Landslides

# Preliminary assessment of series of landslides and related damage by heavy rainfall in Himachal Pradesh, India during July 2023

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Date: November 14, 2023

**To**
**The Editor-in-chief,**
**Landslides.**

**Sub: Submission of a revised manuscript for possible publication in Landslides within News Category (LASL-D-23-00605R1)**

Dear Professor,

Further to your email dated October 25, 2023 with a decision on our manuscript for publication subjected to minor revisions and allowing us to revise our work. Please find revised version of our manuscript titled "Preliminary assessment of series of landslides and related damage by heavy rainfall in Himachal Pradesh, India during July 2023" by Eedy Sana, Ashutosh Kumar, Ellen Robson, R. Prasanna, Uday Kala and David G Toll for possible publication in Landslides within the News category.

We have now addressed all the suggestions and concerns raised by the reviewer(s) and they are highlighted in the annotated version of the manuscript. Please process this manuscript at your earliest convenience.

Thanking you. With best regards,

Yours sincerely,

Ashutosh Kumar.

Name of Journal: *Landslides (Category- News)*

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# Preliminary assessment of series of landslides and related damage by heavy rainfall in Himachal Pradesh, India during July 2023

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**Abstract**

Himachal Pradesh, a northern state of India, experienced unprecedented heavy rainfall between July 7-14, 2023, recording a daily average rainfall level that was 436% higher than the normal daily monsoonal average. This period of heavy rain triggered several devastating landslides across the state, claiming 223 lives, leaving more than 70,000 tourists stranded, and blocking 1,300 roads, directly impacting the lives of thousands. This article systematically discusses the factors contributing to slope instability, infrastructure damage and the social and environmental losses incurred based on data collected through various sources including newspapers, multimedia, discussions with local communities and an on-site field investigation. This data reveals that the districts of Himachal Pradesh that incurred the worst damage were Mandi, Kullu and Shimla which are some of the most populated areas of the state, and these regions require immediate relief and mitigation measures.

## 1.0 Introduction

Rainfall triggered landslides are one of the most destructive natural hazards in the mountainous regions of India, causing significant damage to infrastructure at an estimated cost of 76 million USD each year and resulting in hundreds of fatalities annually (Kumar et al., 2018). These landslides are most often triggered during the southwest monsoon season which runs from June to September where this region receives 68% of its annual rainfall (Guhathakurta et al. 2020). Between July 7-14, 2023, the majority of northern India experienced unprecedented heavy rainfall. The state of Himachal Pradesh, located along the foothills of north-western Himalayas, was severely affected by this long duration rainfall (with daily average rainfall levels 436% higher than the normal daily monsoonal average (IMD 2023a) which triggered multiple landslides and resulted in a humanitarian disaster that claimed 223 lives, closed 1,300 roads and caused extensive damage to properties costing millions of US dollars (The Indian Express 2023a). The Indian Meteorological Department in Shimla, the capital of Himachal Pradesh,

documented evidence of 29 flash flood incidents across the state between 7-14th July, due to cloud bursts at various locations including Thunag, Pandoh, and Seraj in the Mandi district, as well as Sainj and Kais in the Kullu district and Rohru in the Shimla district (Chauhan et al. 2023). Cloud burst is defined as the sudden high-intensity rainfall of approximately 100 mm/h in a short duration over small area (Das et al. 2006).

It was reported by HPSDMA (2023) that 5,400 hillslope landslides and road cut slope failures occurred over a 3-day period from 9-11th of July 2023, leading to unrecoverable loss to the road sector. In addition, multiple road sections and bridges were washed away due to the heavy rain. Over 70,000 tourists were left stranded when a significant portion of the Chandigarh-Manali four-lane highway project was washed away (The Hindu 2023). In the Kullu district, more than 1,700 families were affected by damaged houses, shops, agricultural lands, and road closures, and approximately 10,000 tourists were relocated (Mint 2023a). A 50-year-old bridge at Aut, a lifeline for the largest population of Banjar and remote areas of Kullu, was washed away, in addition to 40 other bridges across the state (The Indian Express 2023a). The Leh-Manali National Highway (NH-3), a critical route connecting to the world's highest single tube tunnel (Atal Tunnel) which allows Indian military to access boarder regions along Line of Actual Control (LAC) with China, was severely damaged by floods at various points (Bodh 2023). According to the state transport department, reported in India Today (2023a), bus services on 1,255 routes of the Himachal Roadways Transport Corporation (HRTC) were suspended and 576 buses were stranded at different locations along the route due to a series of landslide events.

This heavy rainfall event marked one of the most catastrophic disasters witnessed by Himachal Pradesh in the last 75 years (Mint 2023b). Such hazardous events are hypothesized to reflect the coupled impact of meteorological conditions, hillslope strength, weathering patterns and

anthropogenic activities on slope stability (Gariano and Guzzetti 2016; Marengo et al. 2021; Alberti et al. 2022).

We have collected data on the disaster that struck Himachal Pradesh in July 2023 from newspapers, multimedia, local communities and an on-site field evaluation in the Mandi district. Based on the data collected, we present a systematic and timely documentation of the regional setting of Himachal Pradesh, factors contributing to slope instability in the region and the damage resulting from the heavy rainfall. We also discuss a potential strategy for engineering interventions and analysis.

## 2.0 Regional Setting

Himachal Pradesh is situated in the northern part of India and shares inter-state borders with Punjab, Haryana, Uttarakhand and Jammu & Kashmir, as well as an international border with China (Figure 1a). According to the 2011 census, the total population of the state is approximately 6,900,000 (Census India 2011). The state's boundaries span between the coordinates of 30° 22'40" N to 33° 12'40" N and 75° 45'55" E to 79° 04'20" E (Figure 1b), encompassing an area of 55,673 km². The state is divided into 12 districts as displayed in Figure 1b. Figure 1b also highlights the districts of Shimla, Kullu and Mandi which were the most affected districts of Himachal Pradesh during the July 2023 heavy rain event and are discussed further in this paper.

Geographically, Himachal Pradesh located in northwest Himalayas is divided into three distinct regions based on elevation levels: the Shivalik (350 m to 1,500 m), the Inner Himalayas (1,500 m to 4,500 m), and the Alpine zone (above 4,500 m). Five perennial rivers, Sutlej, Beas, Ravi, Chenab, and Yamuna, flow through the state. The region's predominant lithology is Precambrian rock (this can be observed in Figure 1c). The Shivalik region is mainly composed of weathered shale, sandstone, and claystone, the Inner Himalayas is predominantly made up

of granites, and Alpine zone is made up of crystalline rocks (HPSDMA 2023). Figures 1d & e display slope and contour maps derived from a digital elevation model with a resolution of 30×30 meters obtained from the United States Geological Survey (USGS) database (Earth Explorer 2023). These maps indicate that elevations in the region range from 700 meters to 6,300 meters above mean sea level, with slope angles varying from gentle to very steep (10° to 82°). The region experiences an orographic climatic condition due to its dramatic variance in elevation, resulting in high-intensity rainfall in some areas and more moderate rainfall in other areas.

In the following section, we discuss how the combined factors of heavy rain, topographical features, and lithological conditions may have resulted in rainfall-triggered landslides in Himachal Pradesh in the heavy rainfall event of July 2023.

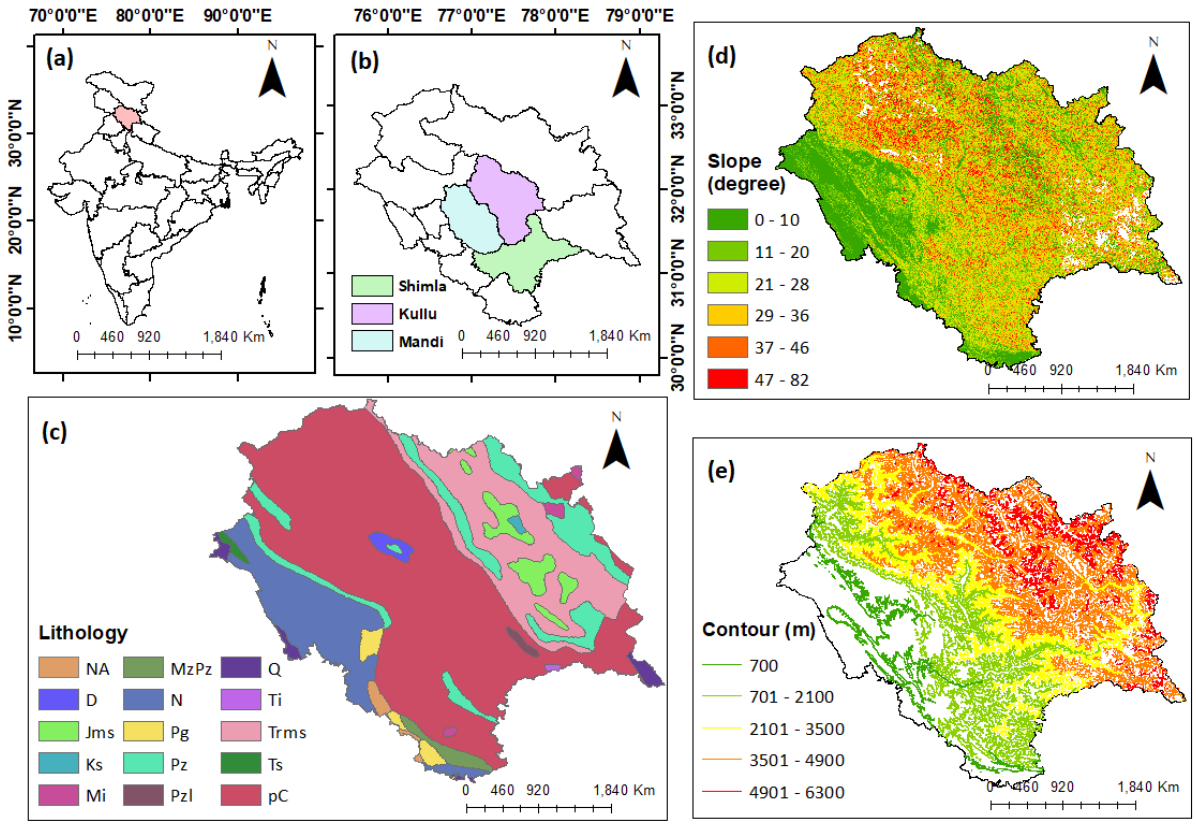


Fig.1 Maps of: **a** India with Himachal Pradesh highlighted, **b** Himachal Pradesh with the most affected districts of Shimla, Kullu and Mandi highlighted, **c** Himachal Pradesh lithology (NA-Description not

available, D-Undivided Devonian rocks, Jms- Jurassic metamorphic and sedimentary rocks, Ks-Cretaceous sedimentary rock, Mi-Mesozoic igneous rock, MzPz- Mesozoic and Paleozoic intrusive and metamorphic rocks, N- Neogene sedimentary rock, Pg- Paleogene sedimentary rock, Pz- Undivided Paleozoic rocks, Pzl- Lower Paleozoic rocks, Q- Quaternary sediment, Ti- Tertiary igneous rock, Trms-Triassic metamorphic and sedimentary rocks, Ts- Tertiary sedimentary rocks, pC- Undivided Precambrian rock) **d** Himachal Pradesh slopes, **e** Himachal Pradesh topography (source: EarthExplorer 2023, https://earthexplorer.usgs.gov/)

## 3.0 Contributing factors to slope instability

### *3.1 Extreme Rainfall*

On June 24, 2023, the southwest monsoon season began in Himachal Pradesh. According to the Indian Meteorological Department (IMD), the state typically receives 68% of its annual rainfall during the southwest monsoon (Guhathakurta et al. 2020). Figure 2a presents thirteen years of monthly rainfall data for July, highlighting an exceptionally high amount of rainfall in July 2023. The cumulative rainfall for the month reached 437.5 mm, with a substantial portion of 223 mm occurring within a span of just four days, from July 7$^{th}$ to 11$^{th}$. This cumulative amount of 223 mm diverged by 436% from the average observed cumulative rainfall of 41.6 mm during those four days. (IMD 2023a).

Figure 2b shows the spatial distribution of rainfall throughout the state of Himachal Pradesh for the month of July 2023. It can be observed that the cumulative rainfall received within the districts of Mandi, Kullu and Shimla was in the high range of 400-700 mm. Figure 2c displays the daily rainfall data from 1$^{st}$ June to 16$^{th}$ July 2023 obtained from India-WRIS platform (WRIS 2023), highlighting a sudden surge in rainfall on July 9$^{th}$ reaching a historically high value of 85.6 mm. This intensified rainfall activity resulted from the convergence of two significant weather systems: (i) the monsoon system, supported by an active monsoon trough, and (ii) a slow-moving, westward-propagating active western disturbance. Furthermore, the

formation of a low-pressure area accompanied by an associated cyclonic circulation over Rajasthan and western end of the monsoon trough caused intense rainfall (IMD 2023b).

Although the intense rainfall of July 2023 ultimately triggered many slopes to fail, it is suspected that the antecedent low intensity and longer duration rainfall from May 2023 to June 2023 (IMD 2023c) is likely to have contributed to increasing the water content within the slopes thereby causing gradual rises in pore water pressure. It is worth mentioning that the cumulative rainfall for the month of May (116.8 mm) diverged by 84% from the normal monthly cumulative rainfall of 63.3 mm (IMD 2023c). The high-intensity and short duration triggering rainfall of July is likely to have caused a more significant increase in pore water pressure, thereby reduced the effective stress within the soil mass along the potential slip surface. This process would have reduced the shear strength of soil below a critical level, thereby, lowering the factor of safety and consequently triggering landslides (Tsaparas et al. 2002; Senthil Kumar et al. 2018).

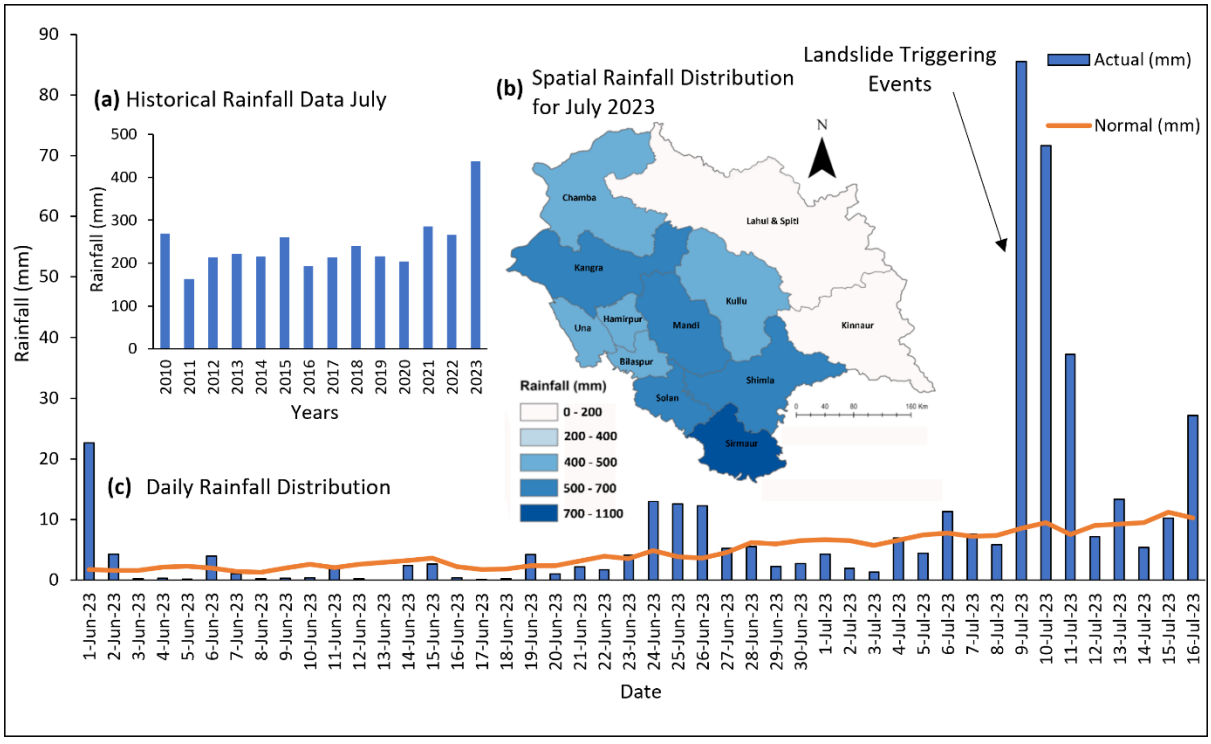


Fig.2 **a** Thirteen-years of rainfall data for the month of July from 2011 to 2023 (Source: IMD 2023b), **b** Rainfall data map showing spatial rainfall distribution throughout the state (Source: Open

Government Data (OGD) Platform India), **c** Daily rainfall data for Himachal Pradesh from the 1st June to 16th July 2023 (Source: WRIS 2023).

### *3.2 Geology and topography of area*

The hills in the region are broadly composed of sandstone, quartzite, granite, schist, shale and claystone. The rock slopes in the Himalayan regions are exposed to a wide range of climatic conditions. Rocks at high altitudes are subjected to extreme temperature variations. These temporal changes in weather and the diverse climatic conditions contribute to the physical weathering of rocks (Verma et al., 2023). These highly weathered rock masses are discontinuous and fragmented. Much of the shale and claystone in the area have been subjected to cycles of drying and wetting due to heavy rain during the monsoon season. It is likely that this will have led to the degradation in bulk density and strength of the shale and claystone making them more susceptible to failure (Nakano 1967).

The Himachal Himalaya is a tectonically active region, with multiple active faults of all types and sizes that create inherent instability in slopes (Mishra et al., 2018; Singh et al., 2020). There are several major thrust faults cutting across the state, including Jutogh and Main Boundary Thrust, which have caused brittle deformation (which can result in rock fall) and brecciated zones (Ghosh and Mukherjee, 2021). Slopes which are made up of rock which have undergone brittle deformation and brecciation are likely to have low strength and high permeability and are, therefore, vulnerable to rock fall under heavy rainfall (Mishra et al., 2018; Yun et al., 2022).

The landslides occurred as debris flow, soil slope failures and rock slides initiated from steep upper slopes. The rugged topography of the region indicated by the presence of steep slopes combined with rainfall infiltration is likely to have reduced the factor of safety of slope below a critical threshold, leading to failure. The higher elevation of the region is likely to have led to greater potential energy for downward sliding masses of rock and soil. The velocity of the

flowing debris noticeably increases when water (rainfall) gets mixed with debris causing reduction in the viscosity of flow (Abraham et al., 2021). It is likely that this process resulted in severe damage to the infrastructure situated in the path of high velocity moving debris (unsorted material ranging from clay to boulders).

### *3.3 Anthropogenic activities*

In addition to the natural factors, various anthropogenic factors such as unplanned construction activities along the riverbanks and landslide-prone areas, non-engineered road cuttings, improper disposal of construction waste and illegal deforestation may have contributed to instability in the region (Kumar et al., 2023). It has been reported that extensive construction has been ongoing in the tourism districts of Shimla and Kullu over past few years (Parashar 2023). Such unplanned and haphazard construction practices could further exacerbate the effects of intense rainfall resulting in maximum damage in these areas, as found in the case of the Josimath landslide in Uttarakhand (BBC 2023).

## **4.0 Discussion on damage**

To assess the magnitude of the disaster that impacted the state of Himachal Pradesh, we gathered data from various sources, including newspapers, multimedia and local communities. Additionally, we conducted a field assessment within the Mandi district, taking crucial observations. This on-site field assessment included examination of the pattern of landslides, landslide characteristics, debris flow and damage to adjoining structures. The investigations are still ongoing to ascertain the actual number of landslides, their pattern and the landslide inventory of the state will be updated accordingly. Distinguishing the damage has become difficult due to the closeness of several high intensity rainfall events during the monsoon season that is still ongoing. Therefore, in this article we have presented the damage that occurred mainly in the month of July 2023.

The data of the damage suffered by individual districts is yet to be retrieved. However, the statistical data for the state from Himachal Pradesh State Emergency Response Centre (HPSERC) reports that there have been 5,480 incidents of landslides, 14 cloudbursts and 83 flash floods since June 24, 2023 (The Indian Express 2023b). The official data from Himachal Pradesh State Disaster Management Authority (HPSDMA) stated that, until 10th August 2023 the monsoon season had resulted in 223 fatalities since its onset. The agency also reported that 295 people have sustained injuries while several people are still missing. The data showed that 800 houses were destroyed, while 7,500 houses suffered partial damage due to various events related to heavy rainfall and landslides (The Statesman 2023a). Moreover, 254 shops and 233 cow sheds were also affected by the natural disaster (The Statesman 2023b). The statement released by HPSERC in July 23 stated that 696 roads were still closed for vehicular traffic and till now the state has suffered a loss of 800 million USD, which can further increase up to 962 million USD (The Hindu 2023; Mint 2023b).

Mint (2023c) reported that approximately 1,000 roads including 5 national highways were blocked due to rainfall-triggered landslides occurring at different locations, thereby, isolating the state from the rest of the country. The Chandigarh-Manali highway, a vital link connecting Himachal Pradesh to the rest of India, remained impassable for two to three days due to persistent landslides at various points along the route. Notably, the section at Pandoh's 6 Miles in the Mandi district witnessed continuous landslides (images of this damage are shown in Figure 3). Similarly, the Kullu-Manali national highway was obstructed due to the collapse of a significant portion of the road near Rohtang pass, resulting from extensive landslides at multiple locations. This was primarily caused by rockfalls obstructing the road, sections of highway being washed away due to the force of debris flow and increased river levels due to partial river stream blockage at certain points. The districts of Kullu, Mandi and Shimla recorded the maximum number of landslides. Table 1 provides the details of affected

subdivisions and the number of blocked roads in Shimla, Kullu, and Mandi. This table highlights the blockage of 392 roads across these districts on 25th July 2023.


Fig. 3 Damages to the Chandigarh-Manali National Highway. **a** Blocked road due to landslide (The Tribune 2023a), **b** Washed away section of the highway (The Tribune 2023b), **c** Blocked highway due

to major landslide (Hindustan Times 2023a), **d** Failure of vertical cut slope (AN1 2023), **e** Washed away highway section (The Hindu), **f** Completely damaged highway (The Tribune 2023c)

Table 1: Affected subdivisions and the number of roads blocked in districts of Shimla, Kullu and Mandi (State Emergency Operation Centre, July 25, 2023)

| Name of District | Affected Sub Divisions | No. of Roads Blocked |
|---|---|---|
| **Shimla** | Shimla (Urban) | 1 |
| | Shimla (Rural) | 4 |
| | Theog | 12 |
| | Kotkhali | 34 |
| | Jubbal | 33 |
| | Rohru | 26 |
| | Rampur | 60 |
| | Chopal | 24 |
| | Kupvi | 10 |
| | Kumarsain | 38 |
| | Dodra Kawar | 4 |
| | | **Total = 246** |
| **Kullu** | Kullu | 27 |
| | Manali | 23 |
| | Banjar | 33 |
| | Nirmand | 25 |
| | | **Total = 108** |
| **Mandi** | Thalout | 17 |
| | Seraj | 14 |
| | Mandi II | 1 |
| | Joginder Nagar | 1 |
| | Balh | 1 |
| | Dharampur | 1 |
| | Padhar | 1 |
| | Karsog | 1 |
| | Gohar | 1 |
| | | **Total = 38** |

Figure 4 highlights the extensive damage incurred to roads and building infrastructure in the Mandi district, including rockslides on the national highway and landslides downslope of major district roads (Figures 4a-e). These incidents led to numerous road accidents. A mudslide in

Thunag market of Mandi damaged 30 shops and 15 houses, with another 70 shops being affected (Figure 4f).

Figure 5 displays photographs of damages within the Kullu district. These include washed-out portion of roads, debris deposition in front of houses, cracks in the houses, washing away of parked vehicles and the ongoing restoration works. In Kullu's Sainj area around 40 shops and 30 houses were washed away in debris flow (The Indian Express 2023a; The Indian Express 2023c). Several houses have developed cracks posing a serious threat to inhabitants.


Fig. 4 Damages in the Mandi district. **a** failed section of the slope (Field assessment), **b** Caved in road leading to formation of tension cracks (Field assessment), **c** Flash floods (Hindustan Times 2023b), **d** Caved in road resulting in accidents (The Tribune 2023d), **e** Rock fall (Ground Report 2023), **f** Mudslide (India Today 2023a)


Fig. 5 Damages in the Kullu district. **a** Washed away road section (India Today 2023b), **b** Debris deposition in front of houses (Outlook 2023), **c** Cracks in houses (ETV Bharat 2023), **d** Damaged agricultural land and vehicles due to mud slide (The Tribune 2023e), **e** Washed away road section (The New Indian Express 2023), **f** Restoration work after a debris slide (Outlook 2023)

Figure 6 displays photographs of damages incurred within the Shimla district indicating the similar damage patterns experienced by Mandi and Kullu districts.


Fig. 6 Damages in the Shimla district. **a** Landslide and caved in road on Kalka-Shimla NH-5 leading to formation of tension cracks (Bhaskar 2023), **b** Blocked railway track due to landslide (The Tribune 2023f), **c** Damage to infrastructure due to mud slide (The Quint 2023), **d** Debris flow and deposition on road (Punjab Kesri 2023), **e** Damaged Road due to debris flow (India TV 2023), **f** Blocked Road due to landslide (The Tribune 2023g)

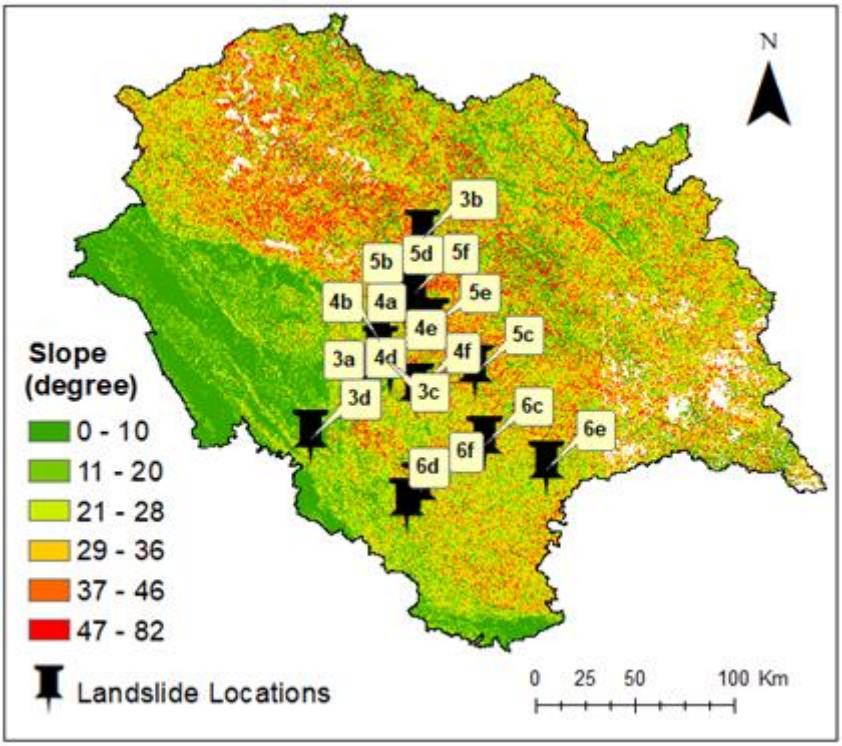


Fig.7 Location of landslides shown in Fig 3,4,5 and 6 compared to slope map (30×30 meters) of Himachal Pradesh (source: Earth Explorer 2023, https://earthexplorer.usgs.gov/)

The landslide data gathered from the aforementioned sources and field observations was carefully examined. Figure 7 shows the distribution of representative landslides from Figures 3-6 plotted on slope map of Himachal Pradesh. We found that many of the landslides took place on slopes having angles in the range of 40 to 80 degree. Also, the data gathered from Geological Survey of India (https://bhukosh.gsi.gov.in/Bhukosh/Public) revealed that rock formations in Mandi region predominantly comprises schist, quartzite, granite and aplite. In Kullu, schist, quartzite, granitoid, limestone, dolomite and migmatite are mainly found, while in Shimla, shale, schist, quartzite, amphibolite, dolomite and phyllite are present.

Shallow translational slides were mainly observed. In the field we observed a well-defined scarp on the failed slope where the slide deposits exhibited a convex shape. In Kullu district debris flows were predominantly observed in Sainj valley (Figure 8), Kharahal valley, Kais and Jilla village. The continuous rain resulted in increased water content of the deposited debris

that transformed it into a fluid flow that carried mud and boulders. The failed debris merged with the river stream for the cases where landslides occurred near the bank of the river. The debris depositions in the river streams had potential to block the flow of the river or even forcing the river to change its course. The debris was mainly composed of silty soils mixed with fragmented rocks. The flowing debris damaged roads, houses, agricultural lands, schools, community centres and hospitals. We also observed the development of tension cracks on the crown of slopes, these cracks pose significant risk of landslide during the next rainfall event. Figure 8 shows the satellite images of a representative area of Sainj in district Kullu before (Fig. 8a) and after (Fig. 8b) the rainfall event of July 2023. The images highlight the multiple damages occurred in the area in terms of landslides and resulting buildings damage. There was a 262% increase in the width of the Beas River from 40 meters before monsoon (Fig.8a) to 145 meters during monsoon (Fig.8b) due to substantial rainfall received in the month of July 2023.

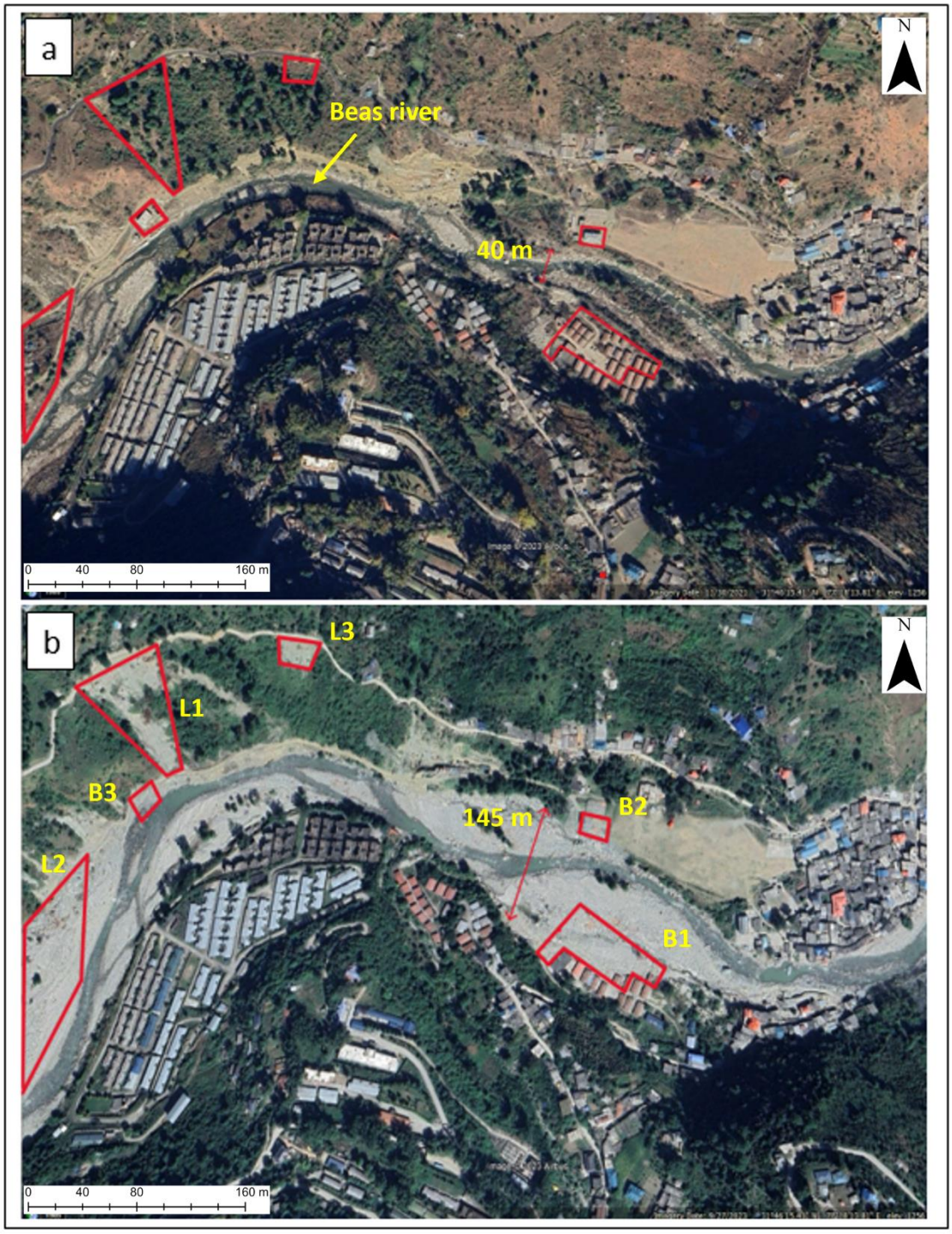


Fig. 8 Satellite images of Sainj area in district Kullu. **a** Before, **b** After the monsoon event of July 2023. [L1, L2, L3 indicate the landslides and B1, B2, B3 indicate building damages] (Source: Google Earth 2023, https://earth.google.com. Retrieved 2 November 2023)

## 5.0 Strategy for engineering intervention and analysis

Based on the preliminary field survey and data collection, we have highlighted the severe damage suffered in Himachal Pradesh in July 2023 heavy rain event through rainfall-triggered landslides. There is a need to conduct an extensive field scale survey to identify the slopes that have potential to fail in future and assess the actual damage incurred in the districts of Mandi, Shimla and Kullu. We propose an approach that can be followed for analysis and timely response to landslides in stages of data collection, analysis, and response (see Figure 9).

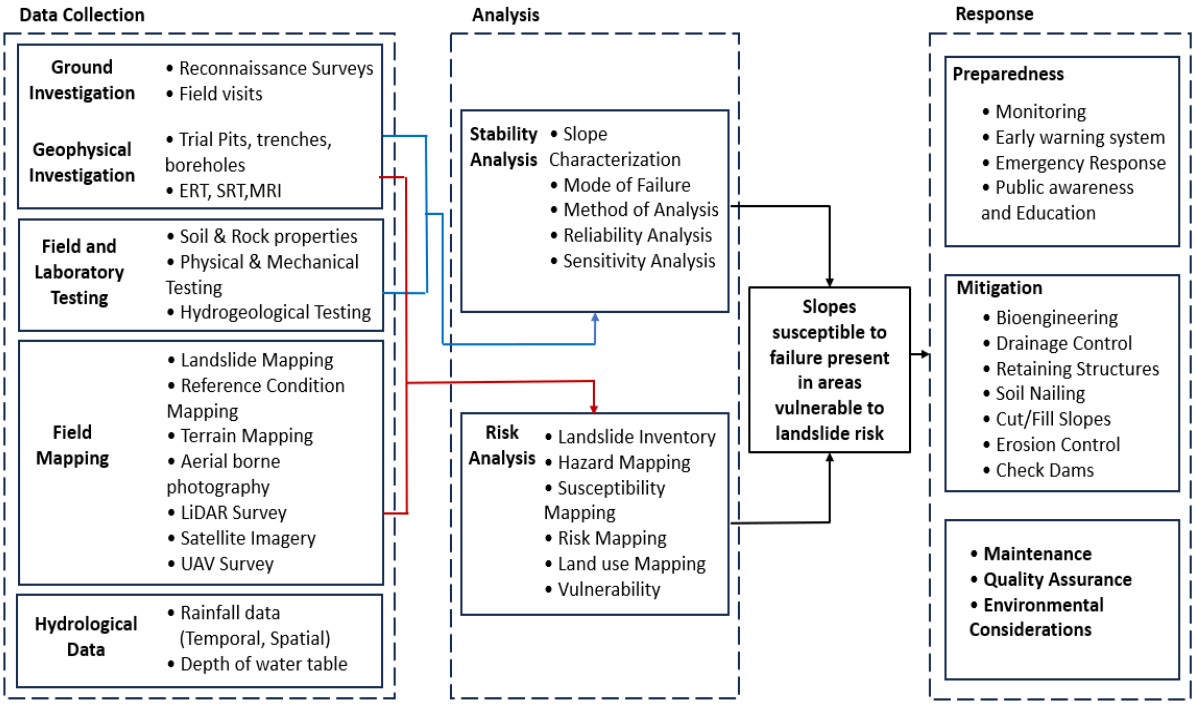


Fig. 9 Proposed road map for landslide analysis and response (ERT: Electrical Resistivity Tomography, SRT: Seismic Refraction Tomography, MRI: Magnetic Resonance Imaging, LiDAR: Light Detection and Ranging, UAV: Unmanned Aerial Vehicle)

## 5.0 Conclusions

The unprecedented heavy rainfall in Himachal Pradesh from July 7 to 14, 2023 led to a series of landslides and debris flow in several parts of the state. After collecting and reviewing data from various sources we conclude that the districts of Mandi, Shimla and Kullu suffered the

maximum damage. The reason for the occurrence of the maximum damages in these three districts needs to be studied in detail as it depends on combination of various factors like rainfall, topography, geology, strength of slope material, weathering patterns, and anthropogenic activities. The recorded data indicates that the geologic and topographic features were preparatory factors that contributed to failure, while intense, long duration rainfall was the main triggering factor. In addition, the unplanned anthropogenic activities (with little engineering design input) further aggravated the damage. The primary form of landslide damages was rockfalls blocking the roads and damaging the residential buildings. Some portions of the roads were washed away due to large forces exerted by debris flow. Rivers at certain locations were forced to change their course because of partial blockage due to deposition of landslide debris. Therefore, considering the presence of complex geology and rainfall patterns in the region, it is required to carry out detailed investigation to understand the characteristics of slope strata, sliding mechanics, building damage patterns and inter-play of rainfall infiltration. Such catastrophes highlight the importance of having effective emergency preparedness plans and response strategies in place to mitigate the impact on human lives and property.

## STATEMENTS AND DECLARATIONS

## AUTHOR CONTRIBUTIONS

**Eedy Sana:** Conceptualization, Methodology, Testing, Writing- original draft. **Ashutosh Kumar:** Conceptualization, Methodology, Resources, Writing- Review and Editing**,** Supervision. **Ellen Robson:** Writing- Review and Editing**. R. Prasanna:** Writing- Review and Editing. **Uday Kala:** Writing- Review and Editing, **David G Toll:** Writing- Review and Editing.

## DATA AVAILABILITY STATEMENTS

The data investigated in this study is available from the corresponding author upon request.

## CONFLICT OF INTEREST

The authors declare no competing interest.

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|---|---|
| Name of Journal: | *Landslides (Category- News)* |
| Manuscript Number: | LASL-D-23-00605 |
| Title of manuscript: | Preliminary assessment of series of landslides and related damage by heavy rainfall in Himachal Pradesh, India during July 2023 |
| Authors: | Eedy Sana, Ashutosh Kumar, Ellen Robson, R. Prasanna, Uday Kala and David G Toll. |

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**Compliance to comments of the Editor in Chief:**

**Comments:** We have received the reports from our advisors on your manuscript, "Preliminary assessment of series of landslides and related damage by heavy rainfall in Himachal Pradesh, India during July 2023", which you have submitted to Landslides. Based on the advice received, your manuscript could be accepted for publication should you be prepared to incorporate minor revisions. When preparing your revised manuscript, you are asked to carefully consider the reviewer comments which are attached (if there is any) and submit a list of responses to the comments. Your list of responses should be uploaded as a file in addition to your revised manuscript.

**Reply:** The authors are extremely thankful to the Editor-in-chief for recommending the publication of this manuscript, subjected to minor revisions. All the peer review comments and suggestions are now addressed, and suitable modifications have been made to the revised manuscript. The

authors are hopeful that the Editor in Chief will find all the changes in proper order. Annotated revised copy and the response sheet shows all the changes made as per the reviewer's comments.

**Compliance to comments of the Reviewer #1:**

1. *Line-52, Page-3: Even though The Indian Express is a renowned newspaper in India, an official source from any government/autonomous/reputed private organization shall be referenced. In particular, 436% higher rainfall within such a short period needs a proper reference.*

   **Reply:** Thank you for pointing this out. We earlier mentioned the required reference of (IMD 2023a) for 436% higher rainfall in line 134 of the revised manuscript (Section 3- Contributing factors to slope instability). Now it is also added in line 53 (Section 1- Introduction) of the revised manuscript.

   Reference:

   IMD (2023a). Government of India Ministry of Earth Sciences (MoES) India Meteorological Department Meteorological Centre, Shimla. (2023). Available online at https://mausam.imd.gov.in/Forecast/mcmarq/mcmarq_data/Press%20release%20for%20Unprecedented%20Rainfall(07th%20to%2011th%20July.pdf

2. *Line-56, page-4: Das et al. published in 2006, and the authors are referencing the 2023 landslide disaster. Isn't it quite surprising?*

   **Reply**: Thank you for pointing it out**.** The authors have used the reference of Das et al. 2006 to describe the definition of the cloud burst based on intensity i.e., (sudden high-

intensity rainfall of approximately 100 mm/h in a short duration over small area) (Das et al. 2006). To avoid any confusion, we have revised the text as follows:

Modified text now reads as:

Lines 56-61: The Indian Meteorological Department in Shimla, the capital of Himachal Pradesh, documented evidence of 29 flash flood incidents across the state between 7-14th July, due to cloud bursts at various locations including Thunag, Pandoh, and Seraj in the Mandi district, as well as Sainj and Kais in the Kullu district and Rohru in the Shimla district (Chauhan et al. 2023). Cloud burst is defined as the sudden high-intensity rainfall of approximately 100 mm/h in a short duration over small area (Das et al. 2006).

Reference:

Chauhan C, Bisht G, Thakur K.N (2023) Floods in Himachal leave trail of destruction. Hindustan Times, July 13, 2023. Available online at https://www.hindustantimes.com/cities/chandigarh-news/devastating-cloudburst-and-flash-floods-in-himachal-pradesh-unplanned-development-and-climate-change-to-blame-101689190799169.html

3. *Line66-69, page-4: This is one of the major incidents due to landslides, and putting the lines without any appropriate/reliable reference is not justified at all.*

**Reply:** We have now addressed this concern by adding a relevant reference in lines 70 and 73.

We have made following changes in the revised manuscript:

A 50-year-old bridge at Aut, a lifeline for the largest population of Banjar and remote areas of Kullu, was washed away, in addition to 40 other bridges across the state (The Indian Express 2023a). The Leh-Manali National Highway (NH-3), a critical route connecting to the world's highest single tube tunnel (Atal Tunnel) which allows Indian military to access boarder regions along Line of Actual Control (LAC) with China, was severely damaged by floods at various points (Bodh 2023).

Reference:

The Indian Express (2023a) Himachal counts losses: 31 dead, 40 bridges damaged, 1,300 roads closed. The Indian Express, July 13, 2023. Available online at https://indianexpress.com/article/cities/shimla/himachal-counts-losses-31-dead-40-bridges-damaged-1300-roads-closed-8827396/

Bodh (2023) Hundreds of tourists stranded in Himachal Pradesh; Manali-Leh national highway caves in near Sissu. The Times of India, July 10, 2023. Available online at https://timesofindia.indiatimes.com/city/shimla/hundreds-of-tourists-stranded-in-himachal-pradesh-manali-leh-national-highway-caves-in-near-sissu/articleshow/101636996.cms

4. *The discussion of the regional setting section is justified; however, the source of Fig. 1 shall be appropriately acknowledged as the reviewer thinks some government agencies may prepare the map.*

**Reply:** Yes, we have used EarthExplorer2023 (https://earthexplorer.usgs.gov) to prepare the map and now it has been duly cited within the Figure caption in the revised manuscript.

Revised caption of Figure 1 now read as:

Fig.1 Maps of: a India with Himachal Pradesh highlighted, b Himachal Pradesh with the most affected districts of Shimla, Kullu and Mandi highlighted, c Himachal Pradesh lithology (NA-Description not available, D-Undivided Devonian rocks, Jms- Jurassic metamorphic and sedimentary rocks, Ks- Cretaceous sedimentary rock, Mi-Mesozoic igneous rock, MzPz- Mesozoic and Paleozoic intrusive and metamorphic rocks, N-Neogene sedimentary rock, Pg- Paleogene sedimentary rock, Pz- Undivided Paleozoic rocks, Pzl- Lower Paleozoic rocks, Q- Quaternary sediment, Ti- Tertiary igneous rock, Trms- Triassic metamorphic and sedimentary rocks, Ts- Tertiary sedimentary rocks, pC-Undivided Precambrian rock) d Himachal Pradesh slopes, e Himachal Pradesh topography (source: Earth Explorer 2023, https://earthexplorer.usgs.gov/)

5. *In discussing the disaster, the authors could use satellite imagery to explain the scenario better. Any aerial views may provide a much detail about the disasters.*

**Reply:** Many thanks for pointing this out. We have now annotated the satellite images of Kullu district of Himachal Pradesh taken pre and post disaster using Google Earth images for providing better picture of the disaster.

We have made following changes in the revised manuscript:

Lines 303-307: Figure 8 shows the satellite images of a representative area of Sainj in district Kullu before (Fig. 8a) and after (Fig. 8b) the rainfall event of July 2023. The images highlight the multiple damages occurred in the area in terms of landslides and resulting buildings damage. There was a 262% increase in the width of the Beas river from 40 meters before monsoon (Fig.8a) to 145 meters during monsoon (Fig.8b) due to substantial rainfall received in the month of July 2023.

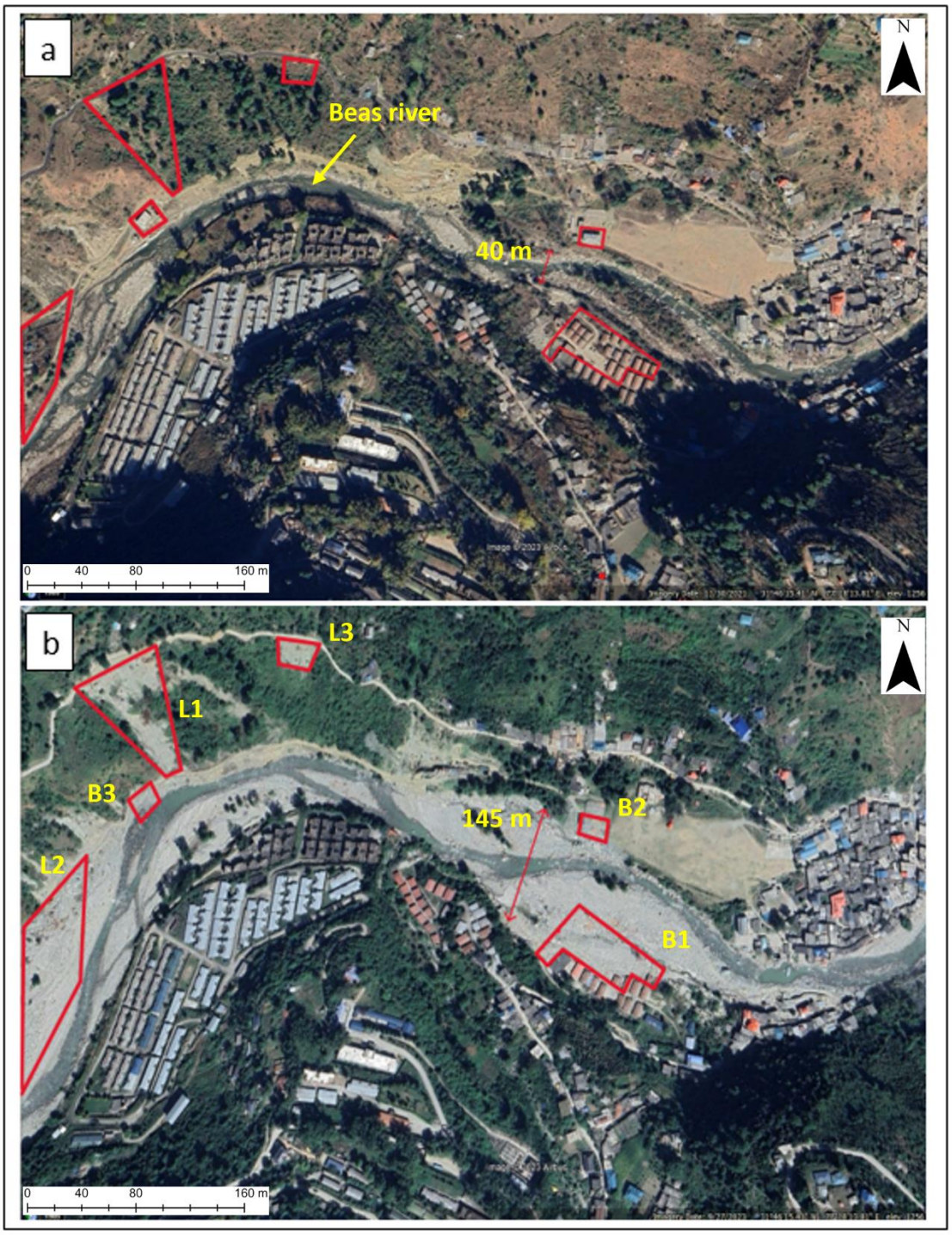


Fig. 8 Satellite images of Sainj area in district Kullu. **a** Before, **b** After the monsoon event of July 2023. [L1, L2, L3 indicate the landslides and B1, B2, B3 indicate building damages] (Source: Google Earth 2023, https://earth.google.com. Retrieved 2 November 2023)

6. *Much information in the discussion section is repeated, unnecessarily prolonging the paper. The authors must reduce the section and add a logical explanation of the reason behind the detachment of mass during short, intense rainfall. It is obvious that extreme rainfall builds up pore pressure and eventually reduces shear strength, leading to the failure of soil slopes. The reviewer expects the relation between soil characteristics and intense rainfall as in the sub-set of topographical variance, which may better explain the triggering mechanics of landslides.*

   **Reply:** Many thanks for pointing this out. We recognise this suggestion that the analysis of soil types and linking the intense rainfall would provide the clear picture to the mechanism of damages occurred. However, it is important to note that the primary aim of this paper was to timely document the contributing factors of slope instability in the region and the resulting damage from the heavy rainfall based on the gathered evidence from newspapers, multimedia, local communities, and an on-site field evaluation in the Mandi district. Providing the information about the soil types based on the available literature such as Bhukosh (gsi.gov.in) may not be a correct representation of triggering mechanism.

   We would like to point out that we are in the process of preparing another manuscript which we will submit as Landslide (Case Studies) to provide a detailed link of the soil type, water-retention properties of soil and rainfall pattern by performing coupled flow deformation analysis of exemplar landslides of Mandi district. We would also like to highlight that any information which appeared to be repeated is now removed.

**Compliance to comments of the Reviewer #2:**

1. *Page 7 - The rains from May to June are mentioned to contribute to "water content". The "extreme rainfall" mentioned in next page (of July?) is mentioned to transition the pore*

*pressure at failure surface from negative to positive. Provide some context of pore pressure for May - June rainfall.*

**Reply:** We would like to highlight that such explanations were presented to explain the likely mechanism of landslides. Initially, low intensity and longer duration rainfall during May to June would have contributed to increasing the water content of soils present within the slopes (Figure 2). Thereafter, high intensity and short duration rainfall in July contributed in triggering the landslides which may be due to the transition in pore-pressure from negative to positive leading to reduced effective stress along the potential slip surface. Considering the main aim of the manuscript is to report the evidence of damage and unavailability of data, it would be difficult to provide the information on pore-pressure distribution of slopes.

However, we have made revisions within the manuscript to bring more clarity in the interpretations.

Lines 148-155: Although the intense rainfall of July 2023 ultimately triggered many slopes to fail, it is suspected that the antecedent low intensity and longer duration rainfall from May 2023 to June 2023 (IMD 2023c) is likely to have contributed to increasing the water content within the slopes thereby causing gradual rises in pore water pressure. It is worth mentioning that the cumulative rainfall for the month of May (116.8 mm) diverged by 84% from the normal monthly cumulative rainfall of 63.3 mm (IMD 2023c). The high-intensity and short duration triggering rainfall of July is likely to have caused a more significant increase in pore water pressure, thereby reduced the effective stress within the soil mass along the potential slip surface.

2. *Page 8 - Rainfall data map for July for Hemachal Pradesh can be included to understand the special distribution of the rainfall over the state? (for example from TRMM)*

**Reply:** Thank you for highlighting this point. We have incorporated the rainfall data map of Himachal Pradesh for the month of July 2023 as an additional figure in the manuscript. This addition provides a visual representation of the spatial distribution of rainfall across the state.

The revised changes now read as:

Lines 138-140: Figure 2b shows the spatial distribution of rainfall throughout the state of Himachal Pradesh for the month of July 2023. It can be observed that the cumulative rainfall received within the districts of Mandi, Kullu and Shimla was in the high range of 400-700 mm.

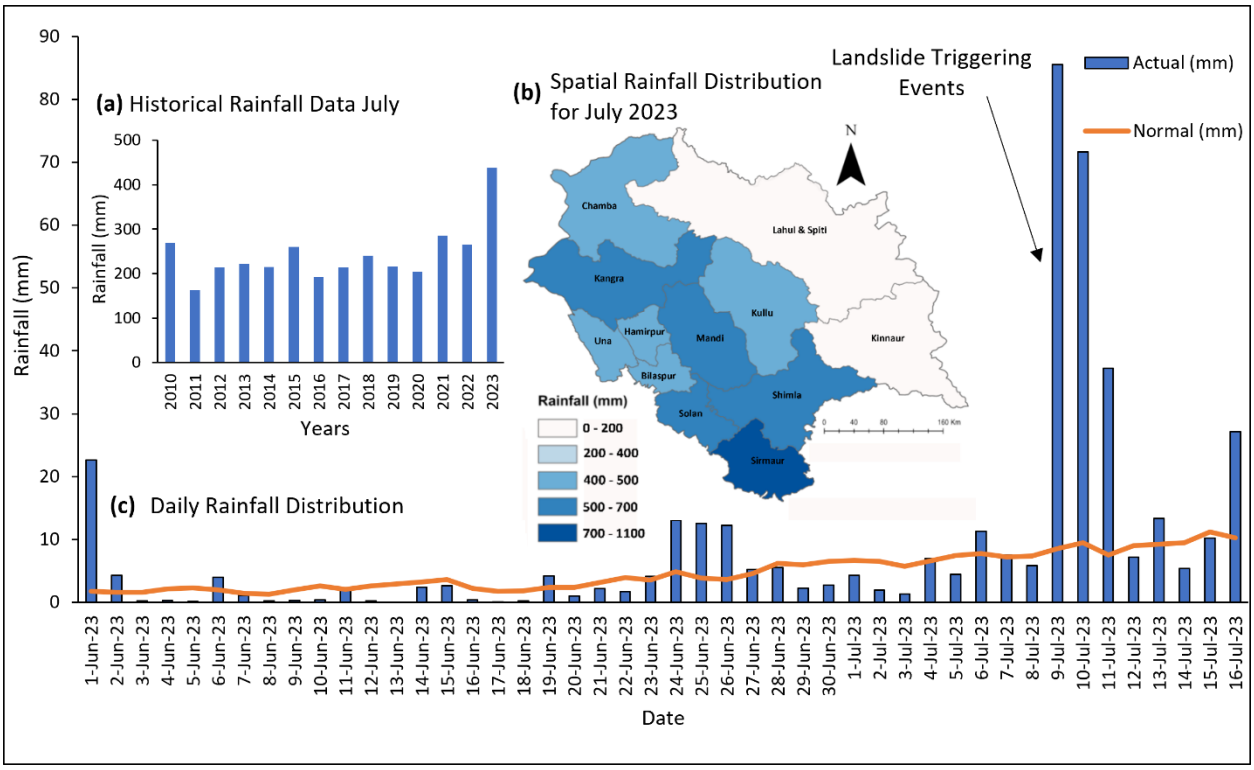


Fig.2 a Thirteen-years of rainfall data for the month of July from 2011 to 2023 (Source: IMD 2023b), b Rainfall data map showing spatial rainfall distribution throughout the state (Source: Open Government Data (OGD) Platform India), c Daily rainfall data for Himachal Pradesh from the 1st June to 16th July 2023 (Source: WRIS 2023). Open Government Data (OGD) Platform India. Retrieved Nov 2, 2023, from https://data.gov.in/

3. *Page 9 - Are there evidence of slaking of rock masses in the area? Please elaborate the predominant weathering mechanism observed.*

**Reply:** Thank you for highlighting this point. Yes, the rock masses in the region are quite fragile and tend to lose its strength when exposed to water. We have now made revisions within the manuscript to better explain the weathering of the rock masses.

The revised manuscript now read as:

Lines 166-170: The hills in the region are broadly composed of sandstone, granite, schist, shale and claystone. The rock slopes in the Himalayan regions are exposed to a wide range of climatic conditions. Rocks at high altitudes are subjected to extreme temperature variations. These temporal changes in weather and the diverse climatic conditions contribute to the physical weathering of rocks (Verma et al., 2023).

Reference:

Verma, A. K., Sardana, S., & Jaiswal, A. (2023). Study of Freeze-thaw Induced Damage Characteristic for Himalayan Schist. *Journal of the Geological Society of India*, *99*(3), 390–396.

4. *Page 9 - In context of the active faults mentioned. it is suggested to include fault map in the paper and indicate which thrust fault is referred to.*

   **Reply:** Thank you for this suggestion. However, authors are less convinced that providing the fault map within the manuscript would strengthen the manuscript as main aim of the study was to report the damage incurred within the Himachal Pradesh due to the occurrence of unprecedented rainfall during the month of July. Assessing the influence of faulting on these landslides is out of the scope of this paper.

5. *Page 9 - It is not clear in last paragraph that if "landsliding" is being referred to or the phenomenon of "debris flow" is being referred to. Please elaborate if two different types of land instabilities were observed.*

**Reply:** Many thanks for pointing this out. We have now made the suitable modification within the manuscript to highlight the changes.

The revised text within the manuscript now reads as:

Lines 183-189: The landslides occurred as debris flow, soil slope failures and rock slides initiated from steep upper slopes. The rugged topography of the region indicated by the presence of steep slopes combined with rainfall infiltration is likely to have reduced the factor of safety of slope below a critical threshold, leading to failure. The higher elevation of the region is likely to have led to greater potential energy for downward sliding masses of rock and soil. The velocity of the flowing debris noticeably increases when water (rainfall) gets mixed with debris causing reduction in the viscosity of flow (Abraham et al., 2021).

6. *Figure 3, 4, 5 & 6 - Please indicate the location of the images in on a state map. Mention the rock formation for each of the landslide location.*

**Reply:** Thank you for this comment. We have now indicated the location of the landslides shown in Figures 3-6 in Figure 7 of revised manuscript.

The revised text within the manuscript now reads as:

Lines 286-290: Also, the data gathered from Geological Survey of India (https://bhukosh.gsi.gov.in/Bhukosh/Public) revealed that rock formations in Mandi region predominantly comprises schist, quartzite, granite and aplite. In Kullu, schist, quartzite, granitoid, limestone, dolomite and migmatite are mainly found, while in Shimla, shale, schist, quartzite, amphibolite, dolomite and phyllite are present.

Geological Survey of India. Retrieved Nov 2, 2023, from https://bhukosh.gsi.gov.in/Bhukosh/Public

7. *Page 17 - If locations of the landslide failure incidences are marked on the slope map, the context of first paragraph would be more clearer.*

**Reply:** Thank you for this suggestion. We have plotted the available landslide locations (Figures 3-6) on the slope map and accordingly revised the manuscript.

The revised text now reads as:

Line 283-286: The landslide data gathered from the aforementioned sources and field observations was carefully examined. Figure 7 shows the distribution of representative landslides from Figures 3-6 plotted on slope map of Himachal Pradesh. We found that many of the landslides took place on slopes having angles in the range of 40 to 80 degree.

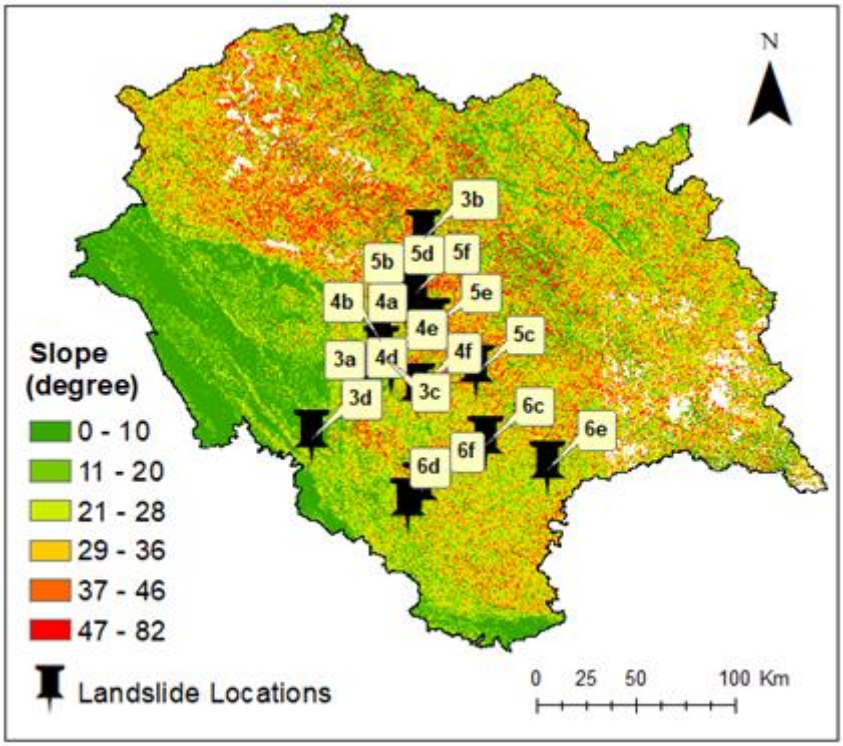

Fig.7 Marked locations of landslides on the slope map (30×30 meters) of Himachal Pradesh (source: Earth Explorer 2023, https://earthexplorer.usgs.gov/)

8. *Figure 7 - Check dams is suggested to include as mitigation strategy for debris/mud flow*

**Reply:** Thank you for your suggestion. We have addressed it by revising Figure 9 to include check dams as a mitigation strategy for debris/mud flow.

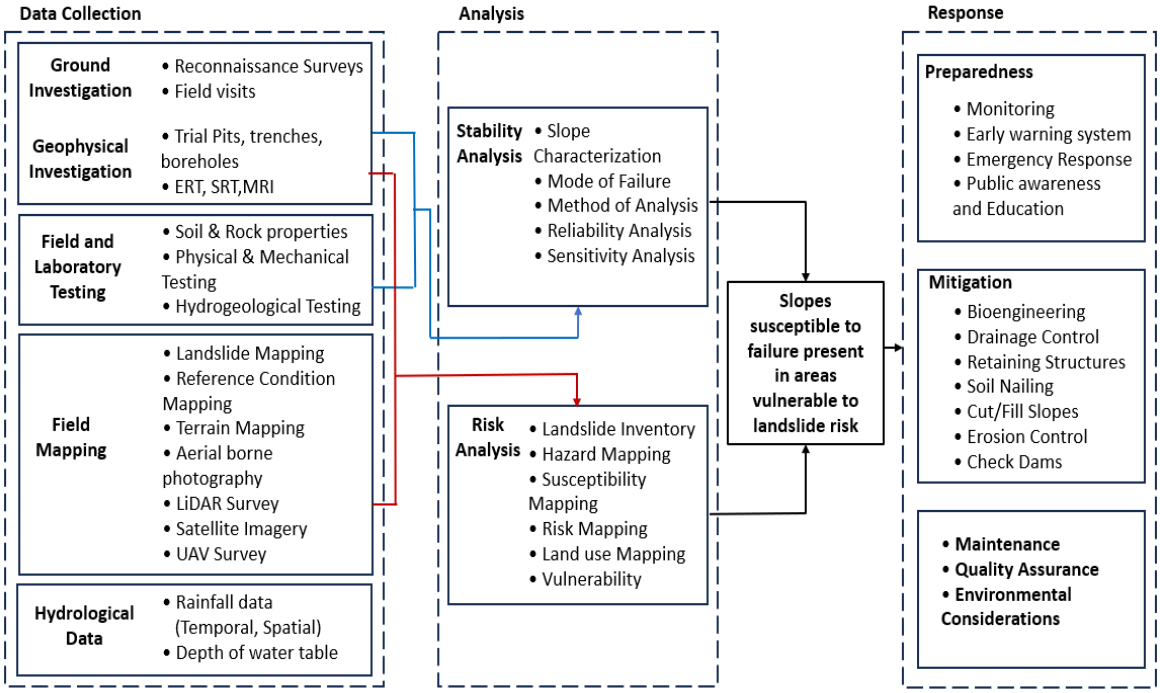


Fig. 9 Proposed road map for landslide analysis and response (ERT: Electrical Resistivity Tomography, SRT: Seismic Refraction Tomography, MRI: Magnetic Resonance Imaging, LiDAR: Light Detection and Ranging, UAV: Unmanned Aerial Vehicle)

9. *It is not clear in the paper that why the three districts suffered the major damage. Was it more rainfall in these districts or the geological factor?*

**Reply:** Thank you for raising this concern. These three districts namely Mandi, Kullu and Shimla suffered major damage mainly due to the interplay of meteorological condition

such as rainfall, geological setting, strength of hillslope materials, weathering patterns and anthropogenic activities. Therefore, based on the preliminary nature of investigation and scope of this paper, providing a detailed explanation on the role of each factor is challenging. However, we have highlighted that the sudden high intensity and short duration rainfall (436% increment from the average observed cumulative rainfall) were the main triggering factor causing huge number of landslides resulting into such damage. We have made suitable modifications in the revised manuscript.

Changes made in the manuscript:

Lines 325-328: The reason for the occurrence of the maximum damages in these three districts needs to be studied in much detail as it depends on combination of various factors like rainfall, topography, geology, strength of slope material, weathering patterns, and anthropogenic activities. This paper briefly addresses the causes, mechanism, and impact of the landslides in the region.