work. It is expected that this material will be remobilised during the forthcoming snow melt/ monsoon period.

Debris Dammed Lake Formation on Rishiganga:

A sharp change in the flow path and the presence of a convergent-divergent section ahead of the Raunthi-Rishiganga confluence reduced the velocity of the front of the moving mass. This resulted in the accumulation of incoming tail mass (from Raunthi) near the Raunthi-Rishiganga confluence. As a result, the accumulated mass climbed into the Rishiganga river for **~450 m** over a slope of about **10°** (degree). During this process, the heavier mass settled on the valley floor of Rishiganga river and the lighter mass flowed back into the main channel on the decrease of inflow from Raunthi. This process led to the formation of a debris flow dammed lake in the Rishiganga River. The dam material consists of angular rock debris of varying sizes, a large amount of fine silt material produced due to grinding, and a large amount of fragmented glacier ice. Till Raunthi-Rishiganga confluence, the flowing mass seems to have dry mass in it.

At present, the dam length is about **375-380 m** and width at the in front of the lake is about **112-115 m**. The length of the lake upto the last visible point is about **430 m**.

- After the Rishiganga-Raunthi confluence, the mass traveled with an average flow height of 30-40 m and a maximum splash height of about 120 m. The splash process also threw large boulders and ice blocks on side slopes. Glacier ice blocks that can still be seen on the bank deposit are melting leading to destabilisation of the slopes
- During the flow along the channel, the process of melt water generation and mixing of the various phases of the mass continued, leading to an increase in water content in the debris flow.
- Due to the presence of a narrow flow section just upstream of the BRO bridge location at Raini village, a large splash of moving mass blew off the Rishiganga power project (HEP-1) and BRO bridge.

Debris Back Flows in Dhauliganga River

Soon after hitting the BRO bridge, the moving mass hit a T-junction where Rishiganga meets Dhauliganga. Due to the normal impact at the junction, the velocity of the flow front was reduced; but continuous inflow led to an increase/ maintenance of the debris height near the confluence. This led to the formation of a gravity wave, both upstream and downstream of Dhauliganga river. The moving mass traveled about **1.2km** into the Dhauliganga river upstream of the confluence destroying a suspension bridge over Dhauliganga at **~140m** from the confluence. Most of the debris mass upto**24m** height from the present bed level at mid-point flowed back to the downstream of the confluence leaving a heavier mass at the river bed.

- After the Rishiganga-Dhauliganga confluence, the water content of the moving mass seemed to have increased and the debris flow moved to the Tapovan dam site (HEP-2) with an average flow height of **20-30m**. An increase in ambient temperature, frictional melting of ice/ snow, and water of Dhauliganga River seem to be the source of the increase in water content in the moving debris flow mass.
- Along its flow path, the moving mass deposited significant mass over the river bed with deposition depth varying from **5-18m**.
- The geometry of the flow channel also led to a significant amount of energy dissipation and reduced impact downstream from the Raini village.
- Due to the presence of a wall-like obstacle at Tapovan (Tapovan dam) a significant amount of solid phase of debris flow mass was entrapped and deposited near the dam.

Impacts

On 7th February 2021~10:08:45 hours, residents of Pang, Raini, and Moranda villagers heard loud sounds and witnessed a huge amount of mass consisting of rocks, mud, water, ice blocks, etc. with dust clouds moving in the Rishiganga River valley, which caused significant damage along its flow path. This event damaged the Rishiganga hydropower station (near Raini), a road bridge (near Raini, constructed and maintained by Border Roads Organisation -BRO), about 5 other suspension bridges. This event also led to significant loss of life, most people working on the construction site of the hydro-electric project at Tapovan (NTPC). The under-construction Tapovan Hydro electric plant (HEP) was also severely damaged due to sedimentation.

The debris transported from the Raunthi River blocked the Rishiganga River at the confluence and created artificial debris dammed lake at 2380m above mean sea level (MSL). Damage to power infrastructure, roads, and water supply was observed. One residential house was completely damaged, beyond repair.

Probable Risks

Presently, there are potential risks of further mass-movement from hanging rock mass at source zone (Raunthi peak) with landslide debris deposited below crash zone in Raunthi glacier valley created a dam of 20m height and formation of debris dammed lake near the confluence of Raunthi Gadhera and Rishiganga River. The hanging rock mass with landslide debris deposition at crash zone and debris dammed lake is analysed to be unstable and may be of potential risk. NDMA in its preliminary interim brief report of field assessment submitted on 15th April 2021, alerted the Uttarakhand Government about probable impending risks and suggested immediate remedial measures.

Lessons learned and Recommendations/ Suggestions

The lessons learnt from this study are divided into five sections i.e., disaster risk assessment; monitoring, early warning & alert system; prevention, mitigation & preparedness; response & recovery and revision & implementation of DM plan by the concerned Central, State and District level authorities. The lessons learnt from this unique event that occurred in the glacier area should be acted upon following the recommendations listed out in this report.

Recommendations/ suggestions are divided into immediate, short-medium term, and long-term measures with action points for the concerned Ministries/ Departments/ Institutions and other stakeholders. The time required for the implementation of short-medium term measures is 3 to 8 years and long-term measures within 11 years.

In India, this is a unique, unprecedented and first reported incident of glacier ice and rock having a cascading impact on debris flow. But, similar types of rock falls and glacieret ice avalanche events took place in European Alps, the Russian Caucasus, Canada, and Nepal in the past. The effect of climate change and global warming are evident in Himalayan glaciers and mountains. Therefore, it is urgently needed to share and learn from the best practices available nationally and internationally to minimize the impact of future hazards and risks in the Indian Himalayan regions. It is also recommended that existing and future HEPs must follow recommendations/ suggestions and implement all necessary safety measures during all phases of activities including planning, feasibility studies, construction, and operation.

1. Introduction

On 7th February 2021 at ~10:8:45 hours, a debris flow event accompanied by a rumbling sound of air blast along with dust clouds was reported in the Raunthi Gadhera, Rishiganga, and Dhauliganga river valley in the Joshimath, Chamoli. The cause of the event and the site of the incident were unknown till 8th February 2021. The site of the incident was identified by the aerial recce done by Indian scientists and the satellite images that were captured by (Indian Space Research Organisation) ISRO.

In India, this wasa unique and previously unreported incident of glacieret ice and rock slide that had a cascading impact of debris flow in the tributaries of Rishiganga and Dhauliganga river valley, Chamoli district in Uttarakhand. The source and the impact areas are located in the Survey of India (SOI) Toposheet No. 53N/11. Prominent localities of the affected areas include Raini, Lata, Tapovan, Joshimath, etc. Similar glacier ice and rock slide events have been reported in European Alps, the Russian Caucasus, Canada, and Nepal (Huggel, C., et. al.; 2012).

It was noted that this event occurred following a huge airblast which in turn was caused by massive dislodgement and sudden fall of rock mass and glacieret ice from a high altitude over steep slopes. The event was triggered by an interplay of multiple factors such as geomorphological (thaw and freeze weathering action), geological, glaciological, permafrost, hydro-meteorological, and climatological processes (i.e., Land Surface Temperature (LST), atmospheric warming, etc.].

1.1 Meetings of National Crisis Management Committee (NCMC) and Union Home Secretary

On 7th February 2021 at 1630 hours, a meeting of NCMC under the chairpersonship of Cabinet Secretary was held, wherein all the concerned agencies were directed to work in close coordination and to extend all requisite assistance to the Uttarakhand State administration. This meeting was also attended by Shri Sanjeeva Kumar, Member Secretary, NDMA; Lt. Gen. Syed Ata Hasnain, Member, NDMA and Shri Rajendra Singh, Member, NDMA.

On 17th and 22nd February 2021, meetings were held under the chairpersonship of Union Home Secretary, Government of India to review the progress of search and rescue operations as well as to decide the future course of action on the artificial lake formed in Chamoli district, Uttarakhand.

1.2 Constitution of Joint Study of NDMA

Following a request by the Government of Uttarakhand, the Ministry of Home Affairs (MHA) requested National Disaster Management Authority (NDMA) to constitute an inter-disciplinary Study Team of experts. On 26th February 2021 based on the deliberation held in the meeting on 16th February 2021 with stakeholders, NDMA constituted a joint study team under the chairmanship of Lt. Gen. Syed Ata Hasnain, Member, NDMA, and co-chairmanship of Shri Rajendra Singh, Member, NDMA. The composition and other details of the joint study team are placed at **Annexure 1**.

The objectives of the study were to understand the causes of the debris flow in River Rishiganga–Dhauliganga, assess the impacts and suggest mitigation/preparedness measures to prevent such future events.

A rigorous consultation process with various stakeholders was undertaken. It included the Government of Uttarakhand, MHA, Ministry of Mines (MoM) /GSI, Ministry of Jal Shakti (MoJS)/CWC, India Meteorological Department (IMD), NIH-Roorkee, DGRE-DRDO, Wadia Institute of Himalayan Geology (WIHG), National Institute of Disaster Management (NIDM), IIT-Roorkee, National Remote Sensing Center (NRSC) - ISRO, Kashmir University, Tehri Hydro Dam Corporation India Limited (THDCIL), National Thermal Power Corporation (NTPC) and National Disaster Response Force (NDRF).

Representatives from Integrated Defence Staff (IDS-HQ), Ministry of Defence (MoD), Garhwal Scouts (Indian Army), National Technical Research Organisation (NTRO), Indo-Tibetan Border Police (ITBP), Nehru Institute of Mountaineering (NIM) Uttarkashi, National Center for Seismology (NCS)-Ministry of Earth Science (MoES) also participated in these deliberations.

Meetings with the above mentioned stakeholders were held pre and post-field visits on 16th February, 4th March, 15th March, 23rd March (in Dehradun), and 4th June 2021.

1.3 Objectives

The objectives of the joint study team of NDMA were:

(a) To understand the causes of the debris flow
(b) To assess the impact of the event
(c) To suggest mitigation/preparedness measures to prevent such future events

2. Description of Study area

2.1 Location

The source of the rock-fall/debris flow is located in the Raunthi glacier and the impact was felt across Dhauliganga-Rishiganga catchments in Chamoli district, Uttarakhand. Maximum elevation in the area is 7816m above mean sea level at Nandadevi Peak. The other high peaks are Lata (3848m), Bugyalpati (5188m), Trishul (7043m), Raunthi (6063m), etc. Dhauliganga and Rishiganga Rivers constitute the major drainage in the area. Raunthi Gadhera originates from the Raunthi glacier, which is a left-bank tributary of the Rishiganga River.

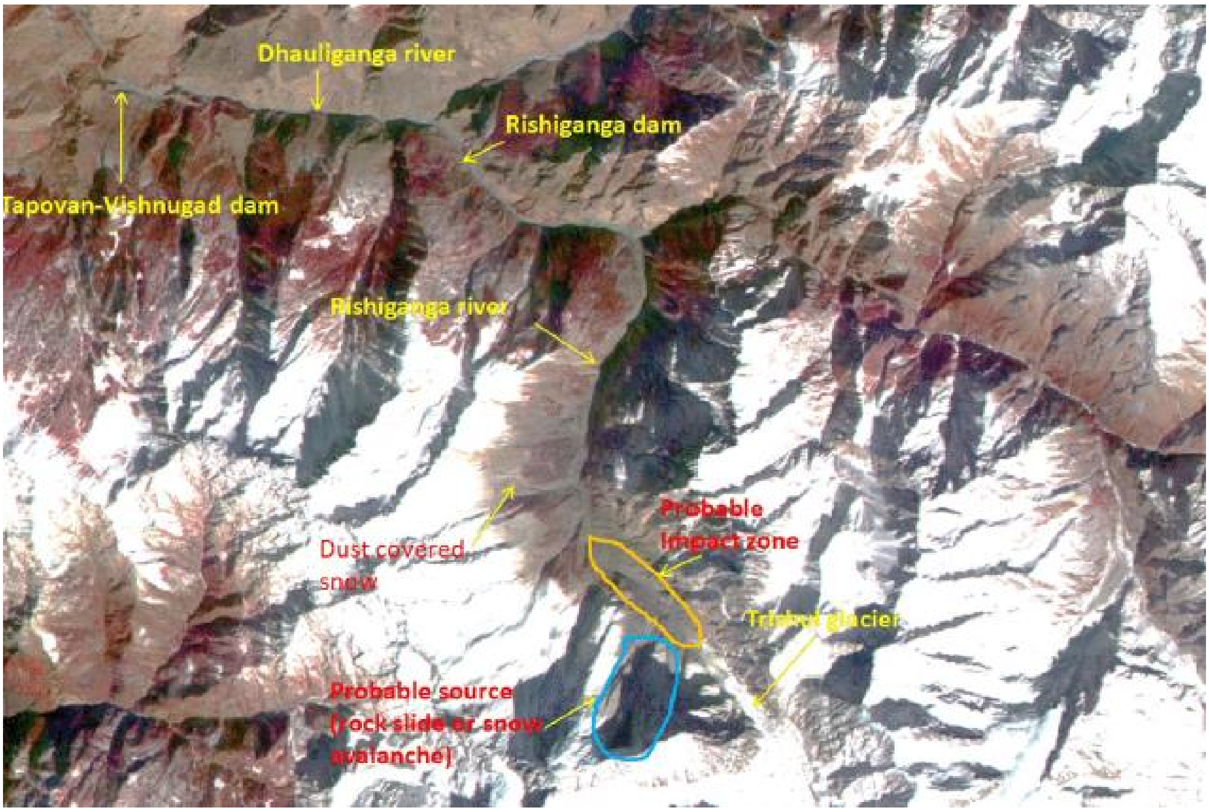

Figure 1: Location of rock slide displaced glacieret zone and affected catchment of Raunthi Gadhera, Rishiganga and Dhauliganga valley.

2.2 Geomorphology and Geology

Physiographically, the area exhibits glaciated terrain characterised by highly rugged mountainous topography in the form of sharp, angular, and serrated ridges, narrow spurs, and valleys with steep slopes.

Geologically, the rocks exposed in the source and affected areas of the recent debris flow in Chamoli district belong to the Central Crystalline Group (Figure 2). The Central Crystallines are of undifferentiated Proterozoic age and are classified into Mana Formation and Helang Formation. Source area and the plausible site of rock/snow/ice avalanche is represented by the rocks of Mana Formation. The Mana Formation (~Joshimath Formation) comprises streaky/ banded/ porphyroblastic/ augen gneiss, migmatite, kyanite-sillimanite bearing schist, and gneiss with pegmatite and quartz veins with lenticular bands of quartzite and marble. Some researchers have classified quartzite associated with garnetiferous mica-schist of Mana Formation as Pandukeshwar Formation. The Helang Formation consists of quartz-sericite schist, chlorite-mica schist, garnetiferous mica schist, porphyroblastic/ augen gneiss with thick bands of quartzite and marble. The Helang Formation has intrusive amphibolite.

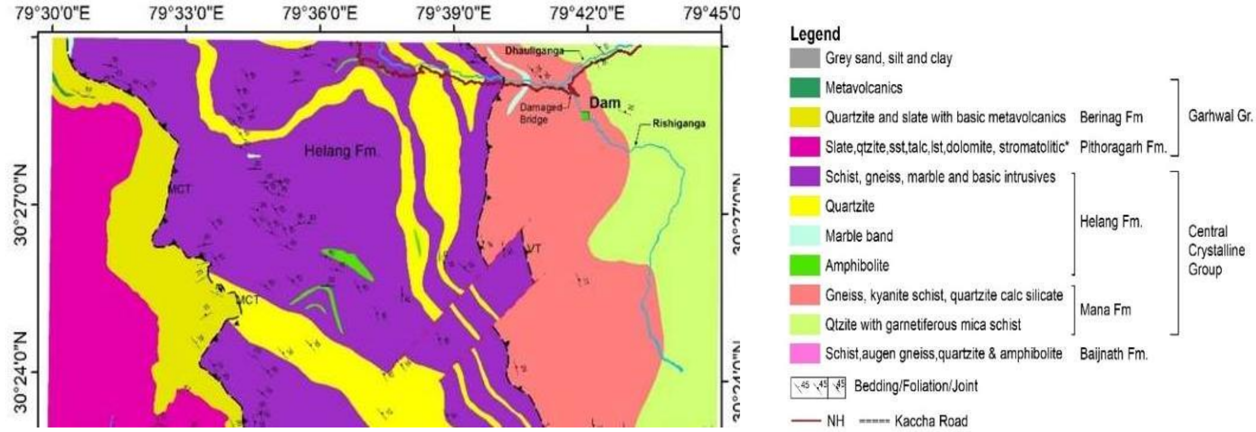

Figure 2: Geological map of the source and affected areas of the recent deluge in Rishiganga-Dhauliganga valley

(**Source:**https://bhukosh.gsi.gov.in/Bhukosh/Public)

The rocks in the area regionally trend NW-SE with moderate dips towards NE. The terrain has undergone complex structural deformation evidenced by major tectonic plates, viz. Main Central Thrust (MCT) separates the Central Crystalline Group from the Garhwal Group and Vaikrita Thrust separating Mana Formation from Helang Formation. Besides, several NE-SW trending faults have also been mapped by the Geological Survey of India (GSI) in the area. Three consistent sets of joints including foliation joints were observed in the rocks exposed in Rishiganga and Raunthi River valley.

The catchment is dominated by Higher Himalayan rugged topography with high elevation ridges adjacent to deep glacial valleys. The Raunthi is a compound valley type glacier formed by two tributary glaciers, extended between 4250m and 6500m MSL laying on 12° surface slope (Kumar et al., 2021). The salient features and geomorphological parameters of the Nanda Devi group of glaciers are given in**Table1** (Kumar et al., 2021).

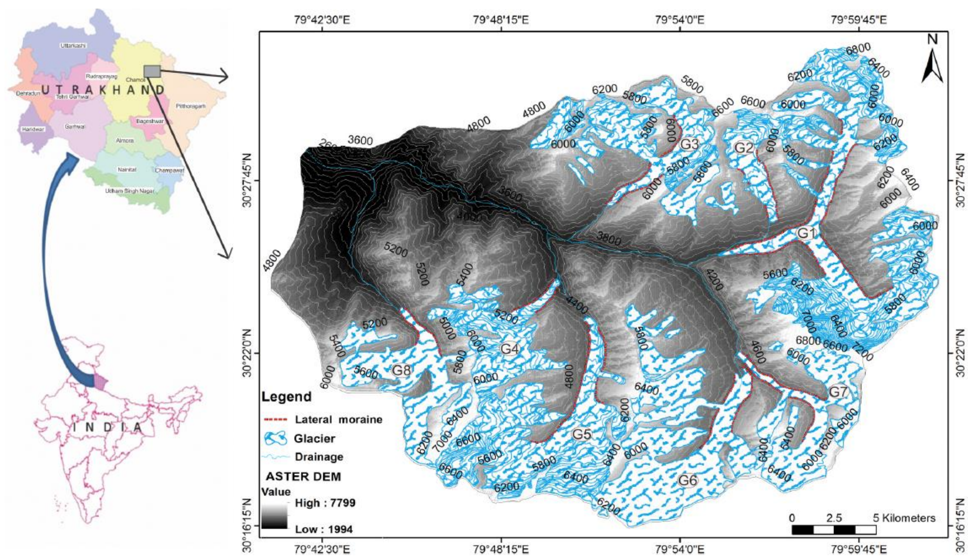

Figure 3: Topographic setting of the area in the background image of ASTER DEM, [red dash line indicating the lateral moraines of the glaciers in the Rishiganga catchment. G1- Uttari Nanda Devi Glacier, G2- Changbang Glacier, G3- Ramni

Glacier, G4- Bethartoli Glacier, G5- Trishul Glacier, G6- Dakshni Rishi Glacier, G7- Dakshni Nandadevi Glacier, and G8- Raunthi Glacier after Kumar et al. (2021)]

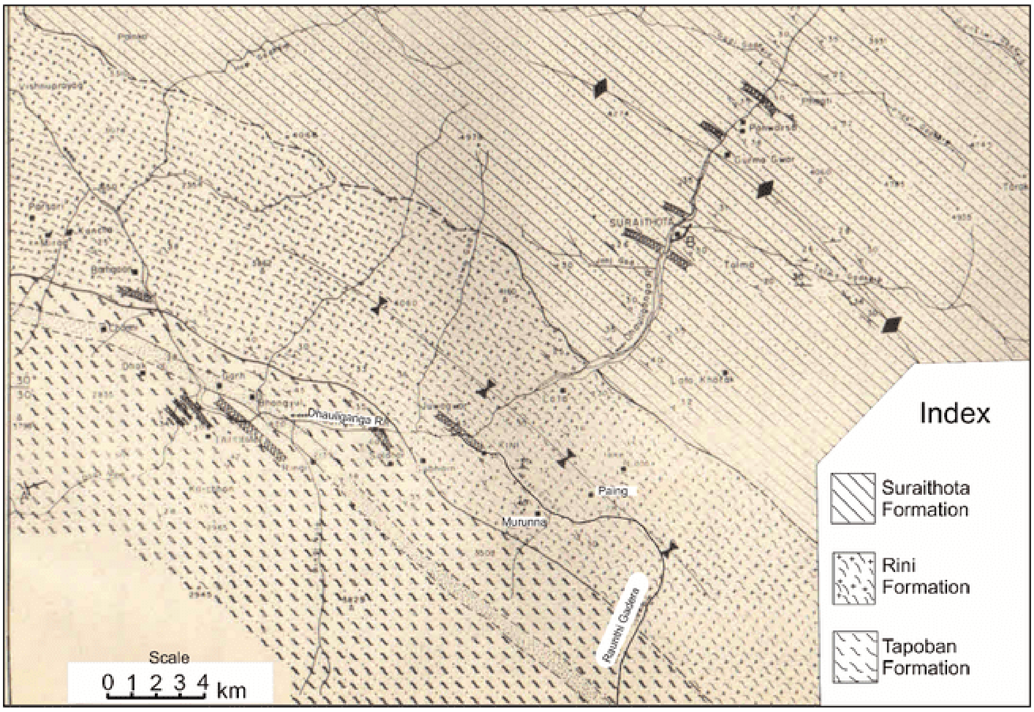

Figure 4: Geological map of the study area

Table 1: Salient features and geomorphological parameters of the Rishiganga Catchment glaciers (Kumar et al., 2021)

Parameters of glaciers	Glaciers Name							
	Uttari Nanda Devi (UND)	**Changbang**	**Ramni bank**	**Bethartoli**	**Trishul**	**Dakshni Nanda Devi (DND)**	**Dakshni Rishi Bank (DRB)**	**Raunthi bank**
Basin type	Compound	Simple	Compound	Compound	Compound	Compound	Simple	Simple
Length km	11.6	5.6	8.8	7.0	12.4	9.6	9.6	7.2
Mean width (km)	0.70	0.40	0.36	0.45	0.50	0.62	0.60	0.40
Orientation	NW	SE	SE	N	N	NW	NE	NW
Average surface slope (degree)	16	15	12	12	10	10	14	12
Elevation highest (m asl)	7700	6700	6400	6400	7000	6600	6700	6500
Elevation lowest (m asl)	4250	4850	4900	4080	4450	4500	4550	4250
General climate	Humid-temperate in summer and dry cold in winter (Kumar et al., 2017, 2020)	Similar	-	-	-	-	-	-

2.3 Glacial History of Rishiganga Valley

The debris flow event of 7th February 2021 originated in the upper glaciated reaches of Rishiganga valley with the source area being Raunthi River. The Rishiganga River originates near Tilchaunani where streams from Dakshni Rishi Gal and Uttar Rishi Gal join to constitute the Rishiganga River. It meets the Dhauliganga River near Raini village. As per the glacier inventory of GSI, the Rishiganga valley contains 52 glaciers having a total 21.24 cubic km ice volume (Sangewar and Shukla, 2009). Out of 52 glaciers in Rishiganga, 39 are mountain glaciers, 8 are valley glaciers and the rest five are glacieret/ snowfield. However, 85% the glaciers of Rishiganga valley are of smaller in size and fall in the category of mountain glaciers and glacierets. In Rishiganga valley, 26 glacial lakes have been identified by GSI. Amongst them, 18 are supra glacial lakes, five are right lateral moraine dammed lake, and three are left lateral moraine dammed lake. However, amongst the 13 most vulnerable glacial lakes identified so far by GSI in Uttarakhand that can cause GLOF (Glacial Lake Outburst Flood), none of them are present in Rishiganga valley.

2.4 River Systems & Hydrology

Dhauliganga - Rishiganga River system is a major tributary of the Alaknanda River. The river originates from an altitude of 5070m in the Niti Pass at Chamoli district of Uttarakhand. Rishiganga a tributary of Dhauliganga originates from the Uttari Nanda Devi glacier. It is also fed from Dakshina Nandadevi Glacier. The river passes through the Nandadavi National Park and joins Dhauliganga River near Raini village which is about 25km from Joshimath. Dhauliganga joins the Alaknanda River at Vishnuprayag, at the base of Joshimath Mountain in Uttarakhand. A catchment area map of Dhauliganga and Alaknanda rivers at Joshimathbridge located after the confluence of Dhauliganga and Alaknanda is shown in Figure 5.

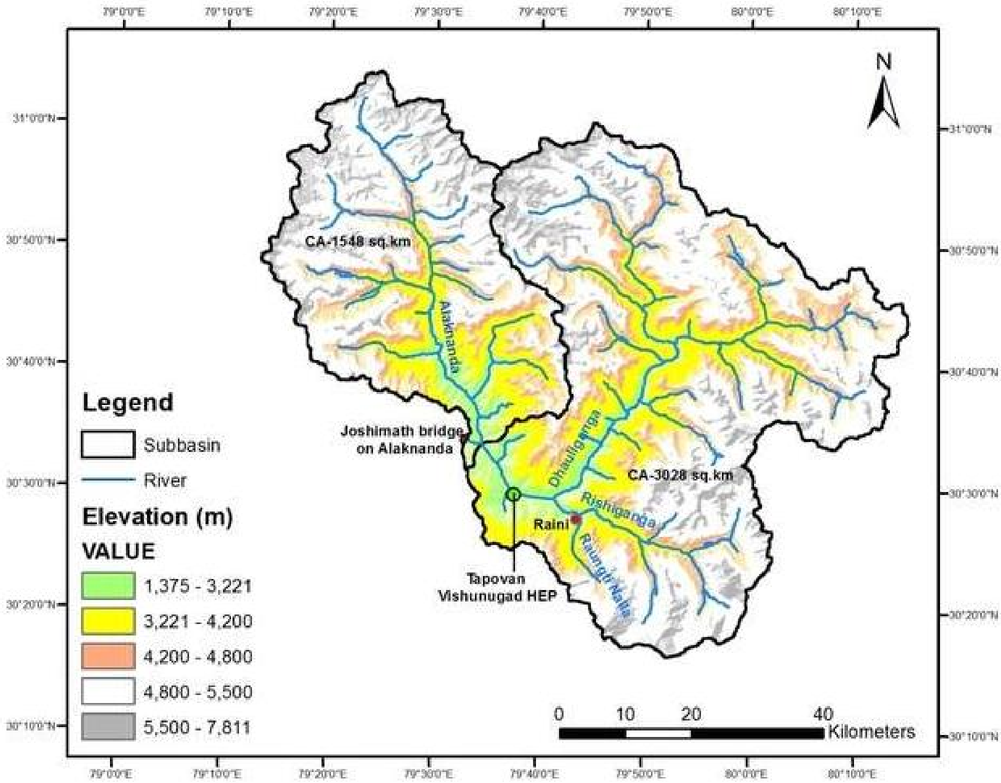

Figure 5: Catchment area map of Dhauliganga-Rishiganga and Alaknanda rivers along with the location of Raini village and TapovanVishnugad HEP

The total catchment area of Dhauliganga and Alaknanda rivers at Joshimath bridge as delineated from SRTM 30m DEM is about 4576 sq.km, out of which catchment area of Dhaulignga River is about 3028 sq.km at it's the confluence with Alaknanda and 2893 sq.km at Tapovan-Vishnugad HE Project. The catchment area of Rishiganga River at its confluence with the Dhauliganga River is about 689 sq.km. The catchment area of the Raunthi River at its confluence with Rishiganga is about 92.5 sq.km.

The total length of the Dhauliganga River along its longest flow path is about 113km whereas the bed elevation varies from 7570m to 1415m. The length of the river between bed elevation 5000m to 1415m is about 98 km. The bed profile of Dhauliganga River along its longest flow path is shown in Figure 6.

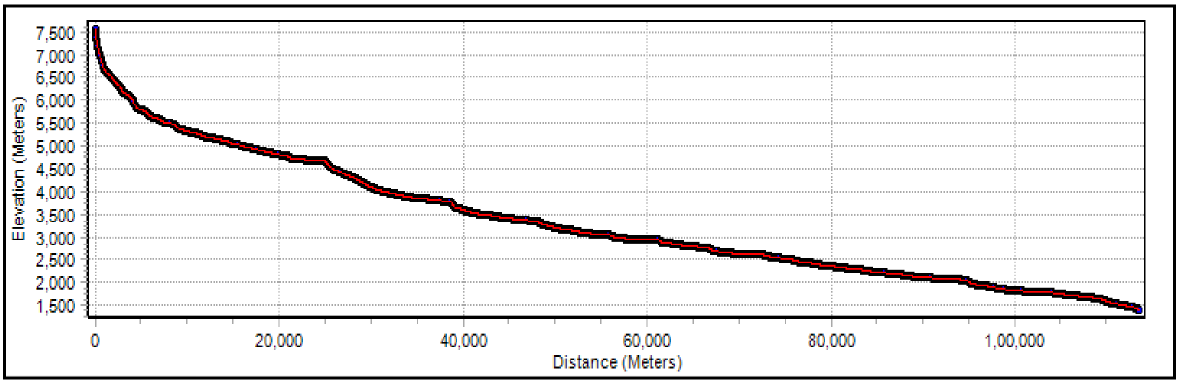

Figure 6: Bed profile of Dhauliganga river along its longest flow path

About 172 sq.km catchment area of Dhauliganga river lies above in elevation band 4500 m to 7570m, from which certain runoff comes into the river as snowmelt and glacier contributions.

2.4.1 Discharge Data Analysis

Central Water Commission is maintaining a Gauge & Discharge (G&D) site at Joshimath bridge (catchment area 4576 sq.km) where discharge data of Alaknanda and Dhaliganga is available since the year 1971. NTPC is also observing the discharge data of Dhauliganga river at its Tapovan-Vishnugad HE Project barrage site (catchment area 2893 sq.km) since the year 2010. The 44 years average, maximum, and minimum monthly discharge at Joshimath G&D site of CWC and 11-year average, maximum and minimum monthly discharge at Tapovan barrage site of NTPC is given in **Table 2** and **3** respectively.

Table 2: 44-years average, maximum and minimum monthly discharge at Joshimath G&D site of CWC

Month	Discharge (cumec)		
	Average	Maximum	Minimum
Jan	34.75	85.39	10.19
Feb	32.63	83.27	9.38
Mar	36.56	81.50	15.38
Apr	61.44	119.56	24.10
May	152.21	312.79	54.13
Jun	315.20	656.06	135.06
Jul	458.71	1207.98	198.32
Aug	424.30	1142.15	150.08
Sep	261.55	1023.68	75.63
Oct	128.70	888.79	18.14
Nov	75.35	577.95	19.95
Dec	48.87	302.71	18.09

Table 3: 11-year average, maximum and minimum monthly discharge at TapovanVishnugad barrage site of NTPC

Month	Discharge (cumec)		
	Average	Maximum	Minimum
Jan	19.09	26.20	15.95
Feb	18.76	25.40	16.00
Mar	21.33	29.08	16.23
Apr	35.38	56.86	19.61
May	80.32	128.20	44.05
Jun	143.29	207.36	103.27
Jul	205.61	284.49	161.14
Aug	202.90	329.04	149.06
Sep	133.62	249.92	90.79
Oct	68.26	126.79	46.91
Nov	32.03	40.29	26.55
Dec	27.36	69.74	18.33

From the above data, it can be said that the significant discharge in the river is during May to October due to pre-monsoon and monsoon precipitation along with snow and glacial melt. From November to April, the discharge in the river is from base flow, snow, and glacial melt.

2.4.2 Observed Flood Peaks Analysis

The daily observed discharge data of Joshimath G&D site of Central Water Commission (CWC), MoJS, and the Tapovan-Vishnugad barrage site of NTPC have also been analysed for annual maximum flood during each year. The observed annual flood peaks at the Joshimath G&D site are given in Table4. The observed yearly peak data of Tapovan-Vishnugad barrage site is given in Table 5.

From the peak discharge data of the Joshimath G&D site, it has been found that the maximum observed flood before February 2021 event at the above G&D site was about 1630 cumec on 27.06.1998.

The peak discharge data of the Tapovan-Vishnugad barrage site shows that the maximum observed flood before February 2021 event at the above location was about 429 cumec on 22nd August 2010.

Table 4: Yearly peak discharge at Joshimath G&D site of CWC

Year	Peak discharge (cumec)	Date of occurrence
1971	356	22/06/1971
1972	391.02	15/09/1972
1973	354.45	13/06/1973
1974	603.58	24/07/1974
1975	846.53	20/07/1975
1976	679.62	27/07/1976
1977	756.31	04/08/1977
1978	731.01	06/08/1978
1979	678.1	30/06/1979
1980	851.47	12/07/1980
1981	481.84	23/07/1981
1982	544.12	10/08/1982
1983	840.87	20/08/1983

Year	Peak discharge (cumec)	Date of occurrence
1984	633.54	19/06/1984
1985	600.36	17/07/1985
1986	1044.9	27/07/1986
1987	911.91	26/07/1987
1988	937.7	24/07/1988
1989	723.73	30/07/1989
1990	749.09	01/07/1990
1991	659.59	21/07/1991
1992	522.63	22/07/1992
1993	468.61	18/07/1993
1994	776.14	20/07/1994
1995	824.47	03/08/1995
1996	731.38	06/08/1996
1997	677.08	29/07/1997
1998	**1630**	**27/06/1998**
1999	584.58	19/06/1999
2000	890	31/07/2000
2001	959.82	26/07/2001
2002	669.62	04/08/2002
2003	668.41	27/08/2003
2004	581.99	09/08/2004
2005	758	03/08/2005
2006	567.21	09/07/2006
2007	535.71	15/07/2007
2008	421	12/07/2008
2009	758.55	13/08/2009
2010	585.64	20/07/2010
2011	493.13	28/06/2011
2012	695.54	04/08/2012
2013	1378.14	27/06/2013
2014	681.64	22/06/2014
2015	754.51	02/07/2015
2016	616.66	16/07/2016
2017	679.42	31/07/2017
2018	734.18	26/07/2018
2019	815.88	03/08/2019

Table 5: Yearly peak discharge at Tapovan-Vishnugad barrage site of NTPC

Year	Peak discharge (cumec)	Date of occurrence
2010	**429.17**	**22.08.2010**
2011	321.98	12.08.2011
2012	381.56	31.07.2012
2013	322.52	17.06.2013
2014	221.49	01.08.2014
2015	198.63	11.07.2015
2016	320.24	16.07.2016
2017	210.14	18.07.2017
2018	230.36	28.07.2018
2019	213.84	15.08.2019
2020	206.78	13.08.2020

2.5 Climate and Weather

2.5.1 Rainfall Climatology of Uttarakhand

Uttarakhand receives around 79% of the total annual rainfall in 4 months of the monsoon season (June to September). The annual average rainfall of Uttarakhand is 1494 mm. The Chamoli district experiences the second-lowest amount of annual rainfall with an average annual rainfall of about 1139 mm and the Pithoragarh district experiences the highest annual rainfall of about 1968 mm. District-wise average annual rainfall of Uttarakhand is depicted in Figure 7.

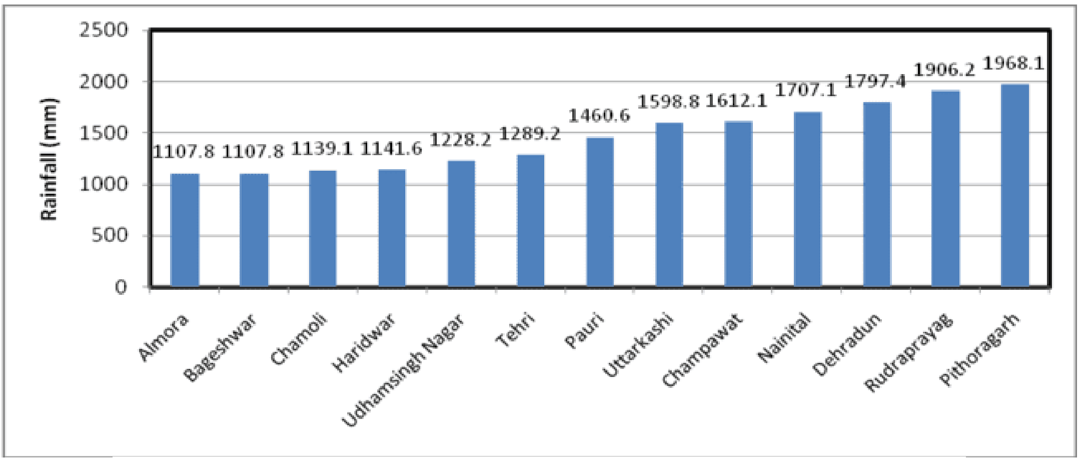

Figure 7: District-wise average annual rainfall of Uttarakhand. **(Source:** IMD**)**

From December to April the Chamoli district receives around 20 to 35% more rainfall than the state average due to the passage of Western Disturbances, whereas during monsoon season it experiences 30 to 43% lesser rainfall. Month-wise average rainfall of Uttarakhand and Chamoli district is shown in Figure 8.

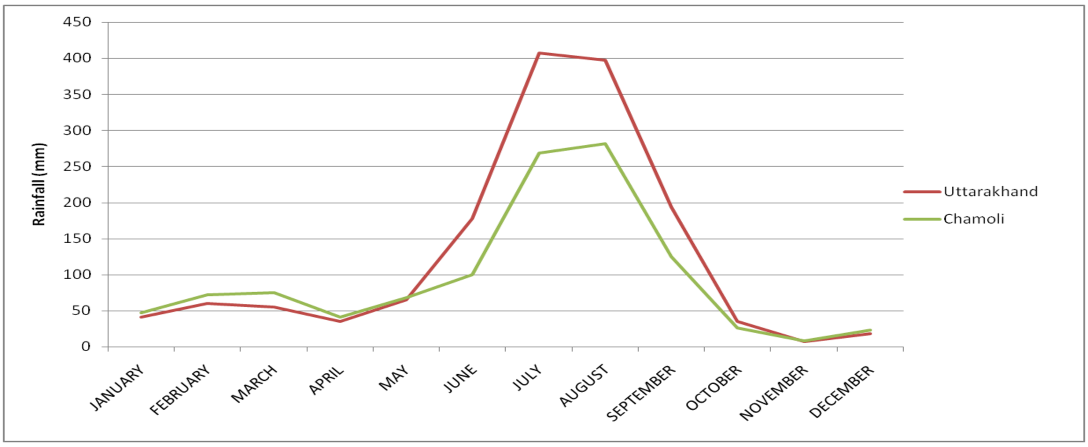

Figure 8: Month-wise average rainfall of Uttarakhand and Chamoli district. **(Source:** IMD**)**

2.5.2 Weather Activity in Chamoli District During the First Week of February 2021

Very light to light rainfall was reported in the Chamoli district of Uttarakhand from 4th to 6th February 2021. The highest rainfall was reported on 5th February which corresponds to the 24-hour accumulated rainfall between 08:30 IST of 4th February and 08:30 IST of 5th February. The 24-hour accumulated rainfall reported at different stations in Chamoli district from 1st to 7th February 2021 is given in **Table 6**.

Table 6: Rainfall at different rain gauge stations of Chamoli district during 1st -7th February 2021

Date / Station	01/02/2021	02/02/2021	03/02/2021	04/02/2021	05/02/2021	06/02/2021	07/02/2021
CHAMOLI	0.0	0.0	0.0	0.2	9.2	0.0	0.0
GAIRSAIN	0.0	0.0	0.0	7.0	12.0	0.0	0.0
JOSHIMATH	0.0	0.0	0.0	3.6	10.0	0.0	0.0
KARNAPRAYAG	0.0	0.0	0.0	0.0	11.2	1.6	0.0
THARALI	0.0	0.0	0.0	0.5	8.5	0.0	0.0
TAPOVAN (AWS)	0.0	0.0	0.0	2.5	6.0	0.0	0.0

The long period average (LPA) rainfall for Chamoli district for January is 47.1 mm and the monthly total precipitation observed during January 2021 was 32.7 mm with a departure of -30% from LPA.

2.5.3 Weather Monitoring and Observational Network in Uttarakhand

The Indian Meteorological Department (IMD) has 6 departmental and 4 part-time surface field observatories in Uttarakhand. There are 71 daily rainfall measuring stations in Uttarakhand. The state has a network of 132 Automatic Weather Stations (AWS) (25 IMD and 107 Uttarakhand Government) and 49 Automatic Rain Gauge stations (ARG) (21 IMD and 28 Uttarakhand Govt.) as depicted in Figure 9. For upper-air observations, there is one Radiosonde/ Radio wind station in Dehradun. One x-band Doppler weather radar is installed in Mukteshwar, Nainital.

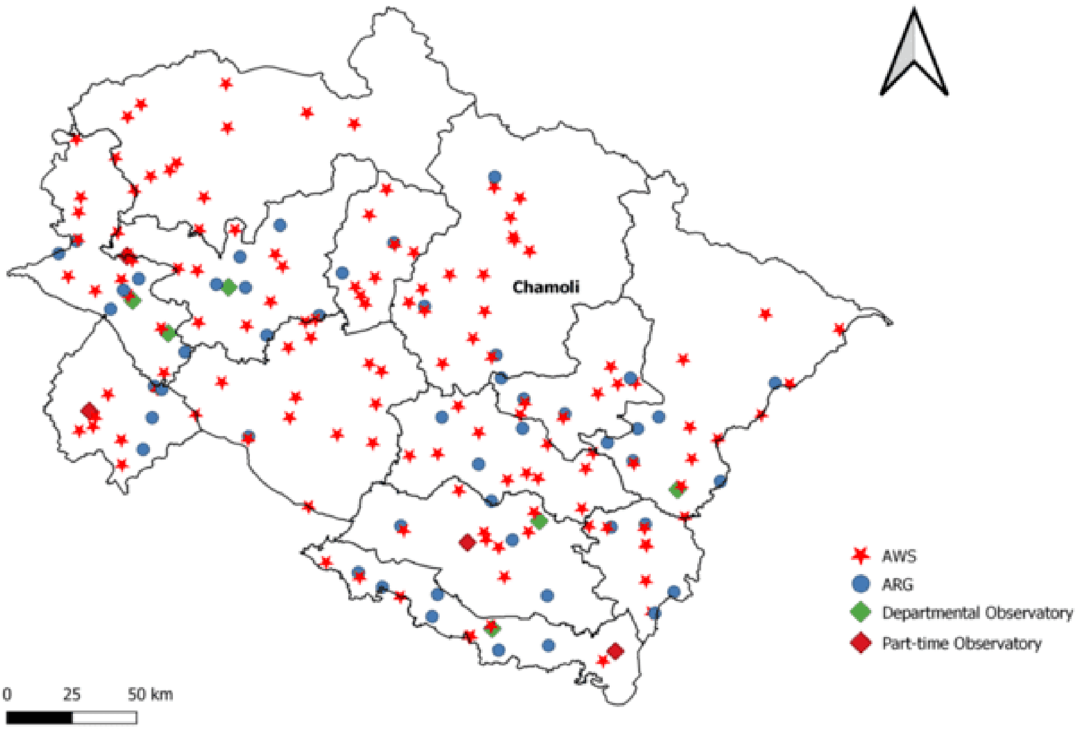

Figure 9: Surface observatory network of IMD and Uttarakhand State Government **(Source:** IMD**)**

2.5.4 Forecasting Services

a) District level weather forecast and warnings for five days with an outlook for another two days for Uttarakhand are being issued thrice daily by Meteorological Center Dehradun.

b) District-level Nowcast for all districts and location-specific Nowcast for 35 locations are being issued at 3 hourly intervals.

c) Current weather observation and forecast of seven days for 26 cities are being issued daily.

d) District-wise agro-meteorological advisory bulletin and value-added weather forecast of different weather parameters like maximum & minimum temperature, relative humidity, wind speed & direction, cloud cover, and rainfall for the next 5 days are being issued every Tuesday and Friday.

e) Weather Forecast for 7-days and 3-hourly Nowcast for Char Dham and Mansarovar Yatra during the Pilgrimage period.

f) Special press releases on expected severe weather in Uttarakhand, as and when required.

g) Extended range forecasts for two weeks are issued every Thursday.

h) For search and rescue operations, a special forecast for Joshimath/Tapovan area has been started from 7th February 2021.

i) Special forecasts are issued for occasions like Flower festival, Skiing Championship, assembly sessions, general elections, etc.

The Forecast and Warnings are Disseminated Through:

- National IMD website (https://mausam.imd.gov.in) and MC, Dehradun's website (https://rmcnewdelhi.imd.gov.in/MET_CENTRES/MCDDN).
- Emails, Social Media (Facebook & Twitter handles), and WhatsApp Groups.
- Electronic and Print media.
- Multi-media messages are generated for dissemination to the general public for awareness and mitigation measures.

2.5.5 General Climate of the Study Area

The general climate of the study area is humid-temperate in summer and dry-cold during winter. The area gets precipitation through Indian Summer Monsoon (ISM) in the summer months (May–September) and western disturbance in winter (November–February) (Kumar et al., 2017, 2020, b). Kumar et al., (2021) used different data sets representing average annual meteorological parameters for the study area. The local temperature and precipitation variability were assessed through Climate Research Unit (CRU) TS3.22 dataset, (on a 0.5-degrees latitude-longitude grid; 30° 00' - 30°25' N to 79° 30' - 80° 00', 1901–2017 CE), and correlated with the annual trend of average climatic conditions of the study area (Figure 10).

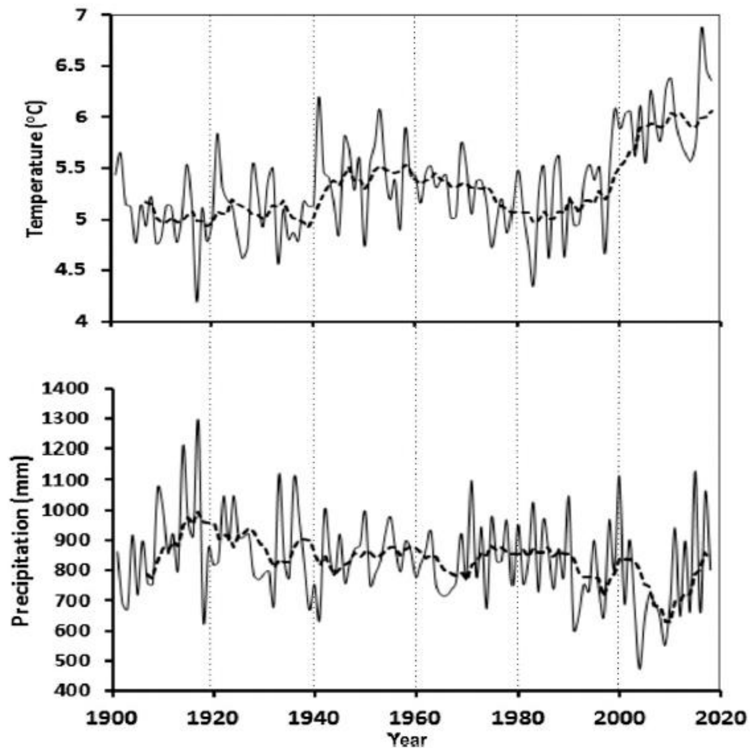

Figure 10: Climate Research Unit (CRU) TS.3.22 (on a 0.5◦ latitude-longitude grid) average yearly temperature (◦ C) and total annual precipitation (mm) recorded for 1901–2017 (N 30.25 and E 79.75) showing long-term variability in the regional climatic trends at studied region (**Source:** Kumar et al., 2021).

2.6 Hazard Profile

Eight major glacier systems exist under Nanda Devi mountain systems. These glaciers feed River Raunthi Gadhera, Rishiganga, Dhauliganga as shown in Figure 3. There is a total of 16 river basin systems in the Chamoli district, Uttarakhand. River Alaknanda is the main river in the Chamoli having a length of 195 km and the basin area is about 10,882 sq km.

The study area has fragile geo-tectonic orogeny and comes under an eco-sensitive glacial system of Nanda Devi. Owing to its proximity to Main Central Thrust (MCT) which is the most active seismic zone and vulnerable to different kinds of hazards such as landslide, avalanche, Glacial Lake Outburst Flood (GLOF), Landslide Lake Outburst Floods (LLOF), cloud burst, debris flow, flash floods, earthquakes, etc.

During the 2013 cloud burst event, a flash flood was triggered in the Alaknanda River catchment causing huge losses to life and the economy. The study area is found susceptible from the point of avalanches, landslide, cloud burst, debris flow, flash floods, Glacial Lake Outburst Flood (GLOF), Landslide Lake Outburst Floods (LLOFs), earthquake etc.

There are many operational dams and Hydro Electric Projects (HEP) in the Alaknanda basin namely Tapovan, Rishiganga Tharali, Vishnuprayag, Srinagar, etc. In addition to these, more HEPs have been planned and are under construction like Kaliganga, Singoli, Bhatwari, etc. There are around 23 Hydel projects in the basin including Alaknanda (Badrinath), Nandprayag Langasu, Lata Tapovan, Devsari Dam, Vishnugad, Pipalkoti, etc. (**http://www.cwc.gov.in/ugbo/gangabasin/alaknanda**).

3. Observations and Findings

3.1 Field Observations on Damages & Losses

Based on the helicopter-recce observations, field visit and analysis of remote sensing data, the team discussed the possible causes of the event and concluded the following:

Table 7: Event Characteristics

SN	Parameters	Data
1	**State**	Uttarakhand
2	**Block, District**	Joshimath, Chamoli
3	**Location**	Raunthi peak (6063m) part of Raunthi glacier
4	**Geographic Coordinates of source area (Lat., Long., Altitude), SoI Toposheet No.**	30° 22' 27.38"N, 79° 43' 52.03"E; 5474m; SoI toposheet no. 53N/11
5	**Date, Day & Time**	07.02.2021, Sunday, ~10.08:45 hours
6	**Duration of event**	~50 minutes (From 10:08:45 hrs to 10:58:35 hours)
7	**Volume of rock and glacier mass from source area**	~29.3 Millionm^3
8	**Velocity of debris flow**	~10.6 m s^{-1}
9	**Height of debris overriding on the opposite slope**	~285m above the valley floor

At the beginning of field visit, the team considered six different hypotheses related to the cause of the event. These hypotheses were proposed by different researchers as mentioned in Table 8. These hypotheses were examined during the field observations and findings w.r.t to each of the hypothesis are reported as under:

Table 8: Hypotheses examined during field visit

Hypothesis -1	Hypothesis -2	Hypothesis -3	Hypothesis -4	Hypothesis -5	Hypothesis –6
GLOF or LLOF	Sub-glacial/ Supra glacial Lake outburst	Landslide + Snow avalanche	**Rock Slide along with dislodgement of Hanging glacieriet (Ice + rock + Snow), followed with river blockade and debris flow**	Any other water storage in the catchment	Hybrid event??
No Evidence	No Evidence	Yes/No	**Yes**	No Evidence	Possible

The incident led to adverse consequences in the form of damages and losses to the economy, infrastructure, and society. The impact included damages and losses to power projects, bridges, houses, infrastructure, and environment as given in Table 9.

Table 9: Impact and Damage Characteristics

SN	Parameters	Data
1	**Damages to projects**	Rishiganga Hydro Project (13.2MW) & NTPC Hydro Power project (520MW)
2	**Damage of Roads (Access routes) and bridges**	BRO Motor bridge on NH-7 at Raini washed away. 5 suspension bridges washed away.
3	**Number of affected villages**	13 villages (Paing, Murranda, Jugju, Juwagwad, Raini Chak Lata, Raini Chak Subhai, Bhangule, Gahar, Tapovan, Ringi, Subhai including Tok) due to damage of utililty supply lines [Electricity and water)
4	**Human Lives lost**	~204 died / missing (Bodies recovered: 80; Missing: 124)
5	**Animal & Livestock lost**	**Dead Animals** -03 (02 Goat, 01 Cow) **Missing Animals** – 186 (02 Cow, 04 Mule, 180 Goat)
6	**Damage to Buildings**	1 Temple & 1 pucca House at Raini Chak Lata
7	**Psycho-social impact**	Fear and panic amongst affected families. Trauma particularly for those families who lost their earning members. The affected families also lost their sources of regular income.
8	**Volume of Debris Dammed Lake**	0.219MCM of lake water **(Impending Risk)**

3.1.1 Chronology of Event (Time Stamping)

Time stamping of the event was deduced from satellite-based observation and validated during the fieldwork at NTPC barrage, THDC barrage, and CWC gauge station near Vishnuprayag. The details of the same are as under:

Table 10: Time stamping and sequence of event

SN	Time Stamping	Sequence of Event
1	**A few minutes before ~10:08:45 hrs**	• Glacieret ice and rock slide happened due to dislodging of triangular shape rock mass due to wedge / planar failure along week joints plane. • Vertical fall around ~1740m of rock and ice mass of ~29.3 MCM created air blast and dust cloud formation near the crash zone. • The high energy impact pulverized the rock and ice and created an air blast that snapped and uprooted trees up to 3.2 km on the downstream direction. The air blast also created dust clouds which settled on the snow cover on the downstream side. The debris also bounced to the top of the mountain in the opposite side of the valley up to a height ~285m above the crash zone.
2	**~10:08:45 hrs**	• Debris flow started downstream from the crash zone and the flow velocity is ~10.6 m/sec. As the slush moved down, it created more heat to melt

SN	Time Stamping	Sequence of Event
		ice, and mobility of debris further increased due to entrainment. The majority of slush flowed downstream but left a chunk of debris in the valley resulting in the formation of an unstable landslide debris dam near the crash zone in the Raunthi Gadhera, which is vulnerable in the future. Currently, there is little impoundment, however, this may increase further during summer due to snow melt.
3	~**10:18:43 hrs**	• Debris blocked Rishiganga at the confluence of Raunthi and Rishiganga and an artificial lake was formed thereafter. Currently, water is flowing over the landslide dam through a channel.
4	~**10:31:51 hrs**	• Active rock avalanche continued, and a thick dust cloud is seen along the rock avalanche path and at the crash zone.
5	**~10:36:00 hrs**	• Debris flow reached the Dhauliganga river and subsequently buried the Tapovan-Vishnugad hydel project of NTPC.
6	~**10:58:35hrs**	• Thin dust cloud was seen near the crown, and no dust cloud was seen at the crash zone indicating that the rock avalanche had subsided. The duration of rock avalanching was **~50 minutes.**
7	~**11:19:00 hrs**	• Debris flow reached Vishnugad-Pipalkoti barrage of THDC.

Photo Plate 1: Before and after images of the Rishiganga HEP

Photo Plate 2: Remnants of damage BRO motor bridge withbailley bridge constructed by BRO for vehicular movement on Joshimath – Malari road after the event

Photo Plate 3: House which was affected. Villagers rescued three girls who were stuck inside the house

Photo Plate 4: Before & after image of NTPC Tapovan-Vishnugad HEP

Photo Plate 5: Damaged barrage of NTPC Tapovan-Vishnugad HEP

Photo Plate 6: Outside of the intake Adit tunnel with HFL of 1801 m with submerged inside of the HRT intake adit

The impact and damage due to the debris flow event were assessed on the basis of the field visit and satellite images are listed as under:

- The **13.2 MW** Rishiganga Hydro-power project near Raini operationalized by Rishi Ganga Power Corporation Limited has been destroyed.
- Excessive deposition of sediment in the river channel, resulting in the rise of river bed level by approximately 2 m to 12 m in the affected streams
- Approach road and BRO bridge at Raini village have been washed away
- NTPC hydro-electric power project (520 MW) under construction phase has been adversely affected (sediment deposition in desilting tanks, HRT and ADIT tunnels filled with thick debris, 11-13 m debris deposition around the Tapovan plant, damage to sluices gates, and other structures).
- Five suspension bridges have been washed away
- Damage to the service roads on either side of the river Dhauliganga
- Some of the residential buildings and a temple close to the banks of the rivers have also been destroyed by the debris flow
- **Affected villages:** 13 villages were affected due to damage to utility supply lines (electricity, water, and bridges)

- Significant loss to lives (workers working in Rishiganga and NTPC hydropower projects)
- **Total missing persons:** 204 [Bodies recovered: 80 (Identified: 48; Unidentified: 32)]
- **Domestic Animal loss:** 186 [Small animals (e.g., Goat) from village Juwagwad: 180 and Big animals (e.g., Cow, Mule) from village Paing: 4]
- The livelihood of the local population, particularly the labour class, has been affected
- The event has also had psycho-social impacts on the population due to the loss of their near and dear ones as well as earning members of their families. The non-recovery of the missing persons is also a cause of panic and confusion amongst the affected families. The local population is concerned about any future flooding event that may be caused by the bursting of the newly formed debris-dammed lake in Rishiganga river.

3.1.2 Impact Assessment through Satellites and Remote Sensing

NRSC, ISRO has made all the efforts to capture the disaster event by tasking high-resolution Indian Remote Sensing Satellites and analysing the satellite images to assess the impact of the disaster in the catchment areas of both Dhauliganga and Rishiganga valleys. In addition to the existing satellites, ISRO has also activated the International Charter for continuous and synoptic coverage of the event.

The impact of the disaster on the NTPC Tapovan plant, which has suffered significant damages to infrastructure is highlighted in Green and Red ellipses are depicted in Figure 11. The Green colour highlights the damages to the barrage and desilting tanks which were submerged in the thick slush and the Red colour highlights the bridge washed away in the deluge.

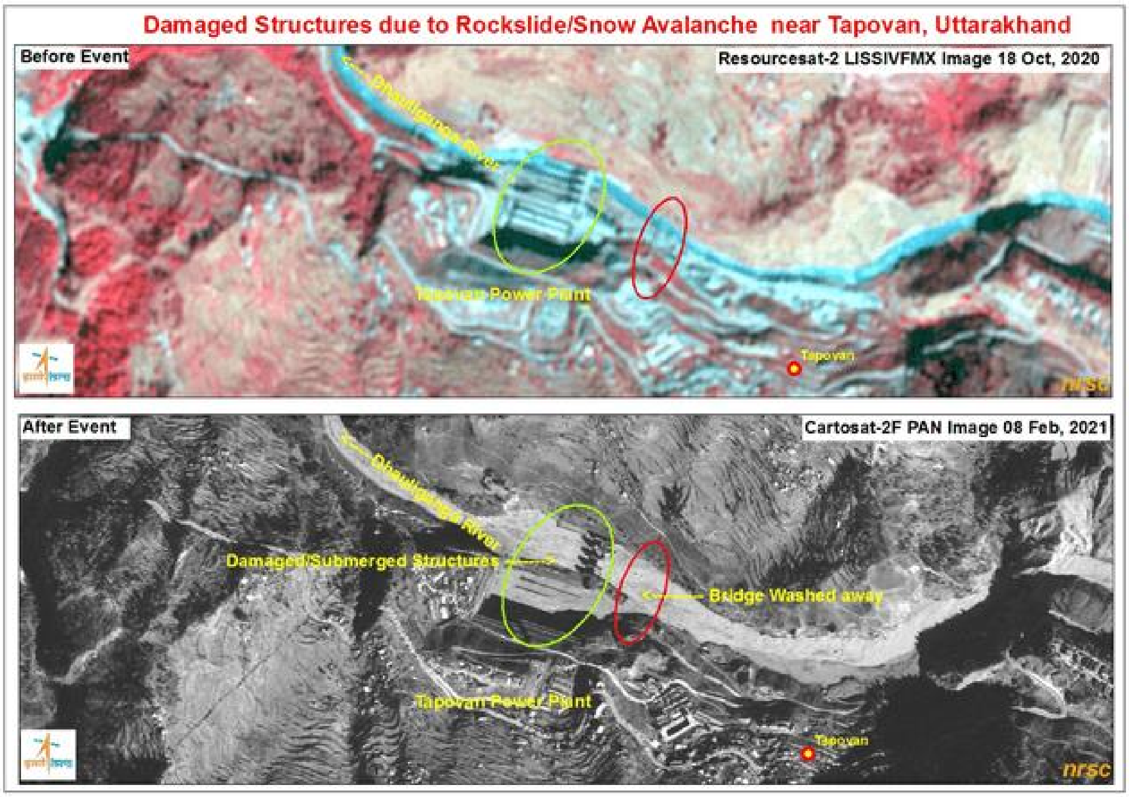

Figure 11: Damage to NTPC Tapovan as viewed from Indian Remote Sensing Satellites **(Source:** NRSC-ISRO**)**

Further, Figure 12 is the zoomed view of the Tapovan plant showing the damages to the structure as viewed by Cartosat 2 series on 9th February 2021.

Based on Figure 11 and 12 the following observations can be made:

1. Damage to NTPC sluice structures due to sediment deposits is visible
2. Damage to the service lanes on either side of the river Dhauliganga
3. Extensive deposits of sediment are seen in the river channel
4. Bridge before the dam has been washed out

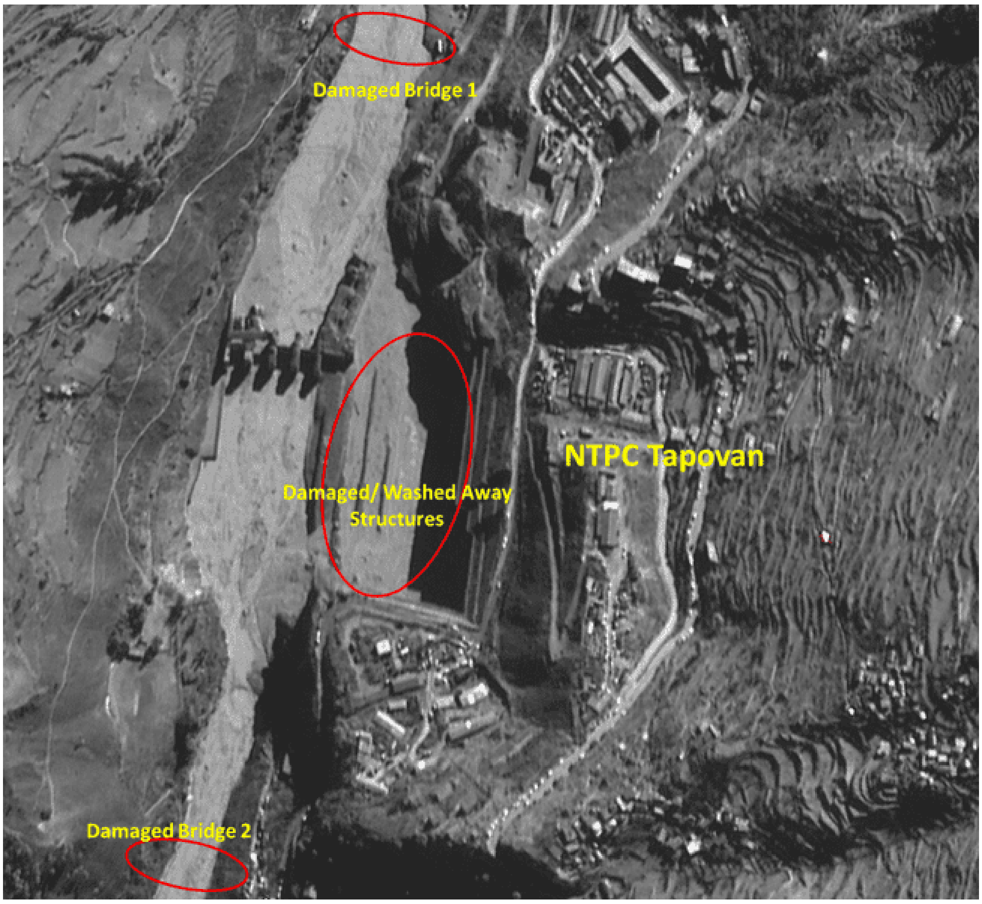

Figure 12: Zoomed view of Tapovan plant as viewed by Cartosat2 series on 9th February 2021
(Source: NRSC-ISRO**)**

The field visit carried out on 26th – 27th March 2021 has enabled us to validate the damages to the infrastructure which were depicted in satellite images. It was also observed that desilting tanks, ADIT tunnels in the NPTC were completely covered with thick slush and sediment/slush deposits; deposits ranging from 11 to 13 meters were deposited in the Tapovan plant as of 27th March 2021.

Figure 13 highlights the damages to the bridge connecting the left and right banks of the Dhauliganga. It was the only road bridge connecting two river banks that were washed away. This is highlighted with a yellow dotted line. The post-disaster image also shows the service roads washed away at the left bank of the Dhauliganga River causing significant damages to the infrastructure.

During the field visit on 26th and 27th March 2021, it was observed that huge boulders and sediment deposits to the tune of more than 20 meters were deposited and washed away the 13.5 MW Rishiganga power house.

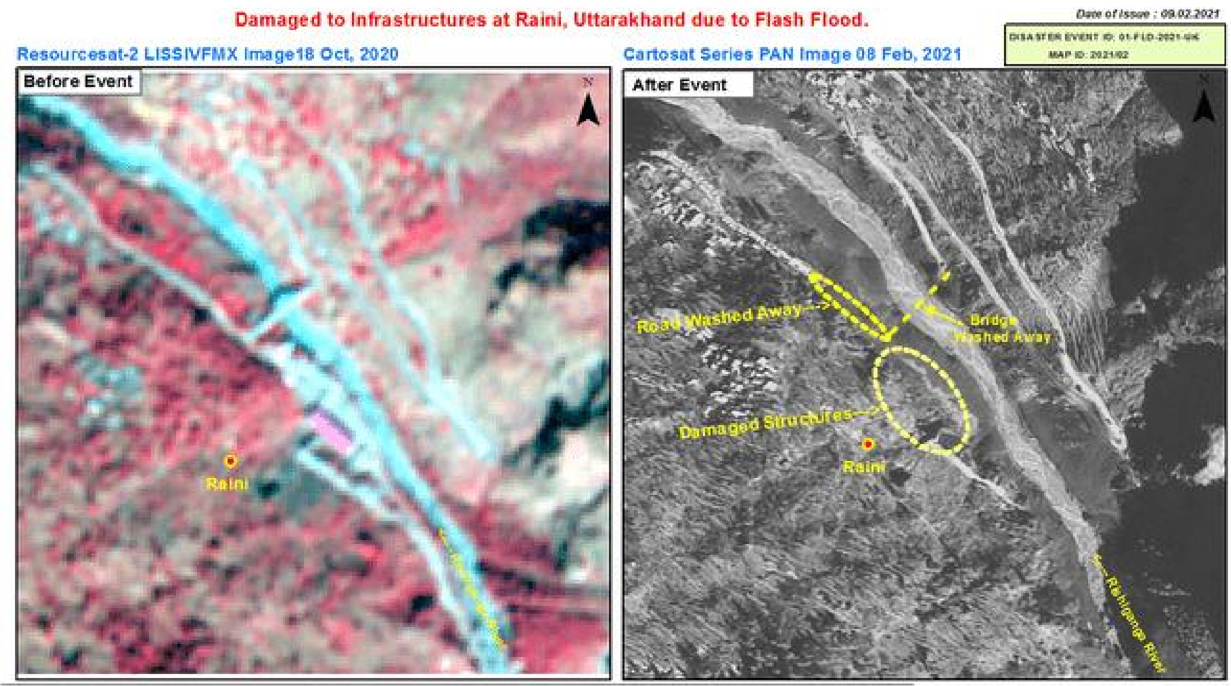

Figure 13: Infrastructure damage at Raini Village (CARTOSAT 2F on 8th February 2021)
(Source: NRSC-ISRO**)**

Figures 13 and 14 depict the damages to infrastructure in Tapovan, Mirg, Raini locations as viewed by high-resolution satellite data.

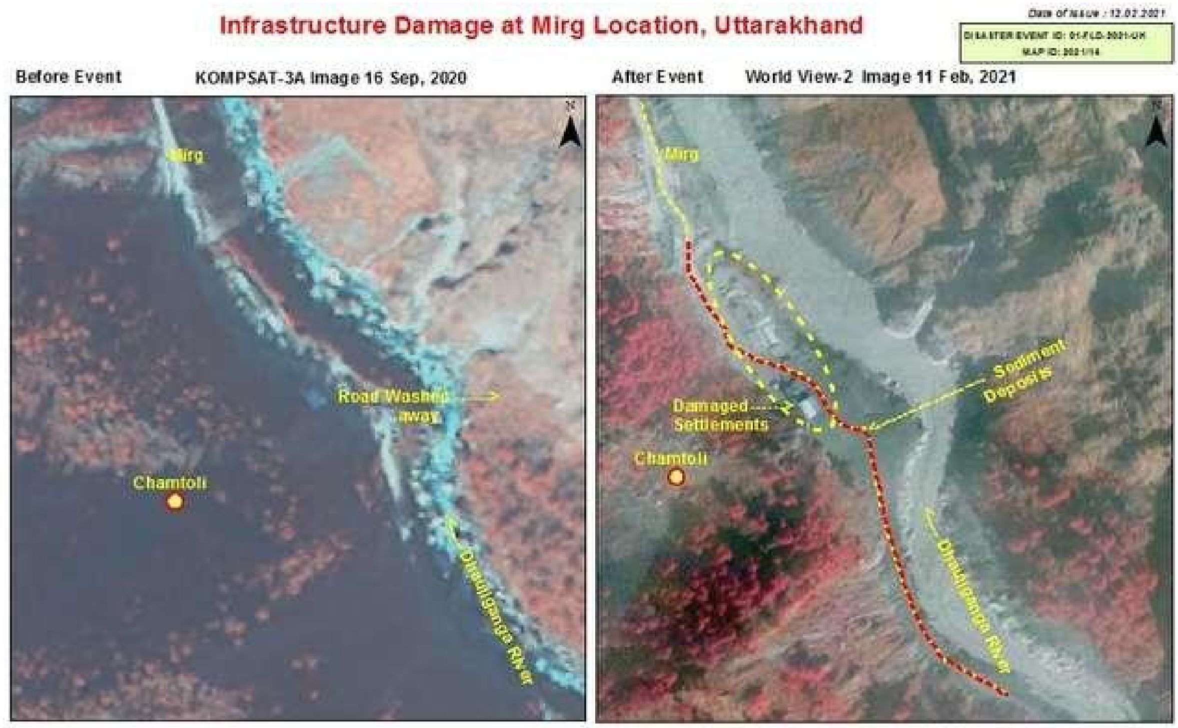

Figure 14: Damages to infrastructure in Mirg as on 11th February 2021
(Source: NRSC-ISRO**)**

Figure 15: Damages to bridges and increased channel width in Tapovan Upstream
(Source: NRSC-ISRO**)**

3.2 Detailed Study of the Event

The event has been studied in detail during the field visit by the Joint Study Team and the same has been described here as below.

3.2.1 Source Area of the Event

The main source of this disaster was a rock avalanche. The crown of the rock avalanche that triggered cascading effect in downstream areas, is located at 5474 m height and longitude 79° 43' 52.03" E and latitude 30° 22' 27.38" N. The rock failure near the crown is controlled by two joint planes (Joint1: Strike - N78°; dip = 79° and Joint2: Strike = N358°; dip = 62°) and one foliation plane (Strike = N28°; dip = 49°). The rock type at the crown is migmatite gneiss and marble bands (**Source:** Bhukosh, GSI). This geometrical disposition of joints and foliation has resulted in a wedge-type failure (Figure 16). The average height of the head scarp is 150 m and the length is 600 m. Head scarp and side scarps are visible in the Pleiades image. Fresh rocks and boulders are also clearly seen in the post-event Pleiades image. A layer of glacier ice-capped over the rock has also moved down along with the rocks. All joints along the avalanche travel path were mapped.

Figure 16: Post-failure Pleiades image showing the crown of the rock avalanche. Scarps exposed due to wedge-type failure along joint and foliation planes are seen. Inset shows pre-failure Komsat-3A image

(Source: NRSC-ISRO**)**

3.2.2 Air Blast

Air blast is an extreme rush of air loaded with projectiles capable of causing severe destruction (Penna et al., 2020). Air blast is one of the prominent after-effects of Rock avalanches. The rock and glacieret mass that has descended from the crown region hit a mountain escarpment on the opposite side of the valley. The escarpment has approx. 900 m length and 500 m height and it is oriented in NNW-SSW direction. This vertical escarpment acted as a reflector and siphoned the displaced air mass towards the valley (Figure 17). As a result of this air blast, trees were uprooted and snapped. The extent of damage to trees is seen upto 3.2 km from the zone of impact.

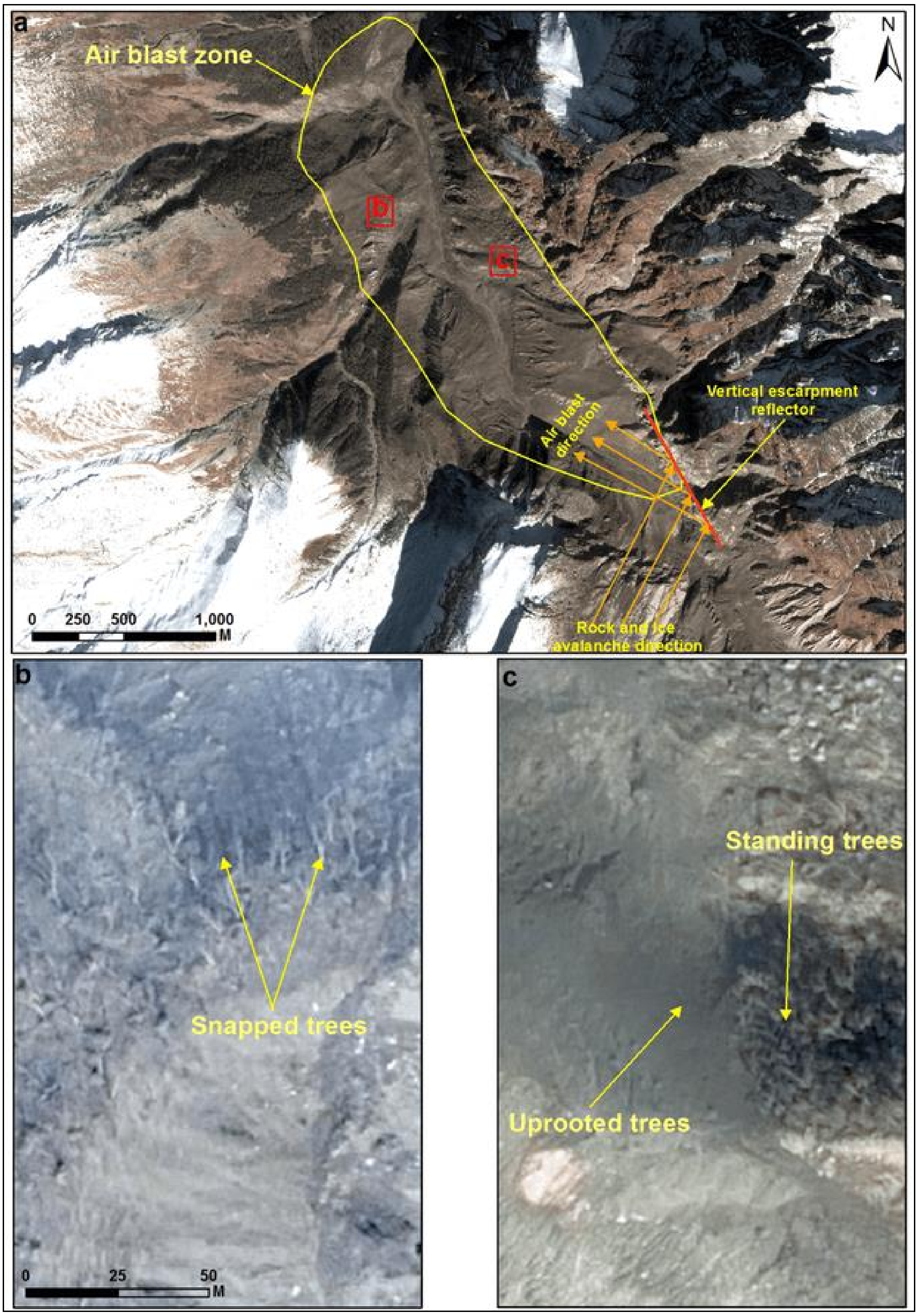

Figure 17: Air blast due to rock and ice avalanche. **a.** Air blast zone and direction illustrated on Post-event Pleiades image. **b.** Trees snapped, and **c.** Trees uprooted due to air blast

(Source: NRSC-ISRO**)**

3.2.3 Debris Bounce and Over-Riding on the Opposite Slope

The impact of rock and ice that crashed to the valley floor was so high that the pulverised rock mass and boulders have over-ridden on the mountain opposite the valley. Satellite data interpretation shows debris and boulders lying at an altitude of4015m which is approx. 285m above the valley floor (Figures 18 and 19).

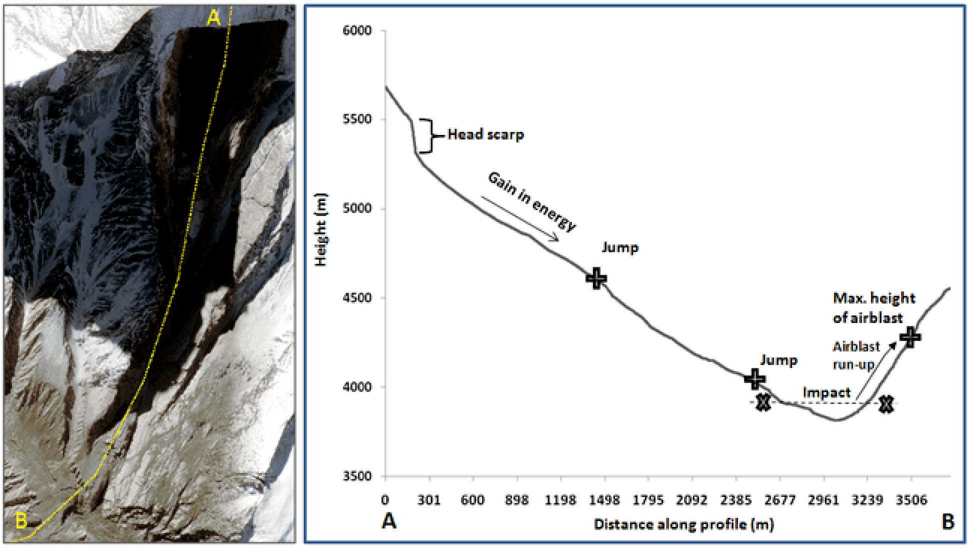

Figure 18: Elevation profile along the travel path showing behaviour of the Rock avalanche

(**Source:** NRSC-ISRO)

Figure 19:a. Zone of debris deposition on the opposite valley shown over the post-event Pleiades image. **b.** and **c.** show after and before images of debris deposition

(**Source:** NRSC-ISRO)

3.2.4 Landslide Debris Dam – Potential Impending Risk

The mass of rock and ice that fell on the Raunthi Gadhera valley was pulverised due to its high impact. The debris was strewn all over the crash zone and to the opposite valley wall. A large heap of debris was mainly deposited on the valley floor. It is seen from the satellite data interpretation that the debris deposited in the valley was removed partially on 7th February 2021. Still, a large chunk of debris is lying in the valley. This has blocked the valley completely by creating a landslide dam. Minor accumulation of snowmelt water on the upstream side is already visible in the image (Figure 20). Since snowmelt is expected to increase during the summer, water will further accumulate due to blockage of flow by the debris dam. The debris dam is unstable and cracks are visible due to slumping. We have evaluated the stability of the dam using two indices i.e., Morphological Obstruction Index (MOI) and Hydro-morphological Dam Stability Index (HDSI).

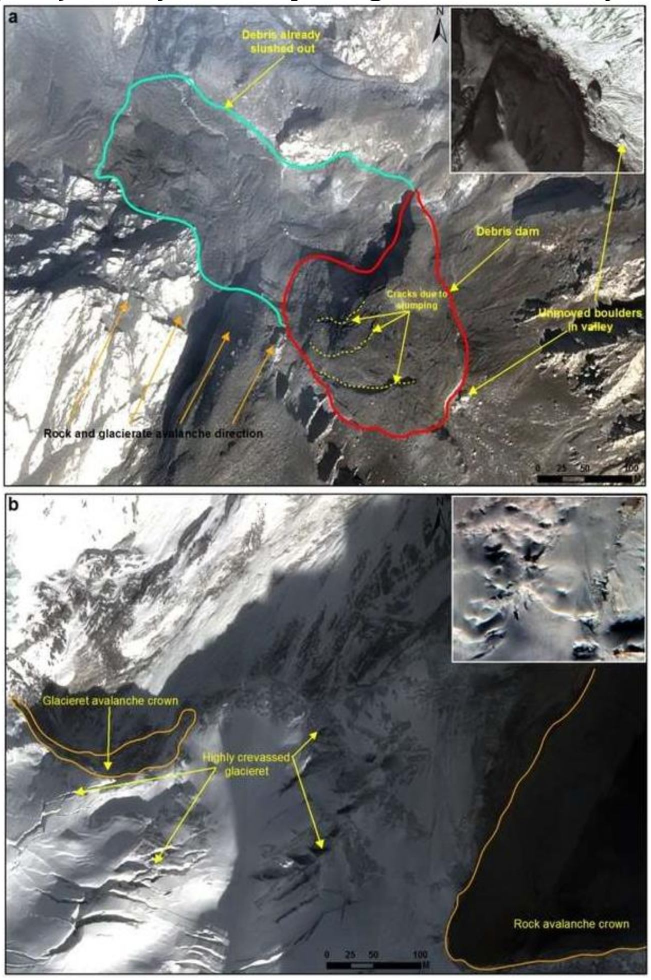

Figure 20: Two potential hazard zones in the Raunthi Gadhera valley mapped using Pleiades image. a. Pulverised chunk of debris blocking the valley. The red polygon shows the extent of the landslide debris that has blocked the Raunthi Gadhera valley. b. Highly crevassed glacieret west of the crown of the rock avalanche. Insets show the pre-event high-resolution image of Komsat-3A.

(**Source:** NRSC-ISRO)

Another critical zone that has potential for failure in the future is the high crevassed glacieret adjacent to the crown of the rock avalanche zone. During summer, due to active melting, the crevasse size will increase, thus further making the glacieret unstable.

3.2.4.1 Landslide Volume Estimation

The release area i.e. the rock and ice mass detached from the crown was identified by photo-geological interpretation of the stereoscopic Pleiades images. Cut and fill analysis within the release area carried out using pre-and post-disaster DEMs estimated the volume of the landslide as ~29.3 million m^3. The height of the release area was estimated by DEM differencing and the maximum height (~197 m) of the release area was found near the head scarp (Figure 21).

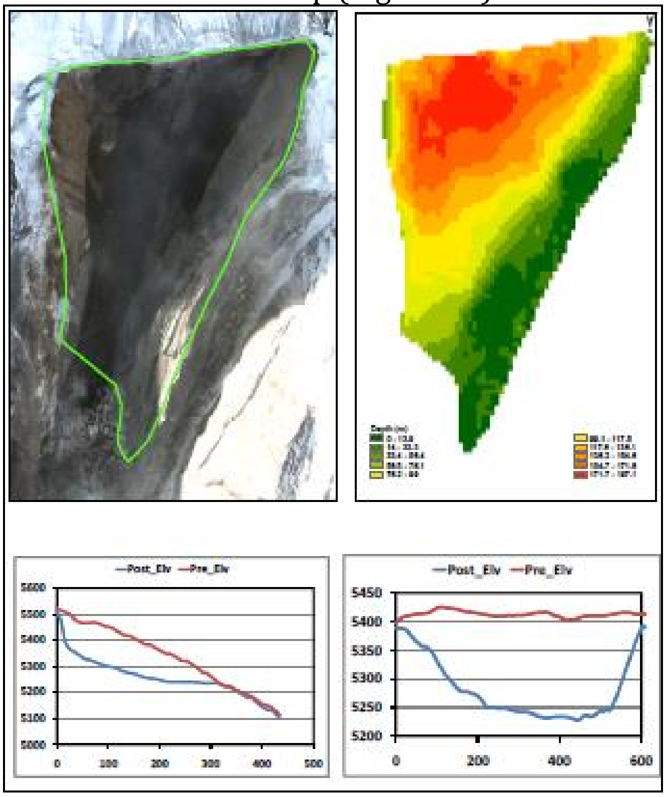

Figure 21: Depth map of dislodged rock and ice estimated using DEM analysis. Longitudinal and transverse elevation profiles derived from Pre- and post-DEM are also shown

(**Source:** NRSC-ISRO)

3.2.4.2 Stability of Landslide Dam Below the Crash Zone

The surface area of the landslide debris dam near the crash zone is 29,630 m^2 with a length across and along the valley as 185 m and 155 m, respectively. The average height of the dam is 20 m. Based on the MOI observation, the area is observed to be in an uncertain evolution domain i.e. MOI is 3.84. It indicates that the landslide dam is unstable. Based on the HDSI observation, the area is observed to be in the instability domain i.e. HDSI = 5.42. The indices are useful to acquire knowledge about the possible instability of the landslide dam. The parameters used for the calculation of the above indices mentioned in section 3.3.4 are given in Table 11.

Table 11: Input parameter for Morphological Obstruction Index (MOI) and Hydro-morphological Dam Stability Index (HDSI).

Sl. no.	Parameter	Value	Index
1	V_l	5,92,600 m^2	MOI = 3.84
2	W_v	85 m	
3	V_d	5,92,600 m^2	HDSI = 5.42
4	A_b	65 Km^2	
5	S	29	

(**Note:** HDSI < 5.74 means unstable dam and MOI between 3 – 4.6 means metastable dam)

3.3 Formation of Debris Dammed Lake in Rishiganga River due to Deposition of Debris from the Backflow of Raunthi Gadhera

The huge debris deposit of Raunthi Gadhera debris flow at Rishiganga confluence blocked the flow of the Rishiganga River resulting in the formation of an artificial lake due to damming by debris material. The site photograph of the lake and blockage is shown in Photo 7.

Photo Plate 7: Site photograph of the lake formed due to debris blockage of Rishiganga river

The volume of the lake has been estimated by different agencies and the estimated volume is 0.5 to 0.7 MCM. The current estimated 0.5 MCM by NRSC has been agreed upon by all concerned.

The debris dammed lake is formed due to sediment obstruction after the major debris flow event that occurred on 7^{th} February 2021. It is reported that water impoundment is taking place at latitude 30˚ 27' 59.24" N and longitude 79˚ 43' 57.7" E in the Rishiganga Catchment as shown in Figure 22. When the water level rises on U/S of the obstruction there is a possibility of overtopping or breach in the obstructions due to water pressure.

When populations located close to a dam are at risk, it is important to predict the breach outflow hydrograph and its timing relative to events in the failure process that could trigger the start of evacuation efforts. The prediction of the outflow hydrograph is our primary interest here; this task has been further subdivided into simulating the dam breaching process and computing the outflow through the breach from the principle of hydraulics.

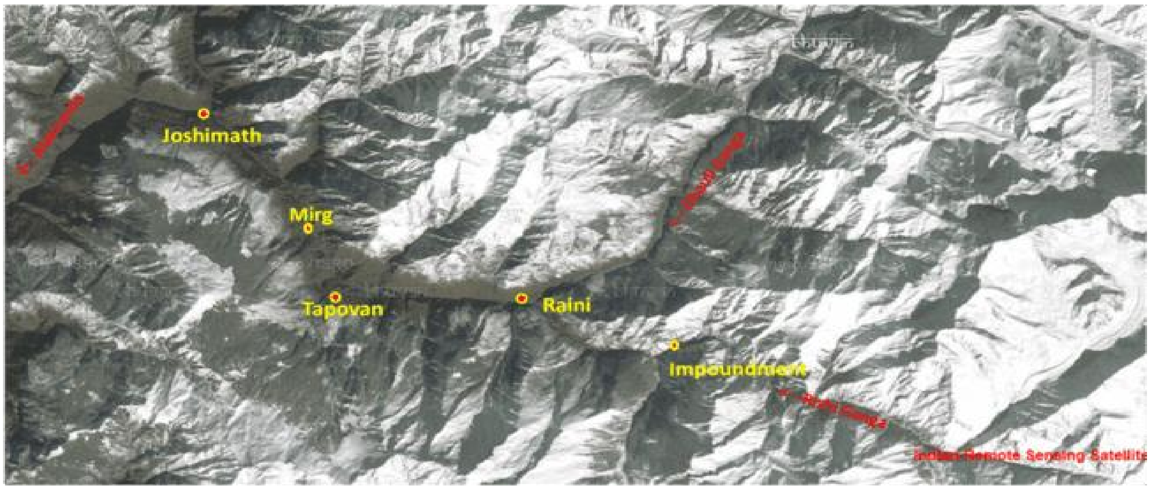

Figure 22: Topographic description of the study area (with impoundment location)

3.3.1 Discharge Analysis of Debris Flow

On 7th February 2021, a debris flow occurred in Raunthi Gadhera due to rock slide and glacieret ice break off from Nanda Ghongati glacier starting at an elevation of about 5600 m. Due to heat generated from friction and impacts, the broken glacier mass got converted into water and mixed with the sliding rock mass and eroded material to form a mud/slurry flow. This slurry flow passed through the Raunthi Gadhera, Rishiganga, and Dhauliganga rivers with a shooting velocity of about 12 to 13 m/s resulting in complete devastation of Rishiganga HEP, the lower part of Raini village and highway bridge on Rishignaga river near Raini village and huge loss of human lives. A location map of Glacier breakage and rock mass slide zone along with Raunthi Gadhera, Rishiganga, Dhauliganga river, Raini village, and Tapovan-Vishugad HEP barrage site is depicted in Figure 23.

Figure 23: Location map of glacier breakage and rock mass slide zone along with Raunthi Gadhera, Rishiganga, Dhauliganga River

When the slurry flow reached the Tapovan-Vishugad HEP of Tapovan, it overtopped the barrage and cofferdam resulting in heavy sedimentation in the Tunnel, desilting chamber, and pondage with heavy loss of human lives.

Onsite inspection it has been found that the sediment deposition in Rishiganga river near the broken highway bridge is of the order of 30 m. The pondage of Tapovan-Vishugad HEP is filled with about a 12 m thick sediment layer. The desilting chamber is filled with sediments. As intimated by the NTPC officials the deposited sediment is having more than 50% fraction of silt and clay particle size of less than 0.5 microns. Due to debris flow, the water level rise at the Tapovan-Vishugad HEP barrage site was more than 25 m. The Full Reservoir Level (FRL) of Tapovan-Vishugad HEP barrage pondage is 1803.50 m. Due to debris flow the water level at the barrage site went about 5 m above FRL.

The design flood for the Tapovan-Vishnugad project is 4640 cumec. On 7th February 2021, the debris flow water level at the barrage site was about 5 m above FRL, hence, it can be concluded that the debris flow peak at the Tapovan Vishnugad barrage site of NTPC was more than the design flood of 4640 cumec.

At the CWC G&D site of Joshimath, the highest observed flood level (HFL) before this debris flow even was at EL 1385.54 m. On 7th February 2021, the observed flood level at 11:00 AM due to debris flow was 1388.65 m, which was above 3.11 m above the HFL. It may be noted that due to backflow of debris flow in Rishiganga, Dhauliganga, and Alaknanda rivers and deposition of huge sediment at Raini, Rishiganga, Dhauliganga, and at Tapovan project site, the debris flow peak reached CWC G&D site is a highly attenuated flood peak. The observed water level on 07th February 2021 at Joshimath G&D site of CWC is given in Figure 24.

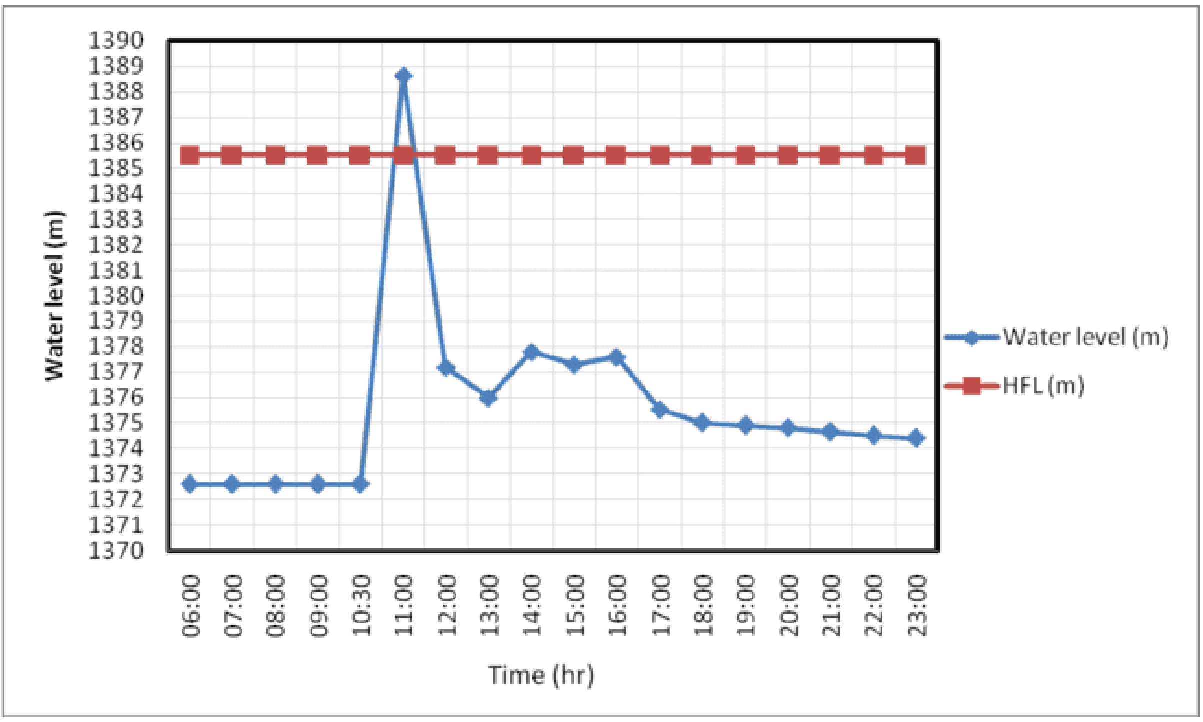

Figure 24: Observed water level on 7th February 2021 at Joshimath G&D site of CWC **(Source:** CWC**)**

The estimated debris flow peak by CWC at Joshimath G&D site is of the order of 1700 cumec. The total derbies/ slurry volume passed through the Joshimath G&D site was about 6 million cubic meters (MCM). The volume of dislodged rock and ice mass at the source of the rock slide was about 29 MCM as measured from DEM analysis by NRSC. Considering the average sediment deposition thickness of about 14 m in the initial 25 km stretch of the river reach, the deposited sediment volume along with trapped water is about 22-23 MCM. Hence, the estimated volume of glacier and rock mass at the source of about 29 MCM seems to be in order.

CWC has also provided the surveyed river cross-sections of the Joshimath G&D site post-monsoon 2020 and after the event of 7th February 2021. From the cross-section data, it has been found that the sediment deposition due to debris flow has resulted inmaximum deposition of about 7 m at the deepest bed level point of Alaknanda at the G&D site. The average sediment deposition at the above location is about 3 m. The plot of the Alaknanda river cross-section at Joshimath G&D site is given in Figure 25.

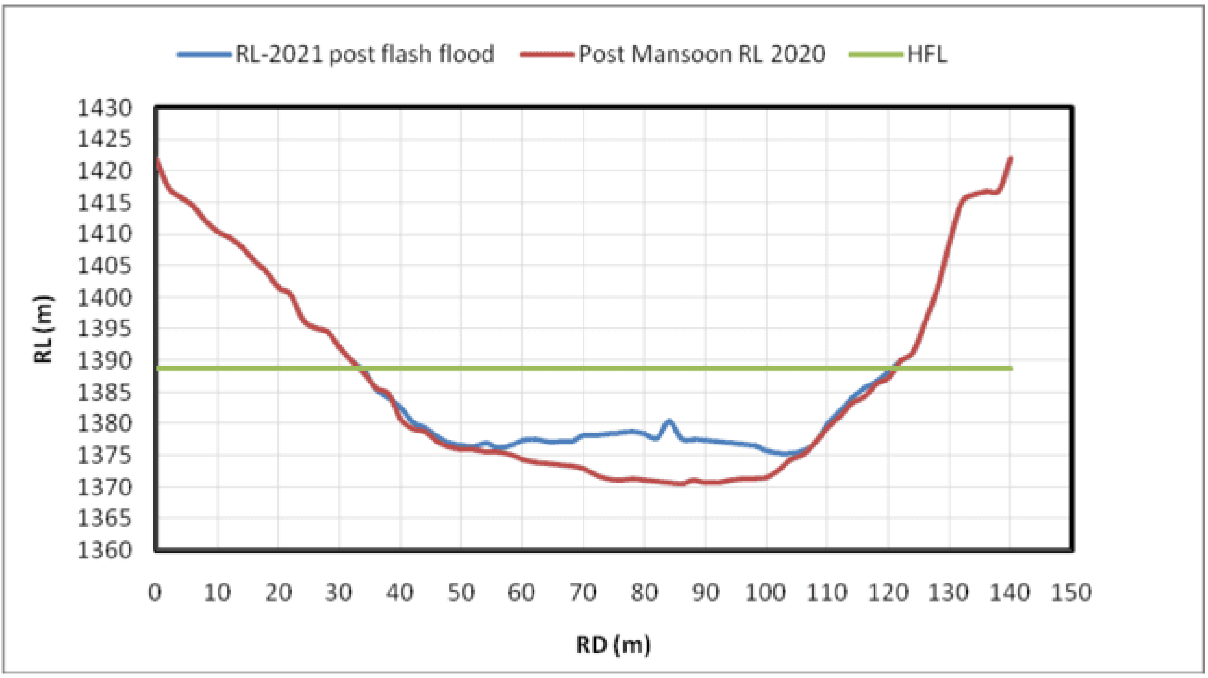

Figure 25: Plot of Alaknanda river cross-section at Joshimath G&D site of CWC in pre and post flash flood scenario

(Source: CWC**)**

3.3.1.1 Findings of CWC About Debris Flow

From the analysis of discharge data of Dhauliganga river, it has been found that the average discharge in Dhauliganga river at Tapovan-Vishugad barrage site remains of the order of 15 to 30 cumec from December to March. Further, the discharge observation records of the Dhauliganga river show that the maximum observed discharge of the order is430 cumec.

3.3.2 Monitoring of Debris Dammed Lake Using Time Series High-Resolution Satellite Data

The lake is being monitored by NRSC using very high-resolution satellite data at regular intervals. Its width at the lakefront, length of the lake, inflow to the lake, outflow breach conditions are being monitored from time to time. Lake location due to sediment deposits on the Rishi Ganga River is shown in Figure 26.

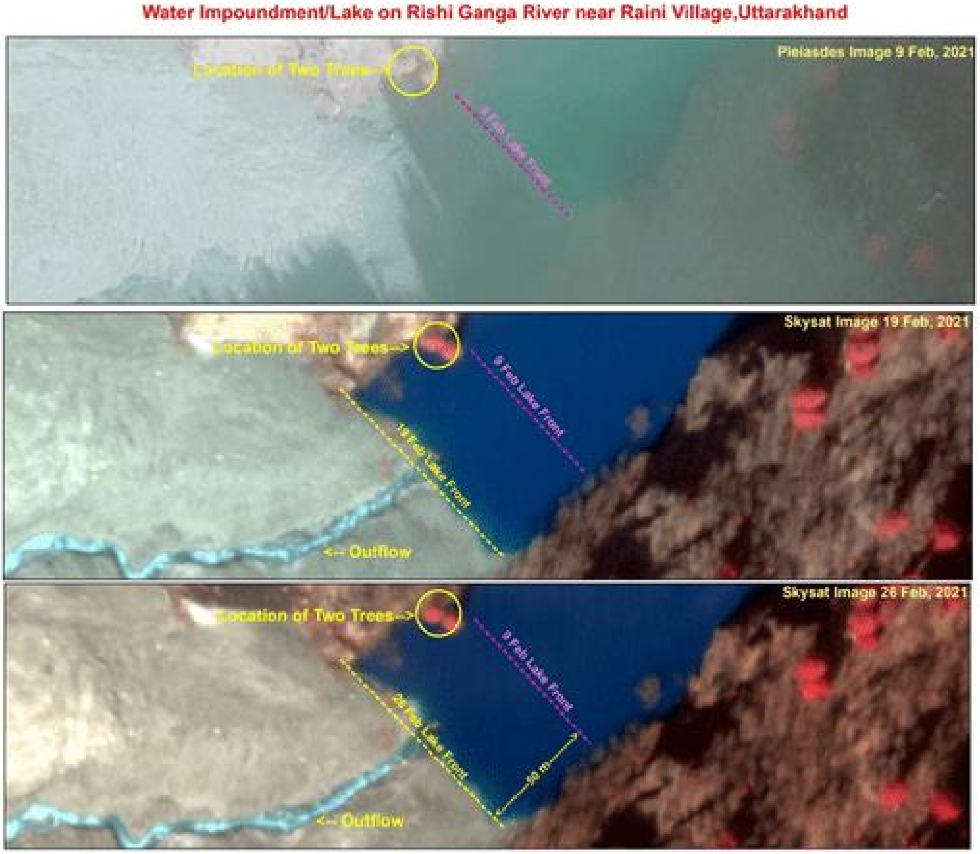

Figure 26: Time series of satellite imageries showing lake monitoring status **(Source:** NRSC-ISRO**)**

From the time series analysis of satellite data, it has been found that the lake front has moved about 50m forward when satellite data of 26th February was compared with 9th February 2021. As the lake water level reached the highest level of sediment deposits, it is found that the lake started overflowing. Breach width is found to be widened marginally. As the inflow to the lake is going as an outflow, there is no significant increase is found in lake volume and area.

3.3.3 Debris Dammed Lake Out Breach Inundation Scenarios

There is an apprehension that the lake may create flooding in the downstream portions if it breaches. Possible scenarios of lake outburst flooding and gradual breach flooding are analysed. The velocity of flooding and depth of flooding along the river stretch from the lake front to the Tapovan project has been computed and flood inundation simulations are computed below.

3.3.3.1 Debris Dammed Lake Volume Estimation Using Conventional Techniques

Lake widths were measured at 50m intervals along the river using satellite data of SkySat 4 of 23rd February 2021 (0.5 m resolution) and shown in Figure 27. Lake depth information provided by the Indian Navy was further analysed and interpolated at required locations and shown in Figure 28. Lake cross-sectional areas at all locations (50m interval) were computed. The bottom width of the river was measured/computed using pre-satellite data and DEM. Lake volume was estimated using the Prismoidal formula. A possible flood discharge scenario has been generated using Froehlich Method using these inputs. Flood inundations simulations were computed from the lake point to the downstream portion of the river using the DEM.

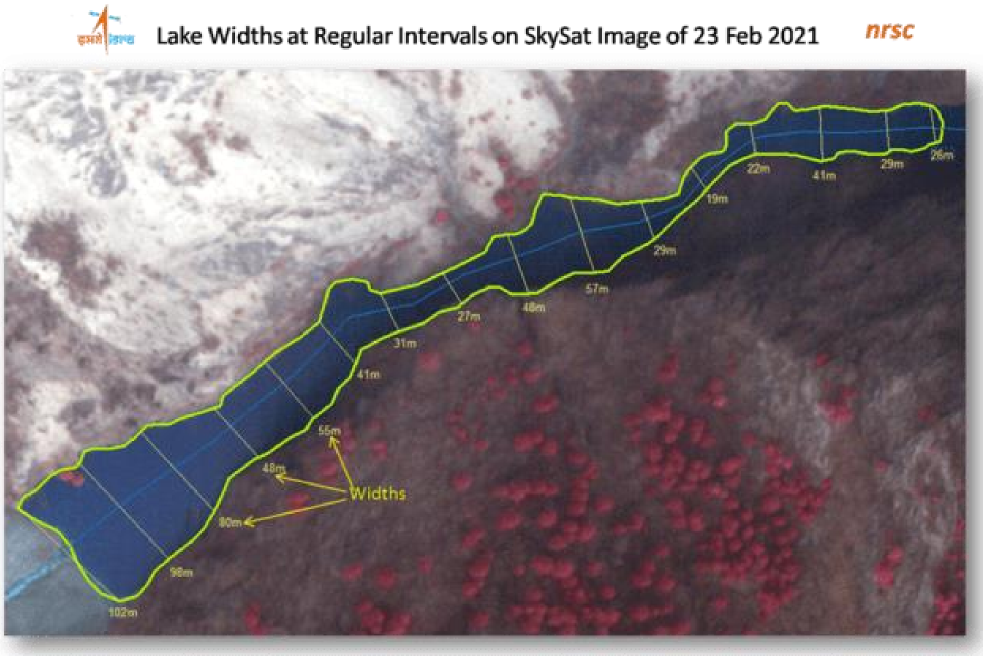

Figure 27: Width of the River at Different Locations (SkySat 23rd February 2021 Image) **(Source:** NRSC-ISRO**)**

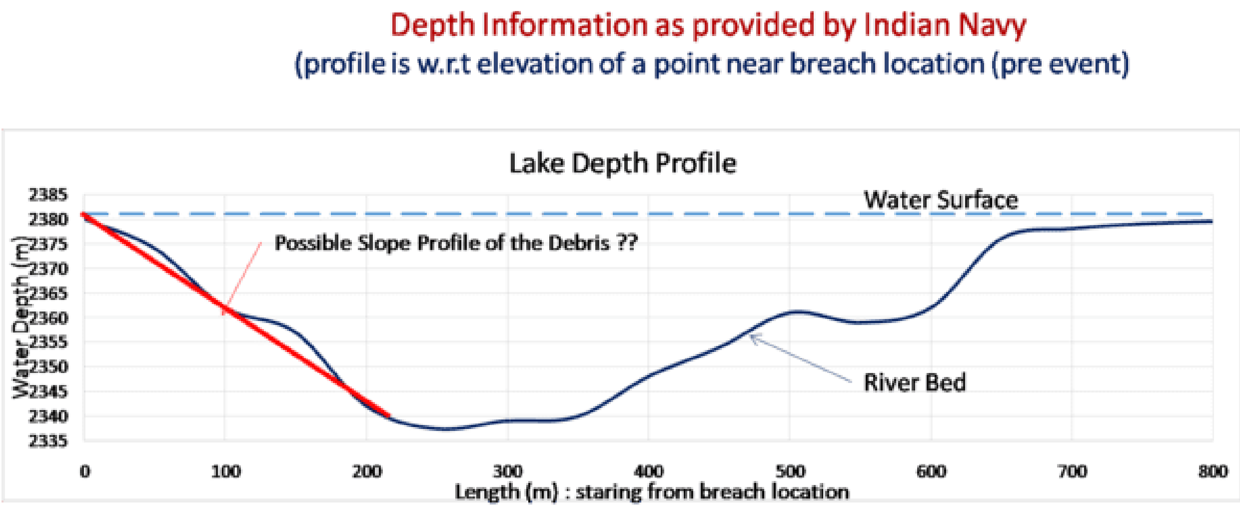

Figure 28: Water Depth in the RiverRishiganga at Debris Dam block site **(Source:** Indian Navy**)**

Lake water-spread area is found to be 3.69 hectares
Lake volume is found to be 0.49 MCM
The average water depth of the lake/impoundment is computed at 13.28m

Scenario 1: Sudden Out Breach of the Lake:

Assuming, the sediment deposits act like an earthen dam, various theories of failure of the earthen dam are examined**.** An empirical method called Froehlich's (2008) method is used to predict time to failure and breach geometry, as well as to predict peak breach discharges. The appropriate equations are mentioned in equation nos. 1, 2 & 3. This method is dependent on: **a)** The volume of the reservoir, **b)** The height of the breach and **c)** The assumed breach side-slope.

Average breach width (B_w) = $0.1803(V_w)^{0.32}(h_b)^{0.19}$(1)
Failure time (T_f) = $0.00254(V_w)^{0.53}(h_b)^{-0.9}$ (2)
Peak flow (Q_p) = $0.607(V_w)^{0.295}(h_w)^{1.24}$ (3)

Where V_w is the volume of water stored above the breach at the time of failure (m^3), h_b is the height of the breach (m) and h_w is the depth of water above the breach at the time of failure (m).

This method also distinguishes between piping and overtopping failure. A failure mode factor (Ko) is used. Froehlich's equation stands valid because with his consideration dams with greater height tend to produce shorter failure times for a given reservoir volume.

In this method, depth of flow, width, and length of water impoundment are the main inputs for computing model parameters like Q_p, T_p. Peak discharge (Q_p), time to peak (T_p) are calculated using the above equations 1 to 3. Considering the water level above breach as 13.3 m, the breach parameters are computed using the above equations, and the computed peak discharge is found to be approximately 585 m^3/sec in case of sudden failure of the dam, and computed flood hydrograph is shown in Figure 29.

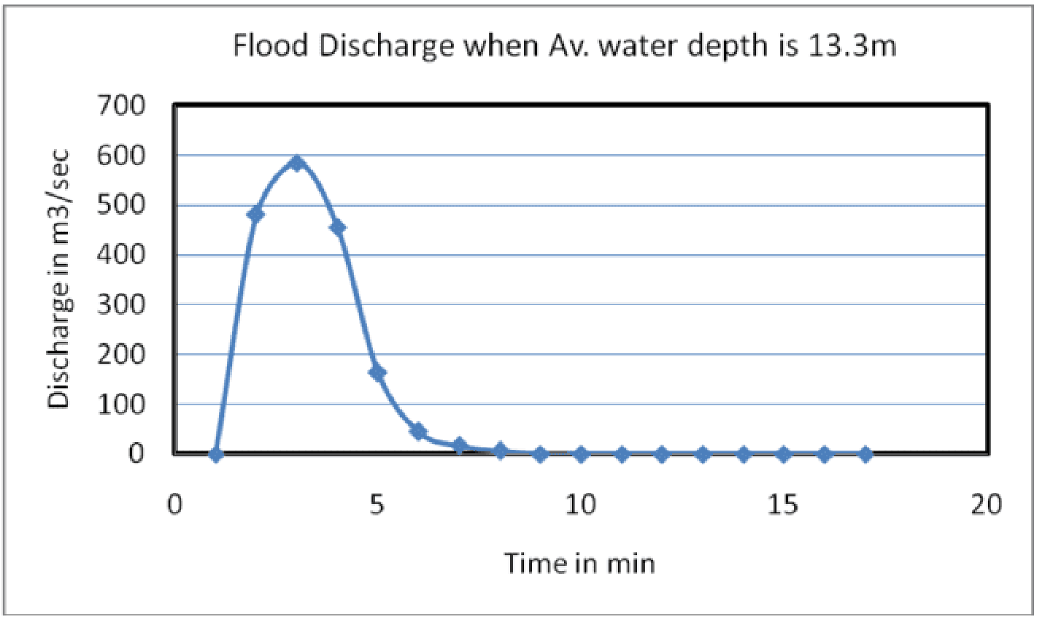

Figure 29: Flood Hydrograph when the peak discharge is 585 m^3/sec

Scenario 2: Gradual Breach of the Lake:

NWS DAMBRK method is popular for computing scenarios due to the gradual failure of the dam. The scenarios are evaluated in the MIKE software environment for which the same breach parameters computed above equations. Peak discharge estimated using MIKE11 is340 m^3/sec shown in Figure 30.

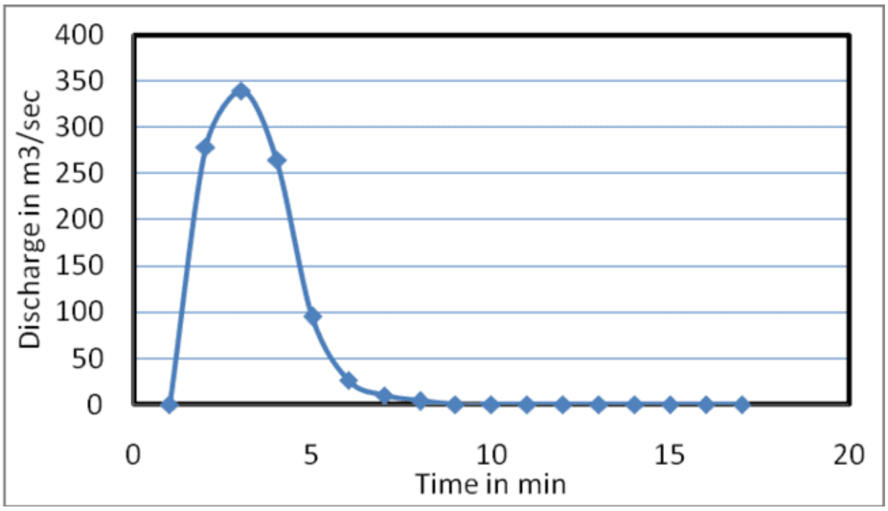

Figure 30: Flood Hydrograph when the peak discharge is 340 m^3/sec

Out of the above two scenarios analysed, scenario two is the more probable scenario considering the blockage width, length, height, etc.

Flood inundation simulations are computed for the worst possible conditions (for sudden breach flood discharge) to assess the depth of flooding, the extent of flooding, and the velocity of flow when the peak discharge is 585m^3/sec. Simulation results at Raini and Tapovan are shown in Figures 31 and 32 respectively. The average depth of flooding was found to vary from 2 to 8.8 m and the maximum velocity of flooding is found to vary from 5.1 to 1.6 m/sec at Raini and Tapovan locations.

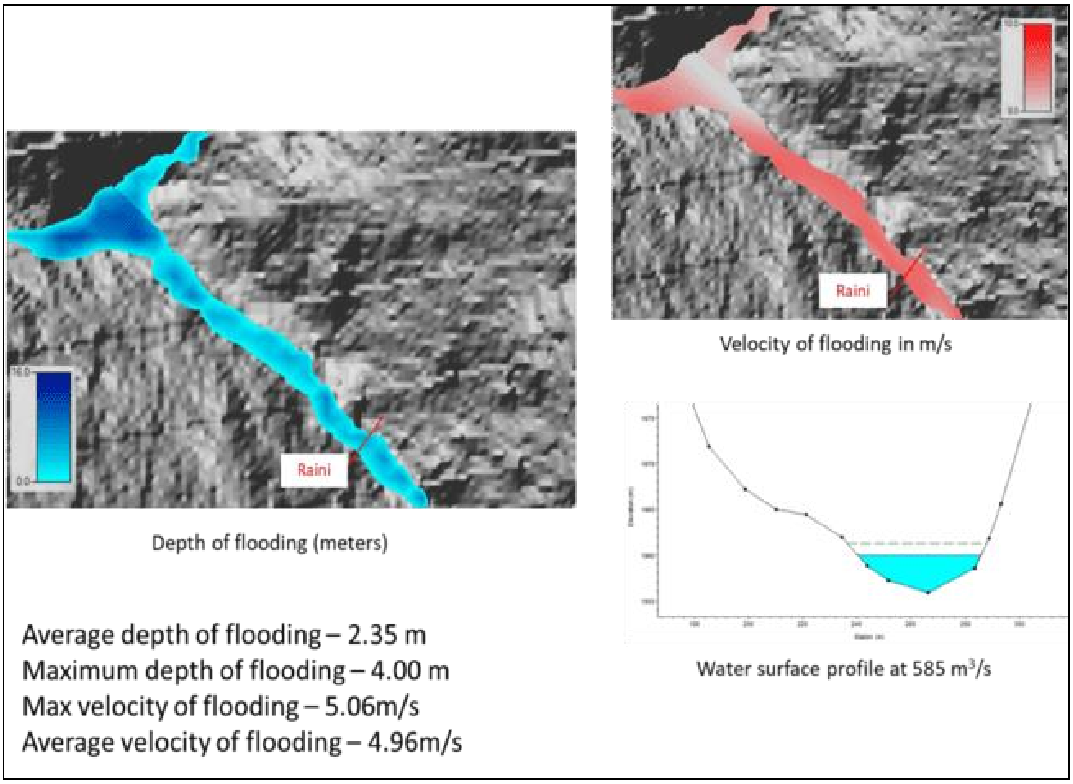

Figure 31: Flood inundation simulations at Raini for peak discharge of 585 m^3/sec
(Source: NRSC-ISRO**)**

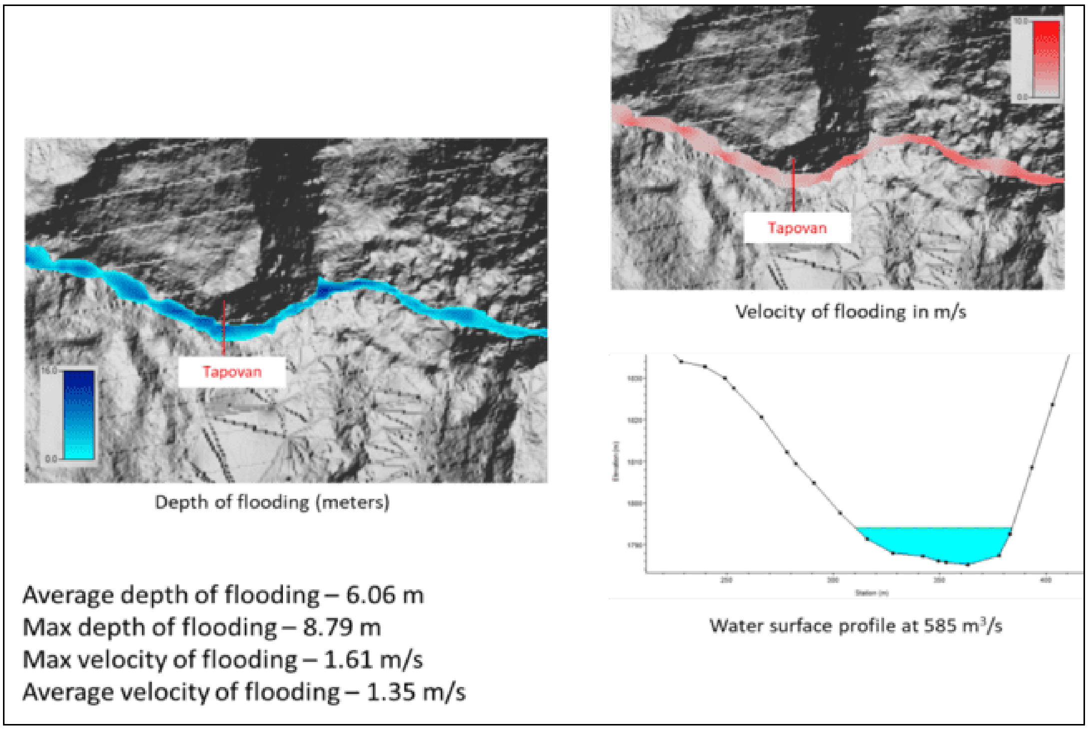

Figure 32: Flood inundation simulations at Tapovan for peak discharge of 585 m^3/sec **(Source:** NRSC-ISRO**)**

Disclaimer/Assumptions: *These simulations have been carried out using satellite imageries and DEM with certain assumptions to understand the approximate picture of the flood scenario. Lake volume estimate may be ± 20 % to the estimated value. The vertical accuracy of the DEM is a limitation in this study. Flood hydrographs have been computed assuming sudden lake burst, and some snowmelt/runoff inflow into the lake.*

3.3.3.2 Lake Volume Computed Using Photogrammetric Technique as on 10th February 2021

NRSC-ISRO has obtained high-resolution Stereo Images of the study area during pre (1st November 2018) and post (10th February 2021) event of the debris flow lake volume is estimated using photogrammetric techniques. The volume of the lake as of 10th February 2021 was found to be 0.219 MCM (±20%). It indicates a significant increase in the volume of the lake from 10th to 23rd February 2021. Depth of debris at the lake is found to be 32 to 36m computed using photogrammetric techniques.

4. Lessons Learnt

The Hon'ble Prime Minister of India, Shri Narendra Modi gave a ten-point agenda (**https://www.pmindia.gov.in/en/news_updates/pms-address-at-asian-ministerial-conference-on-disaster-risk-reduction/**) for disaster risk reduction and resilience during his inaugural address at the 7th Asian Ministerial Conference on Disaster Risk Reduction (AMCDRR) at New Delhi during 2016. Point Number 9 was that the **"opportunity to learn from a disaster must not be wasted".** He also stated that **"after every disaster, there are papers on lessons that are rarely applied"**.

The joint study team of NDMA remained sensitive to the above guidance and worked on both these aspects. The lessons learnt from the Chamoli, Uttarakhand disaster have been briefly documented here in succeeding paragraphs.

4.1 Disaster Risk Assessment (HVCRA)

The Sendai Framework for DRR has provided four priority actions. The first and foremost is the understanding of risks. The team reviewed the disaster risk assessment carried out by the concerned DM authorities at the local and district levels. The Chamoli district had a District Disaster Management Plan (DDMP) but with limited information on potential disaster risks.

Further, the DDMP did not cover the climate change-related risks and the impacts of developmental activities, infrastructure, environmental changes, houses/ buildings, and deforestation. As per DM Act 2005, the DM Plans should be periodically revised and updated. Besides DDMP, there were no DM plans for major hydroelectric projects and other similar infrastructure projects to the following.

- Study on multi-hazards and cascading events by the existing research and academic institutions to generate field validated risk maps, models/ algorithms, etc.
- Re-assessment of the hazard, vulnerability, capacity, and risk of the area is essential and should be periodically updated.
- Mandatory Disaster Impact Assessment for the hydropower projects. Periodically the assessment needs to be rechecked.

4.2 Monitoring, Early Warning and Alert System

It is very important to establish a monitoring, early warning, and alert system for the potential disaster risks in the area so that the people in the affected area can be informed timely through scientifically validated and credible forecasting models by the concerned nodal agencies and the DM authorities.

There was no functional early warning and alert system for the specific event which took place on 7th February 2021. Further, it has been learnt in an unconfirmed way that these issues were not considered in the Detailed Project Reports (DPRs) for these major projects.

As per the discussions and interactions with the concerned stakeholders, it has been pointed out that there is a need for establishing a monitoring and early warning system for hazards in the vicinity of all affected areas and project sites, right from planning to the implementation and operation stages.

- Robust monitoring of the glaciers and connected water bodies could be handy to provide early warning to the downstream community.
- The occurrence of rock avalanche zones in the Himalayan terrain needs to be identified. Monitoring large cracks in mountainous areas is required for assessing a similar type of failure in the future.
- The warning system needs to be integrated with the sirens or hooters and the workers need to be trained in emergency evacuation plans. A system of **Saathi-Rescue (something akin to the Army's buddy system)** needs to be incorporated, where each worker will have a 'saathi'and the safety of the 'saathi' needs to be ensured by each other. Incorporating a public address (PA) system to inform the locals or visitors and other people who do not immediately understand the hooter/sirens may be considered. Over time the public must be fully sensitized.

- Community involvement in the design and implementation of early warning is essential.
- There is insufficient assessment and study of the impact of seismic activities on the glacier bodies and this must be initiated.
- More research is needed on the probable impact of global warming and extreme weather events on the glaciers which leads to hazards in the glacial region.
- It is learnt that there are insufficient constellations of Indian Space Research Organisation (ISRO) satellites, in an inclined path to capture the initiation of such an event as a rockfall in a glaciated area in the Himalayas.

4.3 Prevention, Mitigation and Preparedness

During the field visit and interactions with the DM authorities, and the project authorities it has been learned that though prevention and mitigation measures at Hydro Power Project (HEP) sites do exist, however, they have not been implemented.

The major HEPs have an Emergency Action Plan (EAP) which is implemented when the project becomes operational. But usually, there are no preparedness measures during the construction stage. No mock drills have been carried out as per directions and guidance provided.

If there would have been an early warning system for timely alert and evacuation of the people working at the project site and villages, several lives could be saved. So there is a need for regular/ periodical joint mock exercises and drills for safety and protection against potential disaster risks.

More mock exercises and drills are required to be conducted, without fail. The Army, ITBP, and BRO should be incorporated into all such mock exercises. The NDRF is now tasked to conduct mock exercises of districts under the charge of various units. This is required to be done at least once in three years. Being a disaster-prone zone the training for mountain districts can be done more frequently. Attempts may be made to prevent and mitigate the envisaged risks to the extent possible. For the remnant disaster risks, preparedness and capacity enhancement should be taken up.

- HEPs need to work on strengthening the communication and early warning system with identified signs of danger warnings. Lack of identification of escape and evacuation routes in the HEPs and mock drills for the construction workers.
- HEPs contribute much to the State economy and provide employment. While operations of these projects are managed by the outside technical teams, construction and maintenance (manual labour) involve considerable local and migrant workers. Their safety is an important part of the project's responsibility.
- Build capacity of key players and relevant stakeholders on DM.

The State / District administration should take appropriate steps to enable the local youth to be trained and engaged in the operational and DM aspects of HEPs as they have a better understanding of local terrain.

4.4 Response and Recovery

Due to tough terrain, inaccessible routes, and adverse weather conditions in the high altitudes, the response time in disaster situations gets prolonged and hampered. It has been learnt that the incident response system was insufficiently practiced and there was some lack of coordination in the unified command system during the response phase of the disaster. As it was a unique untimely and unexpected disaster the response actions were very difficult and challenging due to unforeseen conditions. Further, the response was hampered and hurdled due to the lack of information about the layout and various elements of the projects and the lack of technology and equipment for identifying and locating people stuck inside the tunnel.

It has been learnt that appropriate records were not updated for the labourers working on contract and daily wages at the project sites. Further, there is a need to establish an effective mechanism for recovery from such disaster situations at HEP sites. Other observations were:

- Inadvertent delay in sharing of information and layout of HEP tunnels with rescue forces. This would have been obviated with more mock exercises.
- Need for strengthening of coordination and cooperation with each other (departmental within or outside) for a better outcome as a whole with a unified chain of command at the incident site.
- Media briefing and press release at the end of the day's activity by the designated representative of State associated with the rescue teams is necessary.
- The community is always the most affected due to any disaster. There is a need to mitigate /reduce the psycho-social impact of such incidents on the local community. A psycho-social counselling centre needs to be established at Joshimath given the frequency of disasters in the general area.

4.5 Revision and Implementation of Disaster Management (DM) Plans

As per DM Act 2005, the DDMP should be revised and updated on a regular periodic basis or whenever major changes in the area take place. It has been learnt that the Chamoli district DM plan was last prepared and updated during the year 2020, but the plan has not adequately considered the potential disaster risks from the glaciated area. National Guidelines issued for the management of different disaster risks need to be followed by the concerned DM authorities for effective risk assessment, reduction, and resilience measures. It has been learnt that the dynamics of the risks with the changing climatic conditions, environmental modifications, and developmental interventions are not well considered in the DM plans.

- There is a need to update the Disaster Management Plan for the district as per NDMA National Disaster Management Plan (2019) and other guidelines of NDMA. Also to prepare the DM plan and Emergency Action Plan (EAP) of small and big HEPs in the Himalayan and other mountain regions.
- The local community should be taken into account while updating/revising the current DM plan.

5. Recommendations / Suggestions

A. Immediate Measures and Risk Aversion

- Need to foster and implement very first agenda of **Hon'ble PM's 10 Point Agenda** on DRR viz. **"All development sectors must imbibe the principles of disaster risk management"**(Agenda point no. 1). Every development activity should consider the geological, geomorphological, and ecological attributes of that particular terrain in disaster risk assessment and management. Application of mind to potential risks in the area of responsibility is the DDMA's prime responsibility.

[**Actions:** Concerned Ministries / Departments, State Government / SDMA's, and any other relevant stakeholders]

- Raunthi Gadhera has is a steep gradient and fairly narrow valley. The re-occurrence of a similar incident could be very dangerous as the valley sides and floor in the downstream area are laden with loose debris mass. Therefore, as an immediate measure, vulnerable zones of rock/ ice avalanche zones may be identified, and effective communication, alert, and response system may be put in place.

  [**Actions:** NRSC-ISRO and any other stakeholders through USDMA]

- The natural dam created in front of the lake in River Rishiganga seems to withstand the hydrostatic pressure generated by the accumulated water. Any evidence of piping from the dam body needs to be closely monitored for the safety of the dam. The volume of ice blocks in debris could not be ascertained but a higher clay fraction in the material makes the dam body impermeable so far. However, it is strongly suggested that the discharge of lake waters inlet-outlet along with the level of lake water and condition of natural barrier (dam) should be continuously monitored to ascertain any significant changes in real-time.

  [**Actions:** NRSC-ISRO, CWC, GSI, WIHG and any other stakeholders through USDMA]

- The landslide dam near the crash zone needs to be monitored for failure in subsequent summers and beyond. Monitoring can be done by the installation of motion detector cameras with night vision, geo-phone sensors, hooters/ sirens, etc. as per site suitability conditions at appropriate locations such as at confluence of Raunthi Gadhera with Rishiganga River, near Paing and Murranda villages, before BRO bridge and few 100 meters before the confluence of Dhauliganga with Rishiganga Rivers, etc. to know the high flood level (HFL) condition before any threat to downstream.

  [**Actions:** NRSC-ISRO, CWC, and any other stakeholders through USDMA]

- An appropriate and effective alarm system may be put in place at project sites, downstream of such vulnerable glaciated catchments. During construction of hydel projects where tunneling is involved, escape tunnels in the form of designated shafts may be kept as escape routes in the event of any catastrophe and the same are to be made operational from the initial construction stage of any such large hydropower or similar infrastructure projects.

  [**Actions:** MoP/CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- To augment the observational network, fill the data gap areas, and enhance forecasting services, three Doppler Weather Radars (DWRs) are proposed to be installed in Uttarakhand under Integrated Himalayan Meteorological Programme (IHMP) by IMD. Out of these three DWRs, one x-band DWR has been commissioned in Mukteshwar, Nainital. The installation work of the second DWR at Surkanda Devi, Tehri is in progress and the installation of the third DWR in

Lansdowne, Pauri will commence shortly. IMD to ensure the speedy installation and functioning of the other two DWRs in Tehri and Pauri.

[**Actions:** IMD in coordination with USDMA]

- An automated system of hooters and sirens placed along the run of the river and at work sites should be set up which can be activated by a single button at the Control Room. This is an imperative measure that must be instituted at the earliest and drills related to this should be practised.

  [**Actions:** MoP/CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- Provision of hooters/ sirens and early warning system from the Detailed Project Report (DPR) preparation phase in hydro projects and installation of it, before initiation of construction at the site. There should be an Early Warning System (EWS) integrated with hooters / siren in the region where development activities are going on and better monitoring is needed.

  [**Actions:** MoP / CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- The DPR studies of any infrastructure projects located proximal to the glaciate terrain must include detailed geo-hydro-meteorological-hazards (landslides, earthquake, etc.), glaciological, geomorphological, hydrological, meteorological studies of the catchment by the relevant experts, so that all sorts of related hazards if any, their likelihood, possible impacts can thoroughly be examined so that suitable design parameters, remediation, and long-standing monitoring mechanisms are included beforehand in the DPR proposal for implementation right from the construction stage of such infrastructure projects.

  [**Actions:** MoP/CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- Environment Impact Assessment (EIA) of every HEP and development project to be done in consideration of ecological sensitivity of the region and its future consequences can be listed out in the report.

  [**Actions:** MoEFCC, MoP/CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- Planning and provisioning of easy and faster access route to higher reaches providing safety within the construction site be kept in the dam/ barrage areas within the deepest river bed section to facilitate the provision of faster escape routes for the workers/ engineers working at the site.

  [**Actions:** MoP/CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- Registration of all the workers – resident or migrant to be registered with the District Administration along with the project management. This will enable the identification of the missing personnel and other welfare related activities. This registration system will help the project officials to estimate the human loss very accurately in the event of an unfortunate disaster.

  [**Actions:** MoP/CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- As the area is vulnerable to landslides, hence, slope cutting machines and controlled blasting methods may be adopted for the excavation of tunnels and road widening and it should be strictly monitored.
  [**Actions:** MoP/CEA, Ministry of Road, Transport & Highways (MoRTH); Dam Authorities/Agency, State Government (e.g., PWD), State DM Authorities and any other stakeholders]
- No houses, religious places/ buildings, infrastructural projects may be allowed to be constructed near theHigh Flood Level (HFL). Proper site specific studies may be carried out before taking up any infrastructural projects/ construction of buildings etc.
  [**Actions:** State Government, State DM Authorities in consultation with relevant stakeholders]
- The necessity for coordination and cooperation with each other (departmental within or outside) for a better outcome as a whole during any disaster related incident.
  [**Actions:** State DM Authorities in consultation with relevant stakeholders]

B. Short and Medium-Term Measures (3 - 8 years)

- Snow cover and glaciated areas are increasingly becoming vulnerable to mass movements such as landslides and avalanches. The occurrence of rock and glacieret avalanche zones in the Himalayan terrain needs to be identified. Monitoring of large cracks in the mountains is also required for assessing a similar type of failure in the future.
  [**Actions:** NRSC-ISRO/ Space Application Centres (SAC), State Remote Sensing Departments, GSI and any other stakeholders in consultation with State DM Authorities]
- Vulnerable zones in these areas need to be identified using Remote Sensing and GIS techniques and limited field work in accessible areas.
  [**Actions:** NRSC-ISRO/ Space Application Centres (SAC), State Remote Sensing Departments, GSI and any other stakeholders in consultation with State DM Authorities]
- Studies and monitoring of vulnerable glaciers with high resolution satellite data and field surveys are the foremost requirements in the Himalayan region.
  [**Actions:** NRSC-ISRO, CWC, GSI, WIHG and any other stakeholders]
- Macro scale (1:50,000/ 25,000) catchment-based multi-hazard studies may be carried out in such glaciated/ permafrost areas in the Himalayas with regards to GLOF, Landslide Lake Outburst Flood (LLOF), rock/ snow avalanche zones, glacial landforms, and other vulnerable hazards by taking up suitable national-level programs involving all the relevant organisations and institutes to discern such high-altitude terrains based on the likelihood of occurrences of cascading event.
  [**Actions:** GSI, NCS, and any other relevant stakeholders]
- The rock fall/ avalanche incident site was not identified by the Indian Remote Sensing Satellite (i.e., ISRO) during the day of the incident. It is leant that there is a lesser number of constellation of satellites in inclined orbit to capture this event.

Therefore, it is recommended that ISRO may increase the constellation of satellites to capture this kind of event in the future in near real-time. Also, ISRO may take help during this kind of event by activating International Charter (e.g., Sentinel Asia).

[**Actions:** Department of Space (DoS) and ISRO]

- Each project site should set up upstream monitoring and warning systems for the glaciers that feed this river system. The systems can be as simple 24 hours manned control room with 3 shifts of 8 hours. The monitoring personnel can be connected with not only the HEP but also the district administration.

  [**Actions:** MoP/CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- Recently (October 2020), the National Disaster Management Authority (NDMA) has formulated and published detailed guidelines for GLOF and LLOF management, which includes monitoring and early warning system for the above hazards, and the same needs to be consulted too for planning any future projects/ programs to prevent and mitigate the known hazards on immediate basis. (**https://ndma.gov.in/sites/default/files/PDF/Guidelines/Guidelines-on-Management-of-GLOFs.pdf**)

  [**Actions:** Concerned Ministries / Departments, State Government **/**SDMA's, and any other relevant stakeholders]

- Revise and update the District Disaster Management Plan (DDMP) on regular basis with multi Hazard, Risk, and Vulnerability (HRVA) studies. Also, to prepare the DM plan and Emergency Action Plan (EAP) of small and big HEPs in the Himalayan and other mountain regions. Each HEP must possess an updated DM Plan in sync with the local DDMA.

  [**Actions:** State Government, SDMA's in consultation with NDMA and NIDM]

- Pre-emptive emergency action and evacuation plans and arrangements in the event of an unprecedented increase in discharge must be provisioned in place, along with the implementation of periodic safety drilling exercises at the project site, considering faster movement or escape from the deepest valley section to the safer upstream areas.

  [**Actions:** Ministry of Power/CEA, Dam Authorities/Agency, State Government, State DM Authorities in consultation with relevant stakeholders]

- A legal framework such as Mountain Zone Regulation/Building Bye-laws needs to be developed particularly keeping in mind the degree of instability of the area as mentioned in NDMA documents and Guidelines such as National Landslide Risk Management Strategy (Sept. 2019) and NDMA Guidelines on Management of Glacial Lake Outburst Floods (October 2020).

  [**Actions:** State Government, SDMA's in consultation with BIS, NDMA and NIDM]

- The Indian Army has its deployment in the vicinity of most valleys of Uttarakhand. It has a Corps of Engineers component and heavy earth moving equipment at some places. The BRO has similar resources. These organisations have not been suitably incorporated in the DM plans. DDMA's need to carry out more liaison with them and incorporate them and ITBP together for a more holistic response. Indian Army may also be included in the mock drills in the Himalayan States/ UTs.

[**Actions:** State Government, SDMAs / DDMAs]

- Capacity building programs and an increase in mass human resource training on instrumentation, forecasting, and early warning should be carried out in hazard prone areas. Capacity Building, and training to the local people (villagers) should be given from time to time.

  [**Actions:** SDMA's, State ATI's in consultation with NDMA and NIDM]

- Training modules should include a mock drill, learning of some basic instruments like a walkie-talkie, mobile phone, best practices and techniques to escape and rescue people.

  [**Actions:** SDMAs, State ATI's in consultation with NDMA, and NIDM]

- There appears to be duplication with several institutions such as CWC, NIH-Roorkee, GSI, National Centre for Polar and Ocean Research (NCPOR)-Goa, Divecha Centre-Bangalore, other academic-research institutions, etc. working in silos in the field of glaciology and glacier studies with a scattered area of study and there is a negligible sharing of data amongst academic, research, and field institutions. Therefore, it is high time to create a national level **Centre for Glacial Research, Studies, and Management (CGRSM)** as mentioned in the NDMA Guidelines on Management of GLOFs (October 2021) to avoid duplication of efforts in glacier studies-research and cordial sharing of information and data amongst existing institutions for presenting the entire scenarios of Himalayan glaciers at a single platform and reduce the future risks and hazards.

  [**Actions:** Ministry of Jal Shakti (MoJS)/ NIH-Roorkee in consultation with NDMA and any other relevant stakeholders]

- There is an immense need to create a State Institute of Disaster Management (SIDM) in Uttarakhand. The Uttarakhand Himalayas are geo-tectonically fragile young mountain systems and prone to different types of hazards such as landslides, earthquakes, flash floods, cloud bursts, Glacial Lake Outburst Flood (GLOF), Landslide Lake Outburst Flood (LLOF), etc. This institute will identify and study the probable risks and hazards that exist in the State in a technically and scientifically manner in coordination with existing Disaster Management authority (USDMA) and other scientific and training institutions such as Wadia Institute of Himalayan Geology (WIHG), Indian Institute of Remote Sensing (IIRS), Uttarakhand Space Application Centre (USAC), Administrative Training Institutes (ATI's), etc.

  [**Actions:** State Government and USDMA in consultation with NDMA and NIDM]

C. Long Term Measures (11 years)

- High altitude (>4000 m asl) hydro-meteorological data is needed for accurate monitoring and better correlation of it with glacier dynamics. High altitude hydro-meteorological stations are of foremost need and the data policy should be such that it could be shared amongst the organizations for scientific and development purposes.

  [**Actions:** IMD, CWC, and any other relevant stakeholders]

- The necessary action to be taken for augmentation of Automatic Weather Stations (AWS), Automatic Rain Gauges (ARG), and water level sensors network in the Himalayan States to collate and share real-time weather and hydro-meteorological information. All AWS, ARG, water level, and weather monitoring systems are to be installed with full remote functionality and automatic data flow to the control room.

  [**Actions:** IMD, CWC, and any other relevant stakeholders]

- Studies and development of forecasting and early warning models in correlation with weather related disaster risks.

  [**Actions:** Concerned Ministries / Departments, Scientific/academic institution, State Government /SDMA's, and any other relevant stakeholders]

- Installation of an electronic early warning system is recommended for alert and better management of flood conditions in the downstream area. Pre-emptive emergency action and evacuation plans and arrangements in the event of an unprecedented increase in discharge must be provisioned in place.

  [**Actions:** CWC, State Government / SDMA's and any other relevant stakeholders]

- Mainstreaming of climate related risk modeling, monitoring, management, and adaptation in research, study, projects, etc. incoherence with DRR.

  [**Actions:** MoEFCC, DST and any other relevant stakeholders]

- Coherence and integration of DDMP with DRR, climate change action plan, and sustainable development goals by the relevant concerned department.

  [**Actions:** Concerned Ministries / Departments, State Government /SDMA's, and any other relevant stakeholders]

- In the long run, the pursuit of alternative sources of energy will need to be looked at since this zone appears to be environmentally fragile. A separate study on that may be set up by the Ministry of Power.

  [**Actions:** Ministry of Power (MoP), State Government in consultation with relevant stakeholders]

6. Conclusion

In India this is a unique and first reported incident of glacier ice and rock having a cascading impact of debris flow. But, a similar type of rock fall and glacieret ice avalanche events took place in European Alps, the Russian Caucasus, Canada, and Nepal in the past.

The adverse effect of climate change and global warming are evident in Himalayan glaciers and mountains in the form of glacier retreats, extreme weather events, etc. Therefore, this is the time we have to share and learn from the best practices available nationally and internationally to minimize the impact of future hazards and risk that exists in the Indian Himalayas and other mountain regions. It is also recommended that concerned Central and State Government Institutions/ Departments must take appropriate actions and Dam authorities must follow aforesaid recommendations/ suggestions and implement them in existing and future HEPs ensuring all necessary safety measures from the construction phase itself.

7. Acknowledgment

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NDMA appreciates the efforts made by Late Dr. Renoj J. Thayyen (upstream team leader); who unfortunately expired due to Covid-19 on 22nd April 2021, three weeks after the field visit of the Joint Study Team. He was a dynamic and active scientist in this field.

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9. Annexure

Composition of Joint Study Team

S. N.	Institution	Name of Team Leader/ Experts	Expert
1	NDMA	Lt. Gen. Syed Ata Hasnain (Retd.), Member NDMA	Chairman
2	NDMA	Shri Rajendra Singh, Member NDMA	Co-Chair
		TEAM 1 (Upstream Region)	
1	National Institute of Hydrology (NIH), Roorkee	**Late Dr. Renoj J. Thayyen** Scientist–'E' Water Systems Division	Team Leader
2	Defence Geoinformatics & Research Establishment (DGRE), DRDO, Chandigarh	**Dr. Agraj Upadhyay** Scientist- 'E' DGRE, DRDO, Chandigarh	Expert
3	Wadia Institute of Himalayan Geology (WIHG), Dehradun	**Dr. Manish Mehta** Scientist–'D' **Dr. Vinit Kumar** Scientist–'C'	Expert
4	IIT Roorkee	**Dr. Ajanta Goswami** Associate Professor Department of Earth Sciences	Expert
5	Kashmir University	**Dr. Irfan Rashid** Assistant Professor Department of Earth Sciences	Expert
6	NRSC-ISRO, Hyderabad	**Dr. Tapas Ranjan Martha** Head, Landslide Division	Expert
7	National Disaster Management Authority (NDMA)	**1. Dr. Ravinder Singh** Senior Consultant (Landslides and Avalanche) **2. Mr. Prasoon Singh** Consultant (Floods & river Erosion) **3. Ms. Priyanka** Junior Consultant, SDC	Expert
		TEAM 2 (Downstream Region)	
8	NIDM	**Dr. Surya Parkash** Professor & Head, Geo-Meteorological Risk Management Division	Team Leader
9	National Disaster Management Authority (NDMA)	**Mr. Ajay Katuri** Senior Consultant (HRVA)	Expert
10	Border Roads Organisation (BRO)	**Col. Manish Kapil** Commander 21 BRTF	Expert
11	NRSC-ISRO, Hyderabad	**Dr. KHV Durga Rao** Group Head, DMSG NRSC-ISRO	Expert

S. N.	Institution	Name of Team Leader/ Experts	Expert
		Dr. S V Shiva Prasad Sharma Scientist/Engineer 'SF'	
12	NTPC	**Mr. R. P. Ahirwar** GM (Tapovan)	Expert
13	Central Water Commission (CWC)	**Mr. N. N. Rai,** Director, Hydrology (South)	Expert
14	India Meteorological Department (IMD), Dehradun	**Dr. Rohit Thapliyal** Scientist-'C', Meteorological Centre, Dehradun	Expert
15	Geological Survey of India (GSI), Dehradun	**Mr. Bhupender Singh** Director (Coordination), State Unit: Dehradun, Uttarakhand	Expert

Logistical Support Agencies

S.N.	Logistical Support
1	Uttarakhand State Disaster Management Authority (USDMA), Govt. of Uttarakhand
2	Personnel of State Disaster Response Force, (SDRF), Govt. of Uttarakhand
3	Personnel of 1st Battalion Indo Tibetan Border Police (ITBP), Joshimath
4	HQ, Integrated Defence Staff (IDS), Ministry of Defence and Indian Air Force

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