A REPORT

ON

TECHNICAL ASSESSMENT OF THE DHARALI DISASTER OF 5th AUGUST 2025, UTTARKASHI DISTRICT, UTTARAKHAND

Submitted by

ULMMC, CSIR-CBRI, GSI, WIHG and IITR

Submitted to

Uttarakhand Disaster Management Authority
Govt. of Uttarakhand
1st September 2025

PREFACE

A massive debris flow triggered along the Khirgad stream in Uttarkashi district, Uttarakhand which destroyed almost completely the Dharali village situated at the confluence of the stream and the Bhagirathi River. The debris flow deposited a thick layer of sediments burying the habitation and infrastructure of the village. A separate debris flow along the Telgad stream caused damage to the army camp at Harsil and triggered the formation of a temporary lake due to the encroachment into the Bhagirathi river. This, in turn, led to the submergence of the national highway connecting Harsil and Dharali.

In the aftermath of the Dharali disaster, the Uttarakhand State Disaster Management Authority (USDMA) constituted a multidisciplinary technical team to carry out a rapid scientific assessment of the affected area.
The team comprised of:

Dr. Shantanu Sarkar (Director, ULMMC)
Dr. D. P. Kanungo (Chief Scientist, CSIR–CBRI)
Shri Ravi Negi (Director, GSI)
Dr. Amit Kumar (Scientist, WIHG)
Dr. Mohit Kumar Puniya (Principal Consultant, ULMMC)
Dr Ankit Agarwal (Assistant Professor, IIT Roorkee)

A detailed field survey was undertaken by the team from 13 to 16 August 2025. The report presents the observation at site, probable causes contributed to debris flow, extent of damage, rainfall analysis, debris flow modelling and suggestive measures and recommendation.

CONTENTS

REPORT ON TECHNICAL ASSESSMENT OF THE DHARALI DISASTER OF 5th AUGUST 2025, UTTARKASHI DISTRICT, UTTARAKHAND

1 INTRODUCTION

On the afternoon of 5th August 2025, a high-magnitude debris flow occurred along the Khirgad stream in Uttarkashi district, Uttarakhand. The stream, a left-bank tributary of the Bhagirathi River, triggered severe devastation in the Dharali habitation area, located on the banks at the confluence of the stream and the river.

The event originated in the upper reaches of the Khirgad catchment, where large volumes of glacio-fluvial debris (moraine material), mobilized by snowmelt and intense rainfall, rapidly traveled downslope through the steep valley. In its course, the debris flow encroached upon the Bhagirathi River and deposited a thick cover of material at road level and across the riverbed, completely destroying the Dharali locality situated along the confluence.

Post-disaster field observations revealed that the debris flow, characterized by extremely high velocity and pressure, swept away nearly all existing settlements, a section of National Highway (NH-34), communication towers, vegetation, and other infrastructure along its path. The flow ultimately dissipated its energy at the riverbed level, where it deposited debris up to 15 m in thickness, burying most of the settlements and resulting in widespread destruction of infrastructure and significant loss of life.

Dharali, a small village near the Harsil valley, lies on the left bank of the Bhagirathi River along the Gangotri National Highway (NH-34) in Bhatwari Tehsil. The Khirgad stream passes through Dharali before meeting the Bhagirathi opposite Mukhwa village. While the original Dharali settlement was located about 100 m above NH-34, away from the Khirgad stream, substantial unplanned development—particularly hotels and residential buildings—had gradually expanded along both banks of the stream near its confluence with the Bhagirathi. This expansion on the active floodplain and natural drainage channel significantly increased the exposure of the area to hazard impacts (Geological Survey of India, 2025).

The news of the Dharali debris flow quickly became sensitized, spreading across social media platforms, YouTube, and national news channels. Heart-wrenching visuals of destroyed homes, buried roads, and desperate rescue efforts drew widespread attention and sympathy. For the local community, it was an unimaginable loss, while for others it became a moment of reflection on the growing risks faced by Himalayan settlements. Reactions poured in from the public, academicians, scientists, and civil society—some expressing grief and solidarity, others raising urgent concerns about fragile mountain ecosystems and the need for safer, more sustainable development.

Eyewitness accounts describe an extremely rapid rise in water level with a heavy sediment load, leaving residents with little time to evacuate (NDTV, 2025). Reports indicate that 70–90% of the settlement area was destroyed, with several fatalities yet to be officially confirmed.

Fig. 1: Panoramic view of debris flow at Dharali

On the same day, another debris flow occurred along the Telgad stream at Harsil, about 3 km downstream of the Dharali debris flow site. This event destroyed part of the Army camp and partially blocked the flow of the Bhagirathi River. As a result, a temporary lake was formed, submerging a section of the National Highway connecting Harsil to Dharali as well as a nearby helipad.

Fig.2: High resolution satellite imagery showing pre and post Dharali Debris Flow event scenario

Fig.3: The area encroached by the thick debris cover at Dharali shown in red colour

Fig. 4: Formation of a temporary lake caused by the encroachment of the Bhagirathi River's flow due to the debris flow along Telgad at Harsil

Post-event satellite analysis of the Dharali debris flow, carried out by the National Remote Sensing Centre (NRSC), ISRO, using high-resolution Cartosat-2S imagery (06 August 2025) compared with pre-event Cartosat-3 data (13 June 2024), revealed extensive geomorphic and infrastructural impacts. The assessment showed significant widening of stream channels and alteration of the local river morphology, alongside the formation of a ~20 ha fan-shaped debris deposit at the Kheer Gad–Bhagirathi confluence. Additionally, several buildings were found to be completely destroyed or buried beneath thick debris deposits.

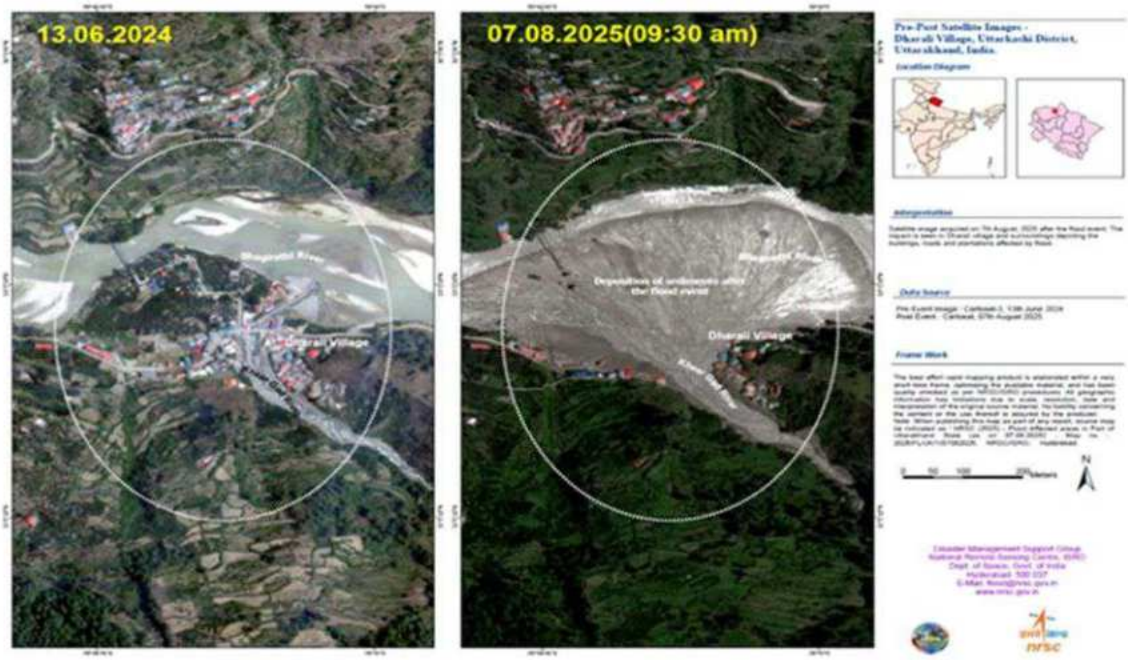

Fig. 5: Pre-event Cartosat-3 image of 13.06.2024 and post-event Cartosat-2S image of 07.08.2025 (Source: NRSC)

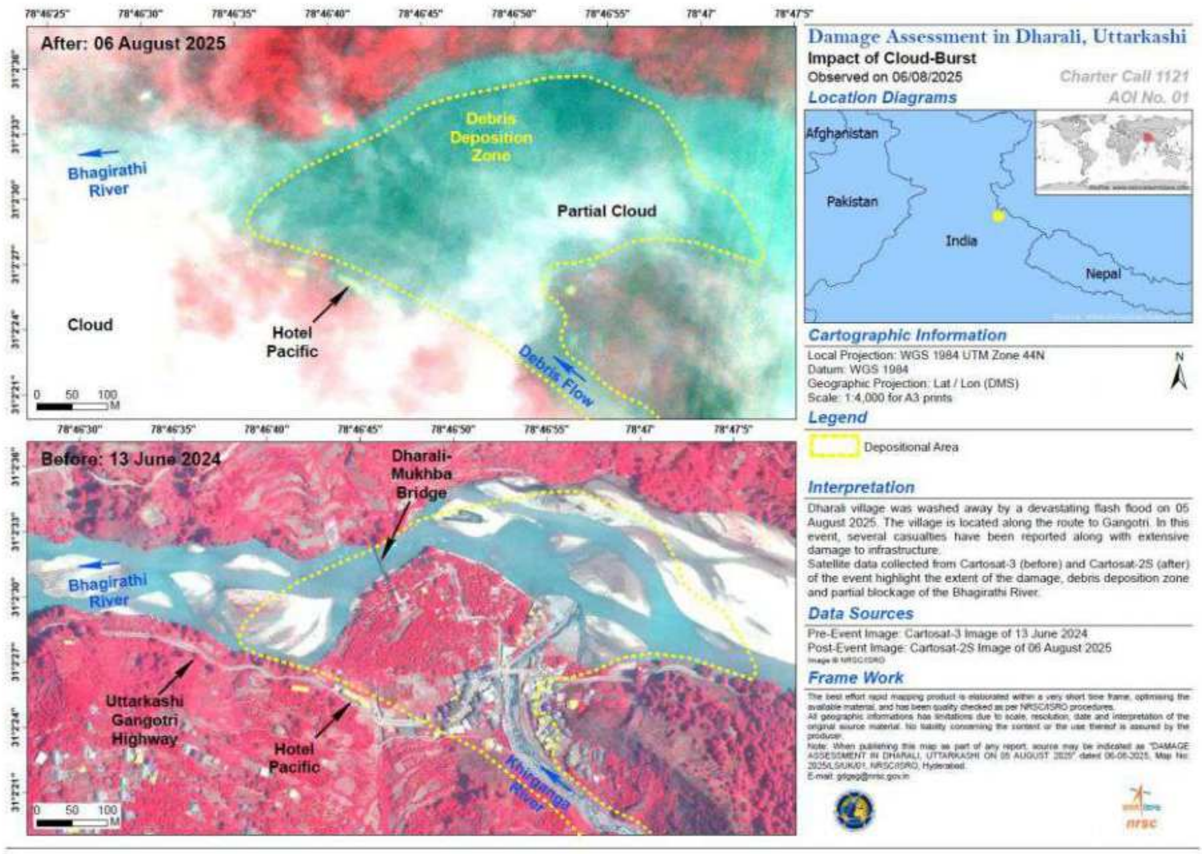

Fig. 6: Damage assessment based on Pre-event Cartosat-3 image of 13.06.2024 and post-event Cartosat-2S image of 06.08.2025 (Source: NRSC)

Following the disaster, coordinated rescue and relief operations were launched by the State Disaster Response Force (SDRF) and the National Disaster Response Force (NDRF), with logistical and operational support from the Border Roads Organisation (BRO), Indo-Tibetan Border Police (ITBP), and the Indian Army and Air Force. Efforts included airlifting stranded pilgrims and residents between Harsil and Gangotri, providing medical assistance, and setting up temporary shelters (India Times, 2025)

2 BRIEF GEOLOGY AND GEOMORPHOLOGY OF THE AREA

The Kheer Gad watershed, draining into the Bhagirathi River, exposes a diverse litho-tectonic framework of high-grade metamorphics, granitic intrusions, and polyphase deformation structures of the Higher Himalayan Crystalline Zone. This geological setup governs the relief, structural patterns, and hydrological behavior of the basin. Complementing this, DEM-derived geomorphometric layers—slope, aspect, SPI, hillshade, stream order, and contours—provide quantitative insights into surface processes, runoff dynamics, and erosion susceptibility.

Together, these datasets offer a holistic appraisal of terrain evolution and geohazard potential in the catchment.

2.1 Geological Framework

The study area lies within the Higher Himalayan Crystalline Zone, structurally emplaced over the Lesser Himalaya along the Main Central Thrust. This zone is composed of high-grade metamorphic rocks with granitic intrusions and younger pegmatitic bodies, well exposed around Dharali–Harshil. The Central Crystalline here comprises augen gneiss, garnetiferous quartz–mica schist, streaky gneiss, calc gneiss, marble, kyanite schist, and quartzite. At Sukki, augen gneiss is prominently developed, showing feldspar augens wrapped by foliation, while the overlying schists contain aligned quartz, biotite, muscovite, and garnet porphyroblasts imparting a distinct spotted texture. Regionally, these rocks are grouped into the Khatling, Yamnotri, and Wajri Formations, represented in the study area by variable associations of schists, gneisses, quartzites, phyllites, and marble bands. Photographs of field exposures of these lithologies are shown in the Fig.7.

The metamorphic sequences are intruded by granitoids of different ages. The Bhaironghati Granite is prominently exposed and is further cut by younger leucogranites of Miocene age. Both the granites and host rocks are intruded by pegmatite and aplite–pegmatite veins, observed around Harsil, Mukhba, and Dharali. These veins, ranging from 10 cm to more than 5 m thick, are composed of feldspar, quartz, muscovite, garnet, and tourmaline.

The rocks of the area preserve clear evidence of polyphase deformation. The earliest phase produced rootless folds, while later events generated NW–SE trending faults, followed by N–S oriented structures. Primary bedding (S0) is preserved in quartzite and phyllite, generally trending NW–SE to E–W with moderate northerly dips. Foliation (S1) is widespread and developed parallel to the axial planes of folds. Around Jhala, foliation trends broadly east–west with northerly dips, while at Harshil and Dharali it shows a NE–SW trend with moderate dips to the north. Slickenlines are well preserved on granitic surfaces, plunging gently northward along NE–SW trends. Folding is common, typically isoclinal to tight, asymmetrical, and in places recumbent, with fold axes trending from NE–SW to ENE–WSW. Faults are mapped at multiple locations, showing both NW–SE and NNW–SSE orientations, while joints are well developed in both metasedimentary and crystalline rocks, displaying three dominant sets.

Foliated Metapelites

Augen Gneiss

Slickensides in granite

Sheared Metapelites near Dharali

Folding in Metapelites

Sheared Metapelites near Harshil

Fig. 7: Lithological details of rocks exposed at site

In summary, the study area exposes a diverse range of lithologies including augen gneiss, quartz-mica schist, and migmatites, intruded by granites, leucogranites, and pegmatitic dykes. These rocks collectively document a long geological history involving high-grade metamorphism, granitic intrusions of multiple ages, and polyphase deformation associated with the Himalayan orogeny. It is imperative to have a significant understanding of the litho-tectonic framework and structural patterns in this sector in order to undertake a detailed appraisal of any kind of geohazard assessment.

2.2 Geomorphometric Assessment

The present morphometric and terrain analysis of the watershed of Kheer Gad, a left bank tributary of Bhagirathi River was carried out using DEM-derived thematic layers including contours, slope, aspect, stream power index (SPI), hillshade, and stream ordering. Together, these layers provide insights into the relief, hydrology, and terrain controls governing surface processes in the catchment.

The **contour map** (Fig. 8a) illustrates the topographic variation of the catchment draining into the Bhagirathi River near Dharali–Harsil, Uttarkashi highlighting the rugged topography, with elevations ranging from ~2500 m near the river valley to >5500 m. The closely spaced contours in the central and southern parts of the catchment indicate extremely steep and rugged terrain, which aligns with the slope analysis showing dominance of 45°–75° gradients. Wider contour spacing in localized pockets represents gentler slopes, mainly near valley bottoms and depositional areas adjacent to the Bhagirathi River. Abrupt relief indicates high-energy geomorphic processes, and vulnerability to landslides, debris flows, and flash floods. The National Highway (NH-34), running parallel to the river at the valley floor, lies directly at the foot of these steep slopes, making it particularly susceptible to slope failures and river-related hazards. This map highlights the rugged geomorphology of the region, underscoring the vulnerability of infrastructure and settlements located along the Bhagirathi valley corridor.

The **hill shade map** (Fig. 8b) illustrates the steep mountainous catchment of Kheer Gad draining northward into the Bhagirathi River in the Dharali–Harsil sector, Uttarkashi. The gray scale hill shade effectively highlights the rugged topography, with deeply incised valleys and steep slopes that are highly susceptible to debris flow and landslide activity. The map provides critical geomorphic insight into the terrain, helping to identify potential initiation zones of debris flows and their direct connectivity to both the highway and the river system. This visualization underscores the high exposure of infrastructure and riverine corridors to geomorphic hazards in the region.

The **slope map** (Fig. 8c) depicts the terrain characteristics of the catchment draining into the Bhagirathi River near Dharali–Harsil, Uttarkashi. The color-coded slope classes reveal a dominance of steep to very steep slopes (45°–75° and above, shown in green to blue shades) across much of the southern and central portions of the catchment. These areas represent zones of high geomorphic instability, where landslides and debris flows are most likely to be initiated, particularly under conditions of intense rainfall or seismic shaking. Moderately steep slopes (30°–45°, shown in yellow) form transitional zones, while gentler slopes (0°–30°, red to orange) are relatively limited and largely confined to valley bottoms and depositional fans near the Bhagirathi River. The National Highway (NH-34), running parallel to the Bhagirathi River, lies at the toe of these steep slopes, making it highly vulnerable to mass wasting processes. The map highlights the critical slope–infrastructure interaction, emphasizing the need for hazard mitigation in order to protect transport routes and settlements in this fragile Himalayan terrain.

The **aspect map** (Fig. 8d) shows the orientation of slopes in the catchment draining into the Bhagirathi River. Different colours represent slope directions, providing insights into geomorphic processes, microclimatic variation, and slope stability conditions. The catchment exhibits a highly diverse aspect distribution, with slopes facing all cardinal and intercardinal directions.

South- and southwest-facing slopes dominate large portions of the area, which typically receive higher solar radiation, leading to greater weathering, drier conditions, and potentially reduced vegetation cover. Conversely, north- and northeast-facing slopes, visible mostly along the upper and central parts, are cooler and moister, favouring snow accumulation and prolonged saturation that can influence landslide susceptibility. East- and west-facing slopes, widely distributed throughout the catchment, experience diurnal variations in solar heating that may contribute to thermal stress and rock disintegration.

The presence of such varied slope aspects within short distances highlights the complex geomorphic setup of the region. For infrastructure such as the National Highway (NH) running along the Bhagirathi valley floor, this variability means differential hazard exposure. For example, southwest-facing slopes above the road may be prone to dry ravel or debris slides, while north-facing slopes may sustain prolonged saturation and instability during monsoons or snowmelt. Overall, the aspect analysis underscores the heterogeneous nature of slope processes, crucial for planning slope stabilization and hazard mitigation measures in the valley.

The occurrence of a seventh-**order stream** (Fig. 8e) within such a relatively small catchment is remarkable; as such high-order streams are usually associated with much larger basins. Its presence here highlights the combined influence of steep slopes, high relief, and intense terrain dissection, where numerous lower-order streams rapidly merge into higher orders due to vigorous fluvial erosion. This configuration leads to a flashy hydrological response, with rainfall quickly translating into concentrated flows, thereby increasing the risk of flash floods, debris flows, and temporary damming along the Bhagirathi River. The high-order channels also exhibit strong sediment transport efficiency, carrying large volumes of debris and sediments downstream, which can intensify aggradation and channel instability. For infrastructure, especially the National Highway (NH) running along this valley, these conditions pose significant hazards, including frequent washouts, debris blockages, and flood-related damages.

Finally, This **Stream Power Index (SPI) map** (Fig. 8f), when interpreted alongside the previous stream-order and catchment maps, gives valuable insight into erosion dynamics and hazard potential of the basin. The distribution shows a mosaic of very high erosion zones (>5), especially concentrated along the main seventh-order channel and its higher-order tributaries. This aligns with the presence of a high-order stream system in a relatively small catchment, where steep slopes and intense dissection accelerate runoff concentration and erosive power. The high and very high erosion zones reflect areas of strong fluvial activity, capable of entraining and transporting large volumes of debris and sediments directly into the Bhagirathi River, intensifying risks of aggradation, flash floods, and channel instability. Conversely, the low erosion and depositional pockets (<0 and 0–1) scattered across the basin indicate temporary sediment storage areas, where material may accumulate before being remobilized during high-intensity rainfall or extreme flow events. These zones often contribute to sudden debris surges once destabilized. When considered together, the maps highlight a catchment highly prone to flashy hydrological responses with significant erosional efficiency. The combination of steep slopes, seventh-order drainage, and widespread high SPI values suggests that even moderate rainfall can trigger rapid erosion, debris flows, and channel blockages, posing hazards to the Bhagirathi River corridor and the National Highway (NH) that closely follows it.

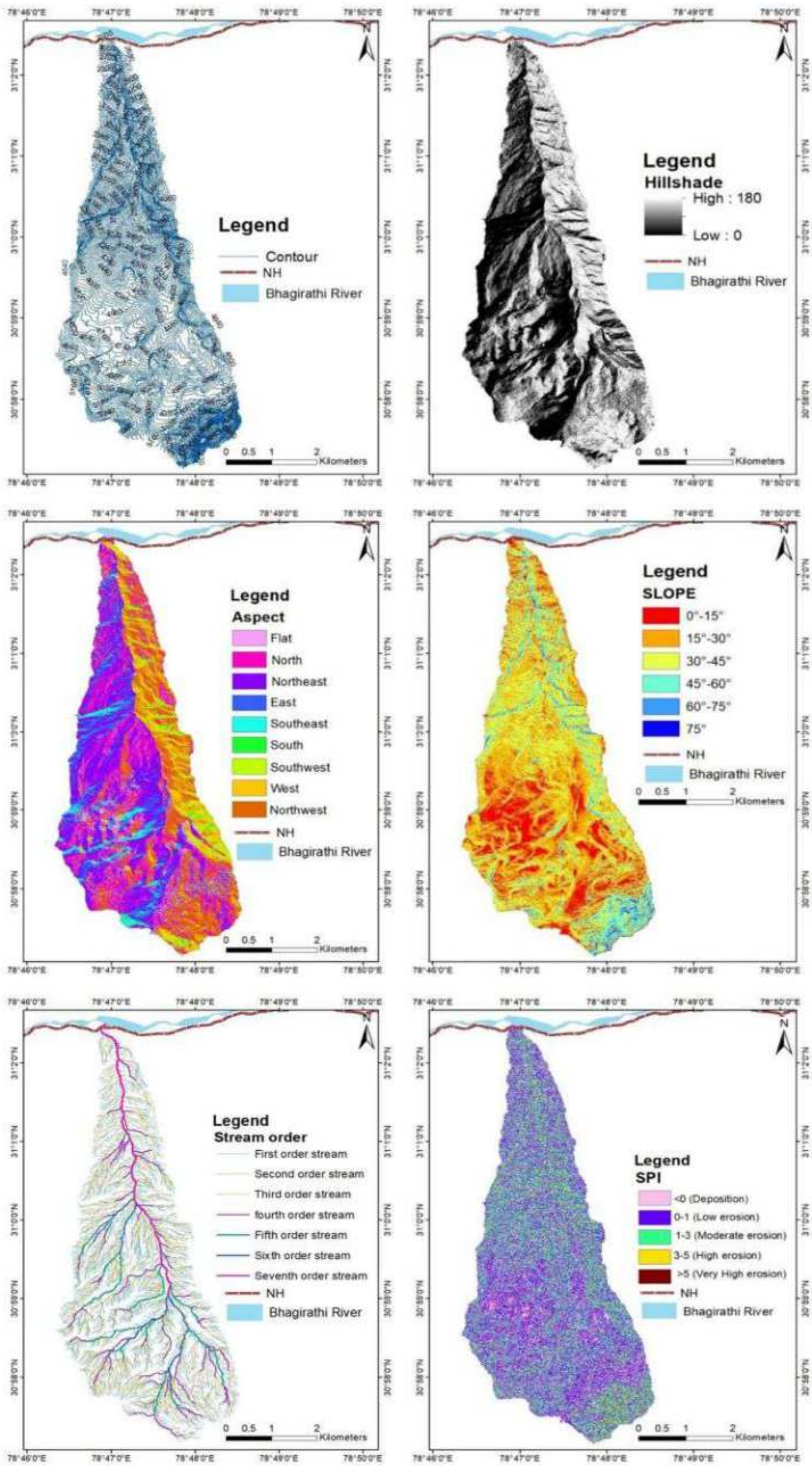

Fig. 8: (a) Contour Map; (b) Hillshade Map; (c) Slope distribution map; (d) Aspect Map; (e)Stream Order Map; and (f) Stream Power Index Map

Frequent shallow landslides occur on these unstable slopes, contributing large volumes of loose material to the channel. This geomorphic configuration promotes high runoff generation, rapid sediment delivery, and channel incision during intense storm events, making the catchment especially prone to debris flow initiation and surge-type failures.

3 POST-DISASTER RECONNAISSANCE SURVEY BY THE TECHNICAL TEAM

In the aftermath of the Dharali disaster, which caused severe disruption along the Bhagirathi valley due to debris flows, channel blockages, and widespread infrastructural damage, the Uttarakhand State Disaster Management Authority (USDMA) constituted a multidisciplinary technical team to carry out a rapid scientific assessment of the affected area. The team comprised Dr. S. Sarkar (Director, ULMMC), Dr. D. P. Kanungo (Chief Scientist, CSIR–CBRI), Shri Ravi Negi (Director, GSI), Dr. Mohit Kumar Puniya (Principal Consultant, USDMA), and Dr. Amit Kumar (Scientist-C, WIHG). A detailed field survey (Fig. 9) was undertaken from 13 to 16 August 2025, focusing on post-event observations, documentation, and preliminary scientific evaluation of the disaster site.

Fig.9: Team visiting the sites affected by the disaster

The primary objectives of this reconnaissance survey were to:

i. Map debris deposition patterns and alterations in channel morphology

ii. Identify the primary triggering factors (e.g., cloudburst, rainfall, glacial melt contribution, slope failure)

iii. Assess damage to settlements, roads, and other infrastructure

iv. Evaluate secondary hazard potential and futuristic risk scenarios

v. Propose preliminary mitigation measures and disaster risk reduction strategies

As a preliminary assessment of the debris flow characteristic and pattern, the technical team visualised the available video on social media captured during the Dharali debris flow event and interpreted the following six distinct subsequent flow surges of the debris flow event:

Debris Flow Surge Sequence	Date &Time (On 05.08.2025)	Classification	Characteristics
Event-1	Around 13:30 hrs	*Classic Debris Flow Surge*	• Most destructive surge – carried bulk of boulders and coarse debris. • Swept directly over main Dharali settlement, uprooting structures. • Maximum coarse load (large boulders, angular blocks, woody debris). • Primary erosional impact on the apex and central fan.
Event-2	Around 14:40 hrs	*Slurry/Hyper-concentrated Flow Hybrid*	• Consisted mostly of slurry (wet, fine-grained debris with some gravel). • Multiple breaking-wave fronts spreading sideways across settlement edges. • Did lateral sweeping of peripheral structures. • Lower coarse boulder content than Flow-1, but very destructive due to fluid pressure and lateral reach.
Event-3	Around 15:30 hrs	*Debris Flood (Sediment-laden water)*	• Mostly watery flow through a newly carved shallow channel over the fan. • Carried limited sediment and minor blocks. • Specifically struck the Base of the Tower, destabilizing and knocking it down. • Acts like sediment-laden floodwater — channeled, less viscous, high velocity.
Event-4	Around 15:45 hrs	*Streamlined Debris Flow/ High-Solid Surge*	• More sediment than Flow-3, and more spread than Flow-3. • Channel-confined initially but begins fanning out. • Carried significant gravel and some blocks, but structured flow with clear front. • Possibly sourced from a secondary slope failure feeding into the main stream.
Event-5	Around 15:50 hrs	*Hybrid Debris Flow Surge*	• Brought additional boulders. • More sediment than Flow-3 and Flow-4. • Showed broad lateral expansion, inundating wider parts of the fan. • Suggests mobilization of stored debris from side gullies and slopes after main blockage breached.
Event-6	Around 18:30 hrs	*Late-Stage Debris Flood/ Fan Reworking Flow*	• Behaviour similar to standard sediment-laden streamflow, but with massive fan-wide spread. • Spread widely across the valley floor. • Laid down 1.5–2.0 m thick fresh sediment blanket over entire debris fan. • Mostly fine sediment, slurry, shallow sheet flow.

Field evidence (Fig. 10) shows a mix of large clasts embedded in sandy–silty matrix, representing different stages of debris transport, from high-magnitude boulder-rich surges to finer sediment-laden flows. The angular to sub-angular nature of the fragments, with minimal rounding, indicates their short-distance transport from nearby source slopes, highlighting the intensity and destructive power of the event.

Field evidence showing the enormous boulder-laden debris that devastated Dharali during the event, highlighting the sheer magnitude of transported material.

Field exposure showing stratified debris flow deposits, with coarse boulders embedded in a muddy–sandy matrix, indicative of high-energy transport and rapid deposition during the Dharali event.

Close-up view of debris material comprising angular to sub-angular gneissic fragments and metapelites embedded in a finer matrix, reflecting short-distance transport and high-energy deposition.

Fig. 10: Field observation of transported material

3.1 Survey and Observation at Dharali Debris Flow Affected Area

The **technical team** carried out both ground surveys and aerial reconnaissance by helicopter during 13–15 August 2025 in and around the Dharali debris flow–affected area and along the Kheer Gad channel. The following key observations were made by the technical team:

a. The debris flow washed away a majority of the settlements (including hotels, homestays, restaurants, shops, and residential houses), a stretch of about 400–500 m of National Highway (NH-34), as well as vegetation and sparse habitations in the floodplain along its flow path.

b. Under normal conditions, the Kheer Gad tributary takes a right turn beyond the National Highway before discharging into the Bhagirathi River. However, during the debris flow event, the tributary diverted into a straight course due to the enormous debris and water load with extremely high kinetic energy, devastating downslope settlements and vegetation along its altered flow path.

Fig. 11: The pre and post event pictures showing the change of flow direction

c. Observations from the surface of the depositional fan indicate a gradational deposition pattern, with coarser material (boulders) near the National Highway location, progressively grading into finer material (sand/silt/clay) towards the periphery of the debris fan deposit.

Fig. 12: Distribution of debris material

d. During the search operations through manual excavation by the SDRF/NDRF team, it was observed that the subsurface showed a gradational deposition from finer to coarser material (i.e., sand/silt/clay to boulders) with increasing depth.

e. At the peripheral areas of the fan deposit, the finer material exhibited high water retention, which hindered both manual and mechanical excavation efforts.

Fig. 13: Thewater getting filled-up during the manual excavation showing the presence of underground water

f. It was further observed that the debris flow and its associated fan deposits encroached upon the original flow path of the Bhagirathi River, shifting it from the left bank towards the right bank (i.e., the Mukhba side), thereby confining the river into a comparatively narrower channel.

g. As a result of this debris flow, the hanging bridge connecting Mukhba and Dharali has been heavily damaged. The bridge pier on the left bank has been severely affected structurally and is partially buried under debris, while the pier on the right bank has also sustained moderate structural damage. Although the bridge remains operational in its distressed condition, it poses a significant risk to stability and safety.

h. The shifting of the Bhagirathi River towards the right bank, coupled with heavy water discharge during the peak monsoon season, is directly impacting the already weakened right-bank pier of the hanging bridge, thereby posing a critical threat to its long-term stability and functionality.

Fig. 14: Impact of water on the right bank of the river damaging the foot bridge connecting Dharali to Mukhba

i. The technical team carried out an aerial survey by helicopter, with support from the district administration, along the Kheer Gad channel to observe and analyze the probable causes of the Dharali debris flow. Due to bad weather and cloud cover, the team was unable to view the glaciated portion upstream. However, the flow channel from just beyond the confluence of two glacier-fed streams up to the depositional fan at Dharali was clearly visible.

j. Observations from the aerial survey indicate that the flow path is confined within a narrow, gorge-shaped valley with dense forest cover on both side slopes. No fresh landslides were observed along the side slopes of the valley, nor were there any signatures of a landslide dam formation. Therefore, the possibility of a landslide lake outburst flood (LLOF) is ruled out.

k. Furthermore, no existing glacial lake was observed by the team during the aerial survey.

Fig. 15: The Khir Gad stream at different heights from the confluence of two drains at upper level to the deposition site

3.2 Temporary Lake Formation at Harsil due to Debris Flow along Telgad

At approximately 13:45 hrs on 05 August 2025, another debris flow occurred along the Tel Gad in the Harshil–Tel Gad sector, about 15 minutes after the first debris surge from Kheer Gad that devastated Dharali. At Telgad, a tributary joining the Bhagirathi upstream of Harsil, a flash flood completely destroyed an army camp. Massive amounts of sediment and boulders were deposited, blocking the river course and leading to water impoundment along a ~2 km stretch, which submerged nearly 200 meters of the national highway.Observations suggest two distinct phases: an initial, high-energy flux transporting large boulders that formed a coarse debris fan at the Kheer Gad outlet, followed by a subsequent debris flood dominated by mixed sediments and finer material, which spread across and overlaid the earlier fan surface. These events partially destroyed the Army Camp at Harshil.

The debris transported along the bed of the Bhagirathi River from the Kheer Gad debris fan reached the Harshil–Tel Gad area under high discharge conditions. Its velocity was subsequently reduced by the additional debris material contributed by the Tel Gad. This interaction caused the deposition of assorted-sized boulders along the Bhagirathi main channel, just upstream of the Tel Gad debris fan. Intermittent high and low flows of the Bhagirathi riverfurther sorted and channelled pebbles, cobbles, and finer gravel toward the left bank, immediately upstream of the Tel Gad fan. Additional obstruction caused by the increased bed load from the Dharali fan, combined with flow dampening near the Tel Gad confluence, generated a temporary impoundment, effectively creating a short-lived lake. The resulting backwater flooding submerged the helipad located near the Tel Gad confluence and inundated the Harshil–Gangotri road stretch along the left bank of the Bhagirathi.

Avulsion of the Bhagirathi River within its active stream domain, driven by altered channel morphology under these conditions, also directly impacted Harshil village on the right bank. This resulted in partial damage to the GMVN Guest House, smaller settlements in its vicinity, partially damaging the bridge abutment and a portion of the Army Camp on the opposite bank.

These impacts underscore the compounding hazard of interacting debris fans in narrow Himalayan valleys, where simultaneous surges from multiple tributaries can amplify downstream risk through channel choking, flow dampening, and transient damming.

. Tel Gad Debris Fan that destroyed the Army Camp partially.

Partially damaged road and bridge abutment.

Damaged settlements at Harshil

Scouring the foundation of GMVN Gust House, Harshil

Fig. 16: Debris flow at Harsil along Telgad

The team surveyed the area and suggested the Irrigation Department to remove the debris by excavation at the outer periphery of the fan so as to channelise the water of the lake. It was observed that as soon as the debris removal began the river started widening and lake water also started flowing sluggishly. In the afternoon of 15th August, it was observed that there is a little decrease in water level in the lake at the Dharali side as measured by the NDRF.

Fig.17: Channelisation of water at Harsil lake

Fig.18: Water level in the lake at Dharali side on 15th August

4. RAINFALL ANALYSIS AND INTERPRETATION

Between 4th and 5th August 2025, a significant high-intensity rainfall event occurred in the upper Bhagirathi Basin, severely impacting the northern slopes of the region. The effects were concentrated along several tributaries of the Bhagirathi, including **Son gad, Tel gad, Lamcha gad, and Kheer gad**, as shown in the Fig. 19. At Lamchagad, a tributary of the Bhagirathi, a flash flood caused the collapse of a bridge near Gangnani. Further upstream, at Songad, near the Loharinagpala project, a debris flow triggered by the flash flood washed away sections of the national highway and another bridge. This resulted in temporary blockages of the Bhagirathi River channel, with large volumes of sediment and boulders deposited. At Telgad, huge amounts of sediment and boulders were deposited, partially blocking the river course causing submergence of the national highway.Finally, at Kheer Gad, upstream of Dharali, there was a deposition of an enormous volumes of sediments into the Bhagirathi River. Collectively, these cascading events along the northern slope tributaries blocked the Bhagirathi River at multiple locations, causing sediment-laden impoundments and highlighting the extreme geomorphic response of the basin to high-intensity rainfall.

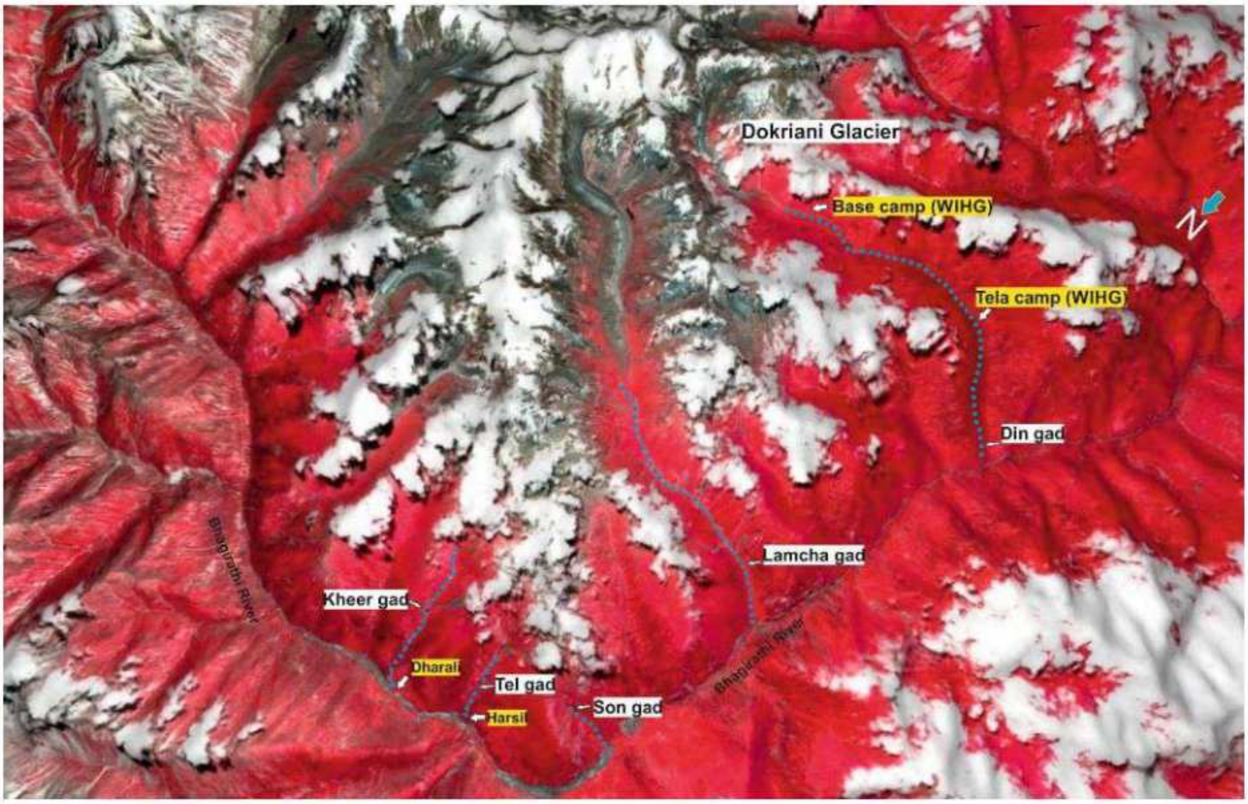

Fig.19: Satellite image showing the locations impacted by a series of events in the Bhagirathi basin during 4–5 August 2025.

To understand the triggering conditions of this event, rainfall data during this period were analyzed by the Wadia Institute of Himalayan Geology (WIHG). The institute maintains two rain-gauge stations in the Dingad catchment, located on the same northern slope and within an aerial range of ~20 km, encompassing all the impacted locations described above. This dataset provides valuable insights into the spatio-temporal distribution of rainfall that initiated the cascading chain of flash floods, debris flows, and river blockages. The data were collected on a daily scale from two ordinary rain gauges (ORGs), strategically installed at different elevations to capture altitudinal variability in precipitation. The gauges are positioned at **Tela Camp (2540 m a.s.l.)** and **Base Camp (3763 m a.s.l.)**, with manual readings taken twice daily at 08:30 and 17:30 hours (Figure 19). This setup allows for assessing both the magnitude and timing of rainfall, which is critical for linking localized precipitation to hydrological responses in the upper Bhagirathi Basin. These stations were originally installed for the long-term monitoring of the Dokriani Glacier, from which the Dingad stream emerges, but also provide valuable hydrometeorological data for understanding of hydrological response of the Dokriani Glacier during melt-season.

Station 1:

Between 3 and 5 August 2025, **Tela Camp** experienced a concentrated spell of heavy rainfall. On 3 August, moderate precipitation was recorded, with 7.4 mm in the morning and 11.2 mm in the evening, though the total value appears underreported in the Figure. This was followed by an extreme rainfall event on **4 August, when 49.2 mm** fell in the morning and **19.6 mm in the evening**, giving a total of **60.4 mm**, the single highest daily rainfall in the record (Fig.20).

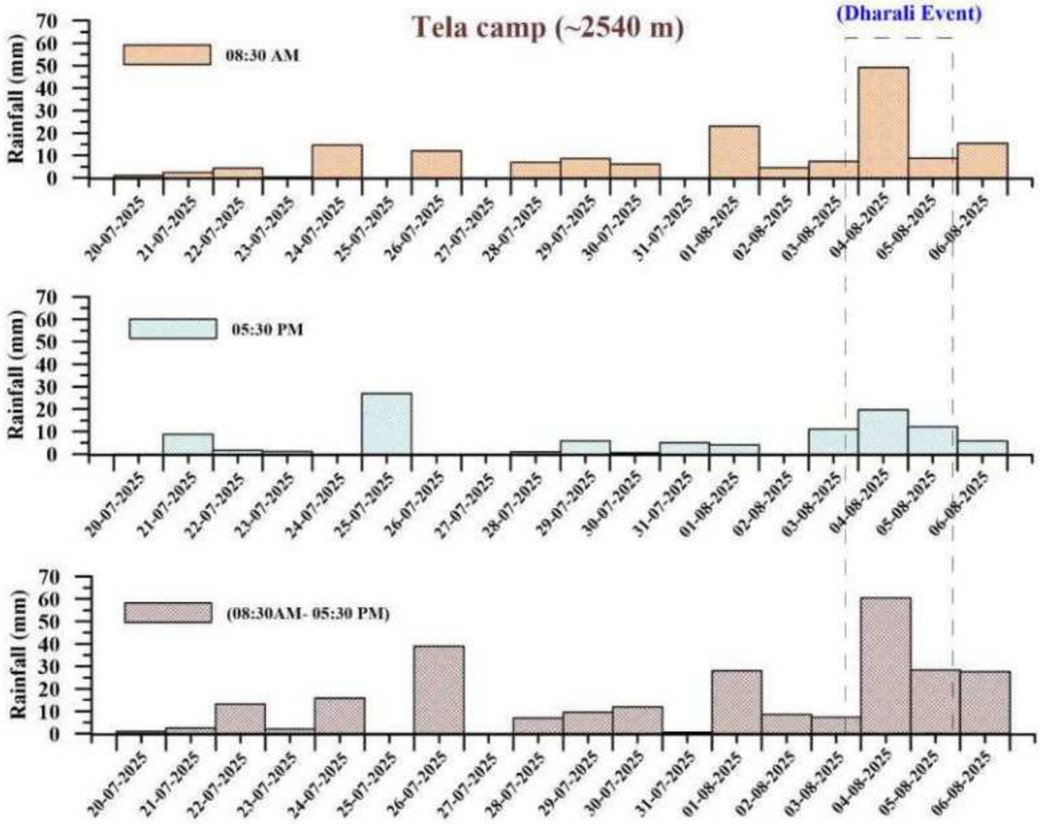

Fig.20: Daily rainfall distribution recorded at Tela Camp station established by Wadia Institute of Himalayan Geology, Dehradun in the Dingad catchment.

The next day, 5 August, rainfall continued with 8.8 mm in the morning and 12.2 mm in the evening, totalling 28.4 mm. **This three-day sequence delivered nearly 96 mm of rainfall**, representing the most intense wet spell of the observation period.

The sharp peak on 4 August, followed by substantial rainfall on 5 August, indicates prolonged saturation of the catchment area, which would significantly increase runoff and heighten the risk of flooding, landslides, and debris flows.

Station 2:

Between 3 and 5 August 2025, the Base Camp station also recorded a significant rainfall sequence, though with a different pattern compared to Tela Camp. On 3 August, only a trace amount was observed (1.6 mm in the evening, total 1.4 mm), indicating the beginning of unsettled conditions. **The situation intensified on 4th August, with 10.6 mm in the morning and 31.4 mm in the evening**, though the total is recorded as 12.2 mm, suggesting a possible reporting inconsistency. This still represents a day of notable rainfall activity, especially during the evening. The heavy spell continued on 5 August, when 25.0 mm fell in the evening, making up the full daily total of 31.4 mm (Fig.21). Thus, unlike Tela Camp, where the extreme burst came primarily in the morning of 4 August, the Base Camp experienced its heaviest rainfall later in the day on 4 and 5 August, with cumulative amounts exceeding 43 mm across the two days. This clustering of high evening rainfall events would have led to sustained catchment saturation, delayed runoff response, and potentially heightened downstream flood and slope instability risks.

The stations record rainfall following IMD observation timings, yet both Tela Camp and Base Camp measured higher amounts compared to IMD reports at Harsil (6.5 mm). The glaciated region received comparatively less rainfall during this event, indicating that areas below 3763 m elevation experienced more intense precipitation. Rainfall recorded between 3 and 5 August 2025 shows a distinct contrast between Tela Camp (2540 m) and Base Camp (3763 m). On 3 August, Tela Camp received 7.4 mm compared to only 1.4 mm at Base Camp. On 4 August, Tela Camp recorded 60.4 mm, nearly five times higher than the 12.2 mm at Base Camp. However, on 5 August the pattern reversed, with Base Camp (31.4 mm) exceeding Tela Camp (28.4 mm).This contrast supports the study, suggesting that continuous episodes of rainfall across elevations played a critical role in mobilizing sediment and triggering the event in such a small and sensitive catchment. However, the magnitude of rainfall differs across basins, and the Dingad catchment, being relatively small and closely monitored, provides a representative picture of rainfall distribution during this event.

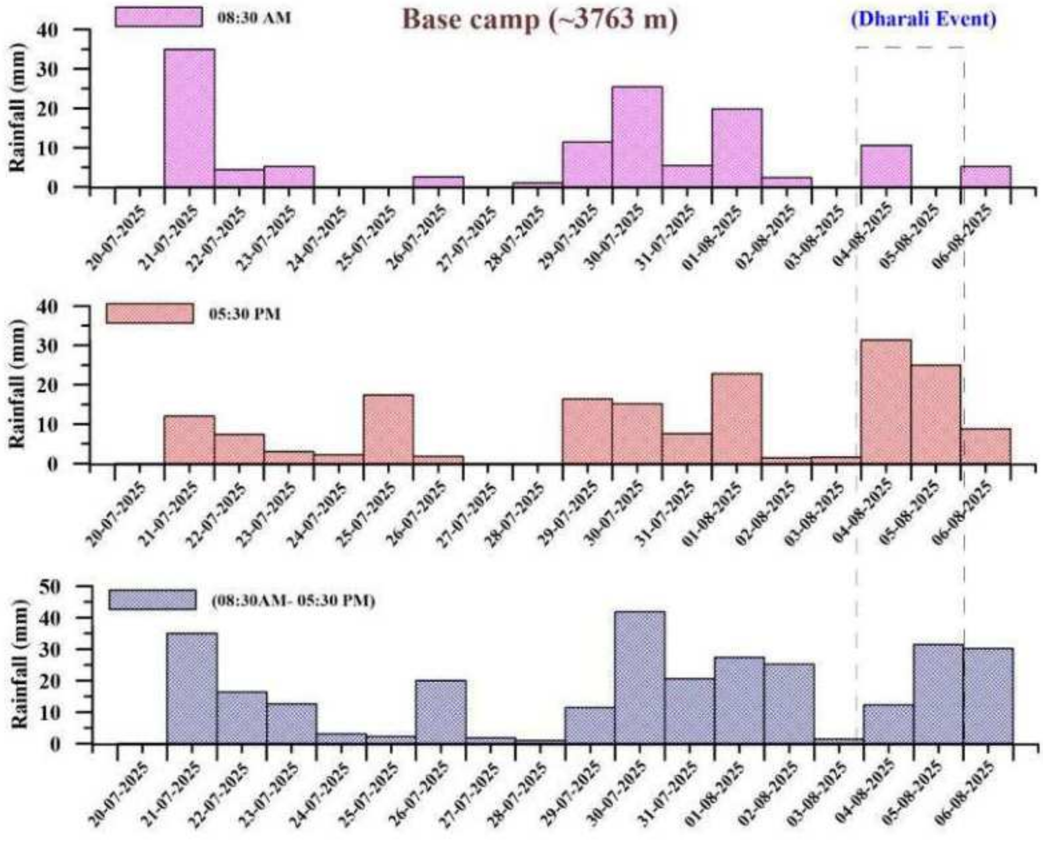

Fig.21: Daily rainfall distribution recorded at Base Camp established by Wadia Institute of Himalayan Geology, Dehradun in the Dingad catchment.

These observations highlight that rainfall is highly variable among meteorological stations, reinforcing the need for installing a denser observational network across basins to better capture spatial heterogeneity in precipitation. Importantly, unconsolidated glacio-fluvial and morainic sediments released by receding glaciers in the basin play a crucial role in such triggering processes, as they are easily mobilized on steep, higher slopes during intense rainfall episodes.

The spatial distribution of rainfall in the upper Bhagirathi basin is strongly influenced by orography and local topography. Steep valley walls, high ridgelines, and deep gorges enhance orographic lifting, leading to higher precipitation at mid-elevations compared to glacierized headwater regions. This explains why Tela Camp (2540 m) received higher rainfall than Base Camp (3763 m) during consecutive days of the event. Such elevation-dependent contrasts highlight the role of terrain in modulating rainfall patterns, where localized topographic effects can produce sharp gradients in precipitation over short distances. These findings emphasize the need to account for orographic and micro-topographic controls when assessing rainfall distribution and its role in triggering sediment mobilization in high-mountain basins.

To evaluate the event, the IMD Realtime gridded rainfall dataset (0.25°x0.25° resolution) for the Uttarakhand state from 24th July to 5th August 2025 has been used to analyse the evolution of area-averaged 24-hour accumulated rainfall over the state along with the daily climatology of the same. The spatial rainfall map over Uttarakhand is also included in the Fig. 22. The result suggests the area-averaged daily rainfall over Uttarakhand has reached around 45 mm on 5th Aug. Additionally, the spatial observation depicts the precipitation over Uttarkashi has not exceeded 60 mm on 5th August. The analysis using the IMERG early run hourly precipitation dataset (0.1° x 0.1° resolution) has also been done to validate the findings of IMD observation dataset.

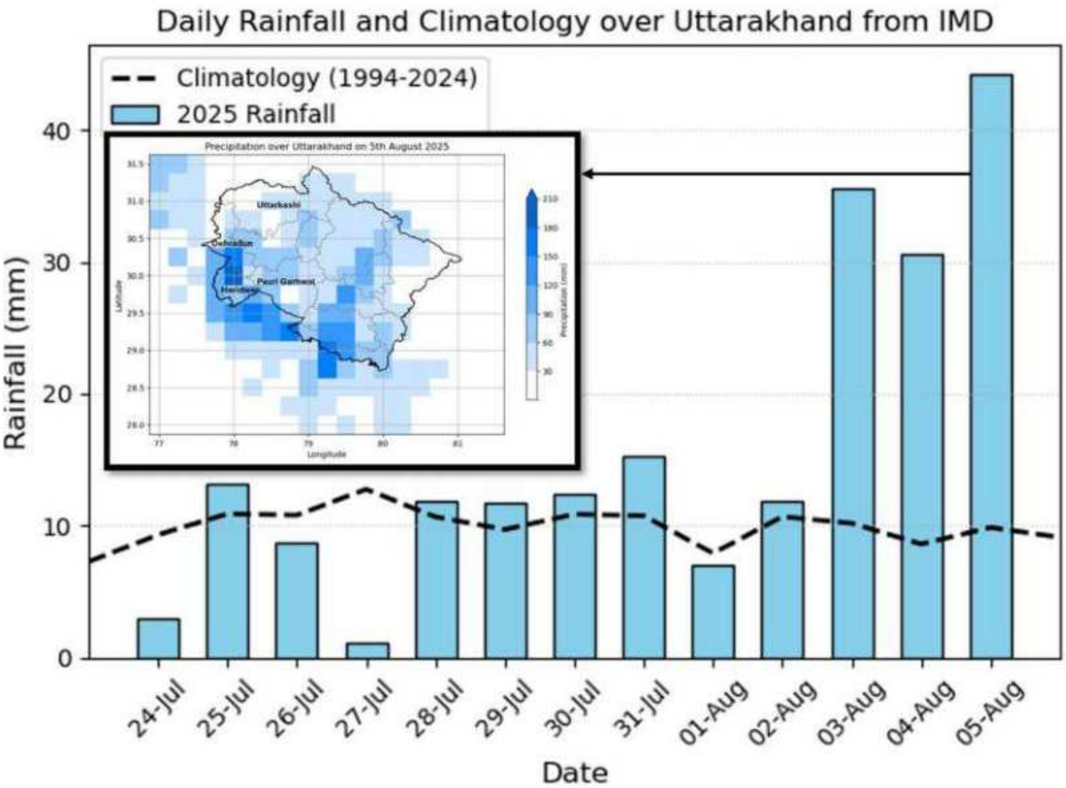

Fig.22: Area-Averaged Daily accumulated Precipitation and Climatology for the Uttarakhand Region (28°-31.5° N and 77°-81.5° E) from 25th July to 5th August 2025, using the IMD Realtime gridded rainfall observation dataset. The spatial map (inset) shows the daily accumulated rainfall of the region on 5th August 2025, the day of the event (Source: *https://imdpune.gov.in/lrfindex.php*, ***downloaded on 6th August, 2025)***

In the days preceding the 5th August 2025 Bhagirathi valley debris-flow events, the India Meteorological Department (IMD) had issued a series of heavy rainfall warnings. An extended forecast on 31 July 2025 highlighted isolated heavy precipitation, followed by a red alert for flash floods on 4 August and an orange alert for 5 August, which was later upgraded again to a red alert extending into 6 August. Complementing this, the National Centre for Medium Range Weather Forecasting (NCMRWF) projected significant rainfall over the region, with forecasts indicating 2 cm at 00 UTC on 5 August and 4 cm at 12 UTC the same day. Despite these alerts, post-event analysis indicated that no confirmed cloudburst had occurred as per IMD's strict criterion of 100 mm/hr rainfall intensity. Alternative definitions, such as that of Raghuvanshi et al. (2025) defining cloudbursts as >200 mm/day with ≥30 mm/hr peaks, suggested the possibility of localized cloudburst-like conditions. However, multiple datasets, including IMD's 0.25° gridded data (≤60 mm over Uttarkashi), IMERG satellite rainfall (20–40 mm/hr peaks at 15:00 IST), and INSAT-3DS retrievals (~36 mm/hr at 15:00 IST), all indicated intense but sub-threshold rainfall. The Tela and Base Camp gauges corroborated these findings, recording elevated rainfall but not exceeding classical cloudburst intensity. The synoptic meteorological environment further shaped the event: NCMRWF forecasts on 5 August revealed a pronounced upper-air trough at 200 hPa, strong subtropical westerly jet streams, and upper-level divergence across northern India, all conducive to deep convection. IMD's 5 August press release confirmed the presence of a western disturbance in the mid-troposphere along ~72°E and a northward-displaced monsoon trough,

Fig. 23: Observed position of monsoon trough from 3rd -5th Aug 2025 of INSAT-3DS Imagery (Source: ISRO-MOSDAC, downloaded on 6th August 2025)

INSAT 3DS captures the evolution and positioning of the monsoon trough during 3rd –5th August 2025 (Fig.23). On 3rd Aug, the monsoon trough is situated at the foot of the Himalayas. By 4th August, it has migrated north-westward, while on 5th August, the trough has become stationary over the central Himalayan region. This progression illustrates a clear north-westward shift and stabilization of the trough in the days leading up to the Dharali event. This observed shift has aligned well with simultaneous IMD reports.

These combined hydro-meteorological factors set the stage for successive debris surges from the Kheer Gad and Tel Gad tributaries that devastated Dharali and Harshil, exacerbated by the interaction of multiple debris fans with the Bhagirathi River, transient channel damming, and subsequent flooding of critical infrastructure.

5. ANALYSIS AND NUMERICAL SIMULATION OF DEBRIS FLOW

The Dharali debris flow event of 5th August 2025 was simulated using RAMMS: Debris flow module. The ALOS PALSAR DEM of 12.5m resampled to 10 m was used and 3 point Hydrograph was selected as release condition. The simulation was performed to examine the flow path, transportation and deposition, and to determine the flow intensity parameters, for event reconstruction. The simulation was performed considering entrainment.

Fig.24: Google Earth Image (29.10.2022) showing different elevations.

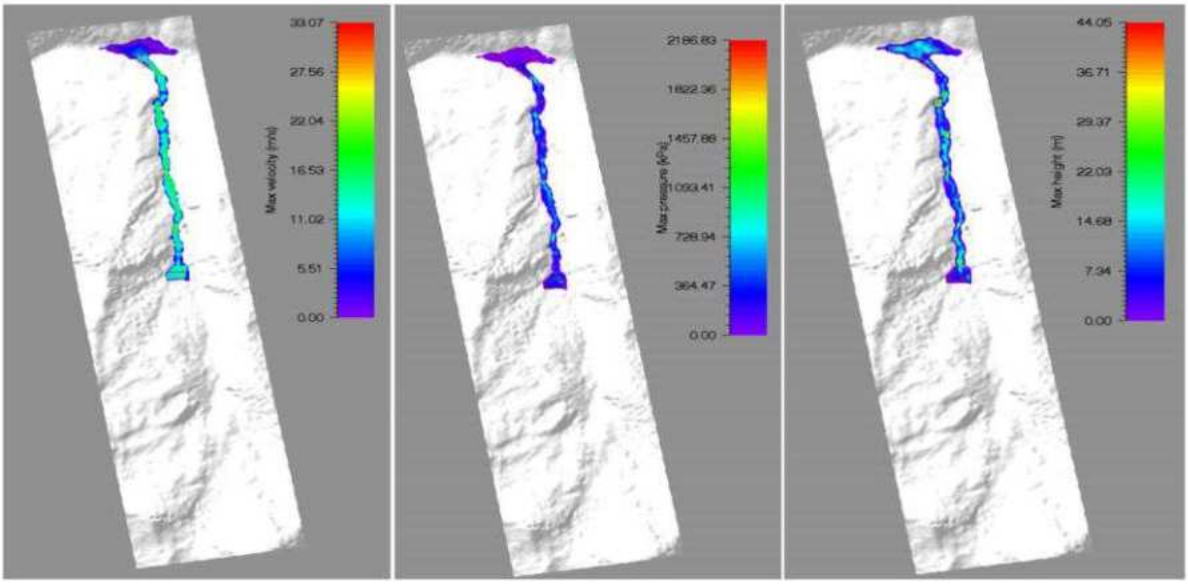

Fig.25: Simulated flow velocity, flow pressure and flow height of Dharali debris flow

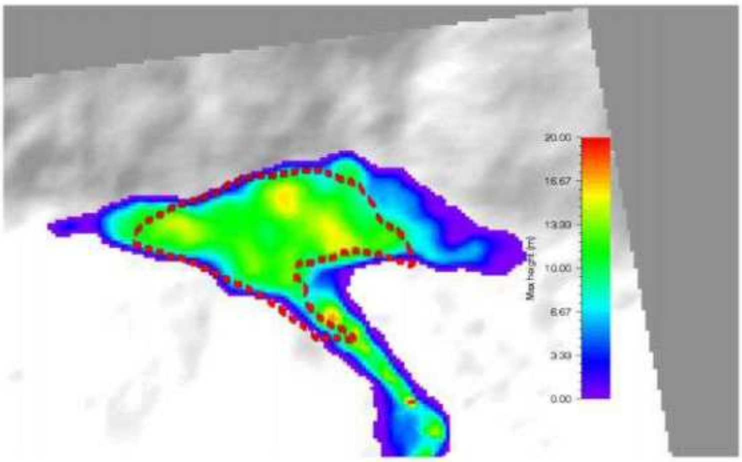

Fig.26: Simulated depositional height at debris fan

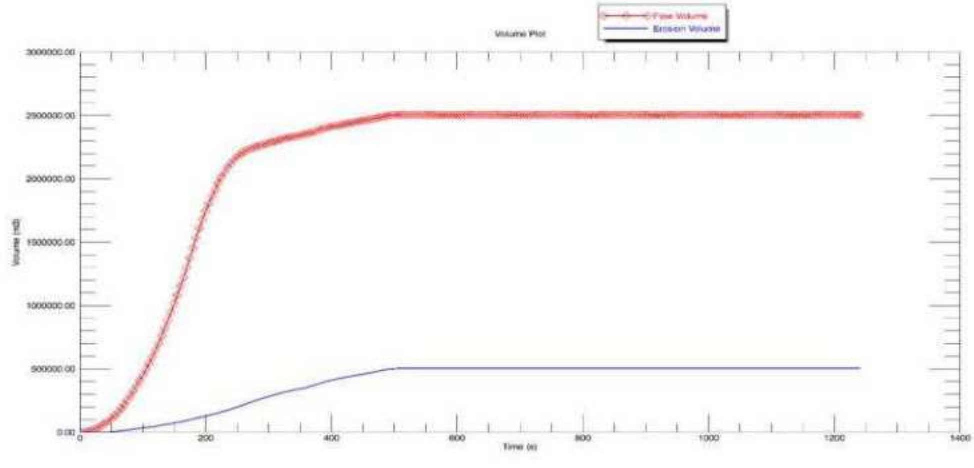

Fig.27: Flow volume vs erosion volume over time

The simulation revealed that, the debris flow travelled in the pre-existing channel without any channel outbreak; however, channel outbreak took place just before the deposition. The maximum debris flow velocity was about 33 m/s and the maximum debris flow pressure was about 2186 kPa. The debris flow height at the deposition was found to be varied between 10-15 m, which buried the infrastructure and caused destruction. Entrainment played an important role in maintaining the momentum of the flow. 2 million m^3 debris material was released using 3 point hydrograph; on its way it eroded about 0.5 million m^3 material and at the deposition about 2.5 million m^3 was observed. NRSC estimated the deposition area as 20 hectare that is about 2, 00,000 m^2 (1 hectare = 10,000 m^2). The height of the debris flow as about 10-15m with mean height about 12.5 m lead to a total volume of about 2.5 million m^3. The simulation estimated the similar volume of materials at the deposition.

The Dharali debris flow of 5th August travelled in a pre-existing channel with shallow-normal erosion throughout its path. It was observed that, when huge volume of materials are involved, the other flow dynamics (velocity & pressure), gets less significant, as it burry the element at risk, under the deposition. The smooth flow of debris doesn't indicate the chances of any temporary dam. The simulated results are similar to the field observations.

6. PROBABLE CAUSES FOR DHARALI DEBRIS FLOW AND SIMILAR EVENTS IN THE UPPER BHAGIRATHI BASIN:

The following observations, field evidence, and expert interpretations collectively point to the most likely causes of the Dharali debris flow event:

i. **Localized, high-intensity rainfall as the primary trigger**

   a) Automatic Weather Station (AWS) data recorded ~70 mm of antecedent rainfall within 36 hours before the event — far exceeding the typical 30–40 mm/day limit for valleys above 4000 m altitude.

   b) Tela Camp (~96 mm, including 60.4 mm on 4 August) and Base Camp (>43 mm) gauges confirmed spatially heterogeneous, orographically enhanced rainfall, much higher than IMD's Harsil station (6.5 mm).

   c) This convective rainfall, combined with steep topography, rapidly saturated the catchments and directly triggered slope failures, and debris flows.

ii. **Snowmelt and saturation of moraine deposits**

  a) The release/initiation zone lies in a glaciated catchment with large volumes of unconsolidated, fragile morainic deposits.
  b) These deposits were further saturated by snowmelt water, reducing shear strength and making them highly susceptible to mobilization.

iii. **Abundant unconsolidated sediments in steep, confined catchments**

  a) Glacio-fluvial and moraine-derived sediments provided massive debris supply.
  b) At ~3730 m elevation, two channels converged before dropping ~1200 m over a 4 km stretch down to the highway (2530 m), creating extreme energy gradients for sediment transport.
  c) Narrow, gorge-shaped valleys (Kheer Gad, Son Gad, Lamcha Gad, Tel Gad) acted as efficient conduits for destructive, debris-laden flows.

iv. **Surge sequencing due to valley morphology**

  a) The valley profile consists of alternating steep and gentle sections. Obstructions along the course and inertia of the mobilized mass produced six successive surges, ranging from boulder-rich debris to slurry-like slush.
  b) Aerial reconnaissance survey confirmed no damming or large-scale landslides along the channel, but multiple toe-cut scars indicated entrainment and successive surges at high velocity.

v. **Geological control of weak rock formations**

  a) The narrow nala sections cut through highly jointed and fractured metapelites.
  b) Disintegration of these rocks contributed fine material to the slurry, especially during later surges, greatly enhancing flow destructiveness.
  c) In contrast, valleys underlain by resistant gneisses (e.g., near Harsil) did not show similar debris surges, underscoring lithological control.

vi. **Regional hydro-meteorological forcing**

  a) Nearly simultaneous debris flow events in Kheer Gad, Tel Gad, Son Gad, and Lamcha Gad indicate a common rainfall + snowmelt driven rather than localized slope failures.
  b) Synoptic meteorology suggests interaction of a western disturbance, subtropical jet, and monsoon trough, producing strong convective activity.

vii. **Absence of other potential triggers**

a) Ground reconnaissance and satellite studies confirmed no Glacial Lake Outburst Flood (GLOF) or Landslide Lake Outburst Flood (LLOF).

b) The Dharali flows were thus dominantly rainfall–sediment driven, not dam-break related.

viii. **Evidence of past activity**

a) Presence of young Deodar and Cedar trees on the debris fan indicates that similar debris flow events likely occurred in the past century, suggesting the area is geomorphically predisposed to such hazards.

ix. **Amplified impacts from geomorphic and sedimentary conditions**

a) Massive debris loads blocked the Bhagirathi River at multiple points, creating temporary impoundments and cascading downstream impacts.

b) This highlights the systemic geomorphic vulnerability of the upper Bhagirathi basin to extreme monsoon events.

Based on the above observations by the team and other organisations, it may be inferred that the Dharali debris flow appears to have been initiated and mobilised by high antecedent rainfall of the order of 70 mm over 36 hours in the catchment prior to the event added to the snow-melt water saturated moraine deposits. Due to the steep longitudinal gradient beyond the confluence of two channels (around 1200 m elevation change over 4 km channel length) and narrow flow path of the Kheer Gad, the mobilised debris material gained the momentum to travel with a very high velocity downstream. Overall, multiple variables such as antecedent rainfall over shorter duration, available debris amount and characteristics at the source, and flow path topography control such extreme debris flow events.

Therefore, the Dharali debris flow can be termed as rainfall-cum-snowmelt water driven debris flow with huge quantity of debris mixed with water and with high momentum at the release zone and thus, displayed a severe devastating effect on the Dharali settlement on its flow path.

7. SUGGESTIONS

Keeping in view the Debris flows at Dharali and Harsil and the alarming increase in such extreme debris flow events, particularly in the Uttarakhand Himalaya, the following recommendations are made to address such types of disasters and similar future events:

- The debris deposits from the Dharali debris flow encroaching into the Bhagirathi River must be excavated in a planned manner to widen the river course and prevent damage along the right bank of the river.
- The sustainable utilisation of the excavated debris should be ensured for river training, mitigation, and protection measures.
- The foot bridge at Dharali must be strengthened on the Mukhba hill side
- Learning from the present disaster, the national highway level in the affected area should be raised by at least 5 m. Proper planning and design must be undertaken to provide culverts and bridges along the Kheer Gad in the elevated road section. The elevated section should be protected with adequate retaining structures, and the excavated debris must be effectively utilised in executing these works.
- The Kheer Gad channel should be realigned and lined along its natural course with proper planning and design to ensure safe discharge of water into the Bhagirathi River. Appropriate debris flow barriers must be installed to minimize the risk of future devastation.
- In the present scenario, the undamaged houses along both the banks of the Kheer Gad should be monitored as this is a hazard potential area. The affected area is not suitable for resettlement and should be declared as no-build zone.

8. RECOMMENDATIONS

Given the increasing frequency and intensity of debris flow events in the fragile Himalayan terrain, particularly in Uttarakhand, there is an urgent need for a comprehensive, multi-dimensional strategy to mitigate risks and safeguard lives, infrastructure, and livelihoods. The recommendations outlined below emphasize the integration of scientific investigations, advanced modelling, real-time monitoring, climate change considerations, resilient infrastructure design, policy interventions, and community preparedness. Together, they aim to provide a robust framework for anticipating hazards, reducing vulnerabilities, and enhancing the overall disaster resilience of mountain communities.

1. **Large-scale Debris Flow Hazard Mapping**: Preparation of debris flow hazard indication (potential) maps along natural drainage channels (tributaries) of inhabited areas of major river valleys in hilly regions.

2. **Identification of Source Zones & Scenario Modelling**: Identification of future possible release zones and scenario-based hazard assessment through numerical modelling of large-scale debris flow processes, their entrainment and phase transitions along the flow path, and their effect on runout.

3. **Vulnerability& Risk Assessment**: Assessing risks to river valley projects, habitations, and other infrastructures exposed to debris flow runout, while facilitating the relocation and reconstruction of resilient townships and promoting community-centric awareness and capacity building.

4. **Real-time Monitoring & Mitigation:** Establishing real-time and periodic monitoring mechanisms for rainfall, soil/moraine saturation, and slope stability is essential. Based on these inputs, site-specific mitigation strategies can be developed to enhance the resilience of exposed elements against debris flow damages.

5. **Geological Investigations & Process Understanding**: A comprehensive approach is required, involving detailed geological, geomorphological, and geotechnical investigations to identify susceptible litho-tectonic zones, unconsolidated sediment deposits, glacio-fluvial terraces, and structurally controlled weak slopes. This should be complemented by the application of deductive approaches, which use established geological and geotechnical principles to infer susceptibility, alongside inductive approaches that derive patterns from past events, satellite imageries, and field data. Process-based modelling tools can be employed to simulate debris initiation, entrainment, and runout pathways, while coupling these with geological mapping to capture realistic scenarios. Furthermore, the integration of field-based mapping, drone/LiDAR surveys, geotechnical testing, and hydro-meteorological data will help develop a holistic understanding of slope dynamics and debris flow hazard potential.

6. **Strengthening Early Warning Systems:** An effective early warning framework can be established by integrating Automatic Weather Stations (AWS), rainfall thresholds, satellite observations, and hydrological monitoring to develop localized debris flow early warning systems. These technical inputs must be coupled with community-level alert dissemination mechanisms, including SMS notifications, sirens, and mobile-based platforms, to ensure timely communication and rapid response at the ground level.

7. **Integration with Climate Change Projections:** Linking debris flow hazard models with climate change scenarios—such as shifts in precipitation patterns, snow and glacier melt, and extreme weather events—is essential for capturing evolving risks. These models must be periodically updated and integrated into hazard zonation maps to ensure that they accurately reflect changing conditions and provide a dynamic basis for planning, mitigation, and risk reduction.

8. **Institutional & Policy Measures:** A focussed and dedicated debris flow study should be carried out in coordination with different institutions for responseand effective interaction during exigencies. In parallel, strict enforcement of building codes, scientific land-use zoning, and the declaration of 'No-Build Zones' in high-risk catchments are crucial to minimize exposure, regulate unsafe development, and safeguard vulnerable communities.

9. **Infrastructure Resilience & Pilot Projects:** Debris flow–resistant design of critical infrastructure such as roads, bridges, and hydropower projects must be prioritized, incorporating protective structures like check dams and debris retention basins to reduce vulnerability. Pilot projects in high-risk valleys such as Dharali and Kedarnath catchments should be implemented as test cases, with the insights and lessons learned serving as the foundation for scaling up resilient infrastructure development across other vulnerable Himalayan regions.

10. **Community Preparedness & Knowledge Sharing:** Strengthening community preparedness is crucial and can be achieved through awareness drives, regular mock drills in debris flow–prone villages. In parallel, establishing an open-access debris flow event database for Uttarakhand would provide a vital platform for knowledge sharing,

scientific research, and informed policy formulation, thereby ensuring both grassroots awareness and evidence-based decision-making.

In conclusion, the path to reducing debris flow risks in Uttarakhand lies in sustained scientific inquiry, proactive planning, and coordinated action across sectors and scales. The adoption of these recommendations will not only help anticipate and manage future hazards more effectively, but also foster a culture of preparedness, resilience, and adaptive governance in the Himalayan context. By bridging science, policy, infrastructure, and community engagement, Uttarakhand can move toward a safer, more informed, and climate-resilient future.

(Dr Mohit Kumar)	**(Dr Amit Kumar)**	**(Dr Ankit Agarwal)**
(Ravi Negi)	**(Dr D.P. Kanungo)**	**(Dr Shantanu Sarkar)**