

# **A preliminary report on the landslides and land subsidence across the Solan District, Himachal Pradesh during the monsoon season 2023**



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# **A Preliminary report on the landslides and land subsidence across the Solan District, Himachal Pradesh during the monsoon season 2023**

## **Executive Summary**

The Solan district of Himachal Pradesh has also been affected due to heavy rainfall in the months of July and August 2023, causing multiple landslide and slope failure events at several locations along the highways and roadside as well as towns and villages situated on the hill slopes. To understand the different causative factors of landslides, flash floods, and vulnerable locations susceptible to such events in the Solan district, preliminary geological and geomorphological investigations have been carried out by WIHG. The team surveyed five transects in the Solan district: (1) Parwanoo – Kandaghat, (2) Baddi – Arki, (3) Nalagarh – Swarghat, (4) Swarghat – Ramshehar, and (5) Nalagarh – Bawasni. The landslides in this area are generally geologically and structurally controlled and occur mostly at places where highly fractured and low-strength sandstone, siltstone, claystone, mudstone, sandstone, and slate rock types are present. The rocks are mostly more than two sets of joints, which increases mass instability and results in planar, wedge, and toppling failure. Prominent weathering in mudstone and claystone rocks has been identified that has also increased the susceptibility to failure. The higher values of the steepness index suggest that transects-1 and -2 are susceptible to erosion. The frequency of such events with increased rainfall is anticipated in the near future. The area is highly critical for landslide occurrences; a detailed investigation is further recommended for the most vulnerable locations.

## **1. Introduction**

A landslide is a natural phenomenon where the bulk of slope material like rock mass, debris, and earth material falls in a downward direction due to gravity (Cruden and Varnes, 1996). Failure of slope is commonly governed by shear strength and shear stress, which is controlled by several internal and external parameters such as material strength, discontinuity parameters, slope geometry, geo-hydrological environment, structural features, and various types of anthropogenic activity in hilly terrain. Landslides are a major problem in the Himalayan terrain because they cause several fatalities and socioeconomic disruptions every year. The primary reasons for slope failures in the Himalayan region are incompetent lithology, prominent weathering in particular rock types, and numerous complex structural discontinuities. Where, extensive weathering along weak planes (i.e., joints and foliation planes) and different

erosional processes caused by environmental conditions and human interventions have further loosened the rock strength. The complex geology and multiple stages of rock deformation in active Himalaya have all combined the rock mass to exacerbate the problem of slope instabilities. However, excessive rainfall and seismic activity in the Indian Himalayan region have been identified as major triggers for these catastrophic events. The state of Himachal Pradesh (HP), in the monsoon season of the year 2023, received a huge amount of precipitation, which is more than the average daily rainfall (IMD 2023), creating multiple landslide events, flash floods, and cloudburst tragedies. From 7<sup>th</sup> to 14<sup>th</sup> July 2023, including Himachal Pradesh, several other states in north India experienced exceptionally heavy rainfall. In HP, there are several episodes of cloudburst occurrences during the said time. The locations include Solan, Shimla, Mandi, Pandoh, Sainj, Manali, Arki, etc. (Chauhan et al., 2023, Hindustan Times). The frontal part of Himachal Pradesh is severely affected by the occurrences of multiple landslide events due to the intense rainfall, resulting in loss of human lives and damage to roads, properties, and buildings. The Indian Express print media reported the loss of 223 lives, 1300 road blockades, 40 major bridges damaged, 3733 water supply schemes affected, and various other properties. This extensive loss of properties is expected in millions of dollars (The Indian Express 2023).

The Solan district of Himachal Pradesh has also been affected due to heavy rainfall in the months of July and August 2023, causing multiple landslide and slope failure events at several locations along the highways and roadside as well as towns and villages situated on the hill slopes. These meteo-climatic events made the boulders and debris material slither along the slopes and damaged roads, bridges, property, population and other infrastructures. The heavy precipitation has also produced flash floods in the valley and formed landslide dams in places. The landslide triggered due to heavy rainfall on August 11, 2023, caused a blockade of Shimla National Highway 5 in Solan district at Chakki Mod and Thambu Mod in Solan district (Hindustan Times 2023). The heavy rainfall (cloudburst) triggered landslides on 14<sup>th</sup> August 2023 in the Solan district where seven people of a single family were killed in Jadon village in the Kandaghat subdivision, and four others were also killed at other places in the Solan district on the same day. Two houses have also been washed away due to this event (India Today 2023). On 2<sup>nd</sup> August 2023 near Prawanoo, a 40-meter stretch of Chandigarh - Shimla National Highway 5 was washed away due to a landslide (The Free Press Journal 2023). A huge landslide on 10<sup>th</sup> July 2023 occurred at Chewa village in Solan district due to a cloudburst (The Tribune 2023). Some buildings at Shamti village in Solan district have been damaged due to a

landslide on 11 July 2023. Apart from the above, there were several small and extensive landslides and land subsidence that occurred in the recent rainy season of 2023 in the Solan district, which were not reported by any news agencies.

To understand the different causative factors of landslides, flash floods, and vulnerable locations susceptible to such events in the Solan district, a preliminary geological investigation has been carried out by WIHG. The team surveyed five transects in the Solan district: (1) Parwanoo – Kandaghat, (2) Baddi – Arki, (3) Nalagarh – Swarghat, (4) Swarghat – Ramshehar, and (5) Nalagarh – Bawasni. In addition to these transects, a few other locations were also marked in the Solan district where landslides have occurred. There are almost 40 landslide locations or sites that our team has reached, and their preliminary data regarding slope failures are collected. Of these, many vulnerable locations are found along the Parwanoo – Kandaghat and Nalagarh – Swarghat routes. However, a few more destructive sites are marked near the Bawasni village along the transect-5. As per the primary investigation, slope failures in this region are mostly controlled by geological and structural discontinuity. Geomorphologically, steep slopes, deep V-shaped valleys and high relief have facilitated the occurrence of landslide events in the region. During the fieldwork, mostly softer lithology (sandstone, shale, siltstone, claystone, mudstone, and marl) dominated regions are found susceptible to slope failure. The majority of rocks have more than two sets of joints, which increases mass instability and results in planar, wedge, and toppling types of failure at various locations (**Fig. 1**).

It has also been identified that at many locations, rocks are weathered into debris materials or soil-type material due to tectonic activity and environmental degradation. In the field, debris slides are observed and occur along the scarp of circular failure following the shallow translational slides due to loose material or very weak rock mass (**Fig. 2**). These debris slides may be the old debris that got reactivated during the extreme monsoon events. There are numerous spots along the roads and highways where fluvial deposits are found adjacent to the rock mass formation, where slope failures have also been marked. Further, anthropogenic activity such as the widening of roads, human settlements, various types of constructions along the valley side of hills, tunnel constructions and industrialization have changed the natural environment. The geology of the area, structurally controlled weak rock mass, steep slopes, and considerable high rainfall have all contributed to creating havoc in the Solan district. There are some locations where huge landslides occurred and extended towards the valley side up to the river channel, where landslide dams have been formed due to the deposition of debris

materials across the river channel (Example - Sheri Khad on Swarghat – Ramshehar road, (Fig. 10).



**Fig. 1** Planar failure (due to joint J1) along the National Highway (NH-5) between Parwanoo and Kandaghat in Solan district. Yellow lines show joint sets.

## 2. Scope of work

To understand the different causative factors of landslide and land subsidence in the Solan district during monsoon season 2023, the Govt. of Himachal Pradesh proposes Wadia Institute of Himalayan Geology, Dehradun carry out the preliminary investigation on the landslide/land subsidence in the said district. The major terms of reference for proposed studies are:

1. The study is conducted to understand the cases of landslide/land subsidence reported during the current monsoon (2023) and the old ones that have been reactivated.
2. The preliminary geological investigations include causative analysis for the activities that took place during the Monsoon 2023 and the major parameters that have played a dominant role in the collapse of the structure.



**Fig. 2** Debris slide near Chakki Mod, where the damage to the road was marked.

3. The prominent and chronic vulnerable locations are identified and a detailed study is recommended for mitigation.
4. Based on the preliminary geological investigations, broad strategies and mitigation measures are suggested for immediate management of the landslide/land subsidence case.
5. The correlations between the instabilities and lithology, soil and overburden material, topography (slopes), land use, hydrology (rainfall, sub-surface infiltration) and the most significant factors are discussed.

### **3. General geology of Solan district**

Solan district lies within the Lesser Himalaya and the Siwaliks and is comprised of rocks ranging in age from the middle Proterozoic to the Quaternary (Srikantia and Bhargava, 2021) (**Fig. 3**). On the eastern side, the older Proterozoic Lesser Himalaya, i.e., the Simla group of rocks are mostly exposed. Out of four formations of the Simla Group, only three, i.e., Basantpur Formation, Kunihar Formation, and Chhoasa Formations are exposed in the Solan District. Basantpur Formation mainly consists of Conglomerate, quartzite, massive bedded limestone-

dolomite and shale. Kuniyar Formation is dominated by limestone alternating with siltstone and shale. Chhoasa Formation shows the presence of shale-siltstone alternation with quartzites. Simla Group of rocks is succeeded upward by the Neoproterozoic to Cambrian Jaunsar Group. Jaunsar Group of rocks mainly consists of limestone, dolomite, black shale, and minor quartzite. In the Solan area, the black shale of Infra-Krol (Jaunsar Group) passes upward through a transition unit of shale and quartzite of Krol sandstone. Northwest of Solan, the development of thinly-bedded sandstone is noticed. Krol sandstones are generally massive, pale grey, and coarse to medium-grained rock. The friable variety is mainly developed in the Solan- Barog area. The general trend of the rocks is NW-SE and E-W directions with dip varying from 10° to 40° on either side. Besides the Main Boundary Fault, Krol, Giri, Chail, and Jutogh Thrust, two major synformal axes running NW-SE also pass through the Jaunsar Group of rocks. Nalagarh, Barsar, and Bilaspur thrusts are, in general, parallel to the Main Boundary Fault. The central part of the district is mainly dominated by the rocks of the Sirmur Group (i.e., Dharamshala Group) of rocks. The Sirmour Group is represented by a thick pile of Palaeogene sediments exposed in the foothill, bounded by the Main Boundary Fault and Krol Thrust (Valdiya, 1983). Sirmur Group is divided into three formations, i.e., Subathu, Dagshai, and Kasauli Formations, and comprises mainly of shale, fossiliferous limestone, quartz arenite, siltstone, clay, sandstone, and local pebble bed. The western part of the district is mainly composed of rocks of the Siwalik Group, which is mainly composed of conglomerate, pebbly sandstone, and shale. Older alluvium and newer alluviums are exposed in between and over the Siwaliks in the western part (Sinha, 1981). The Dun is boarded by Nalagarh thrust in the north and detached Siwalik hills (mainly comprising of Upper Siwalik) in the south. Within the Dun, Quaternary sediments are exposed as alluvial fan and river terraces. North of the Nalagarh thrust, Tertiary (Siwalik Group) and lower Tertiary (Subathu Group) rocks are exposed. The Nalagarh Thrust marks the northern boundary of the Dun, which brought the Tertiary/Lower Tertiary rocks over the Quaternary sediments.

#### **4. Geomorphology of the area**

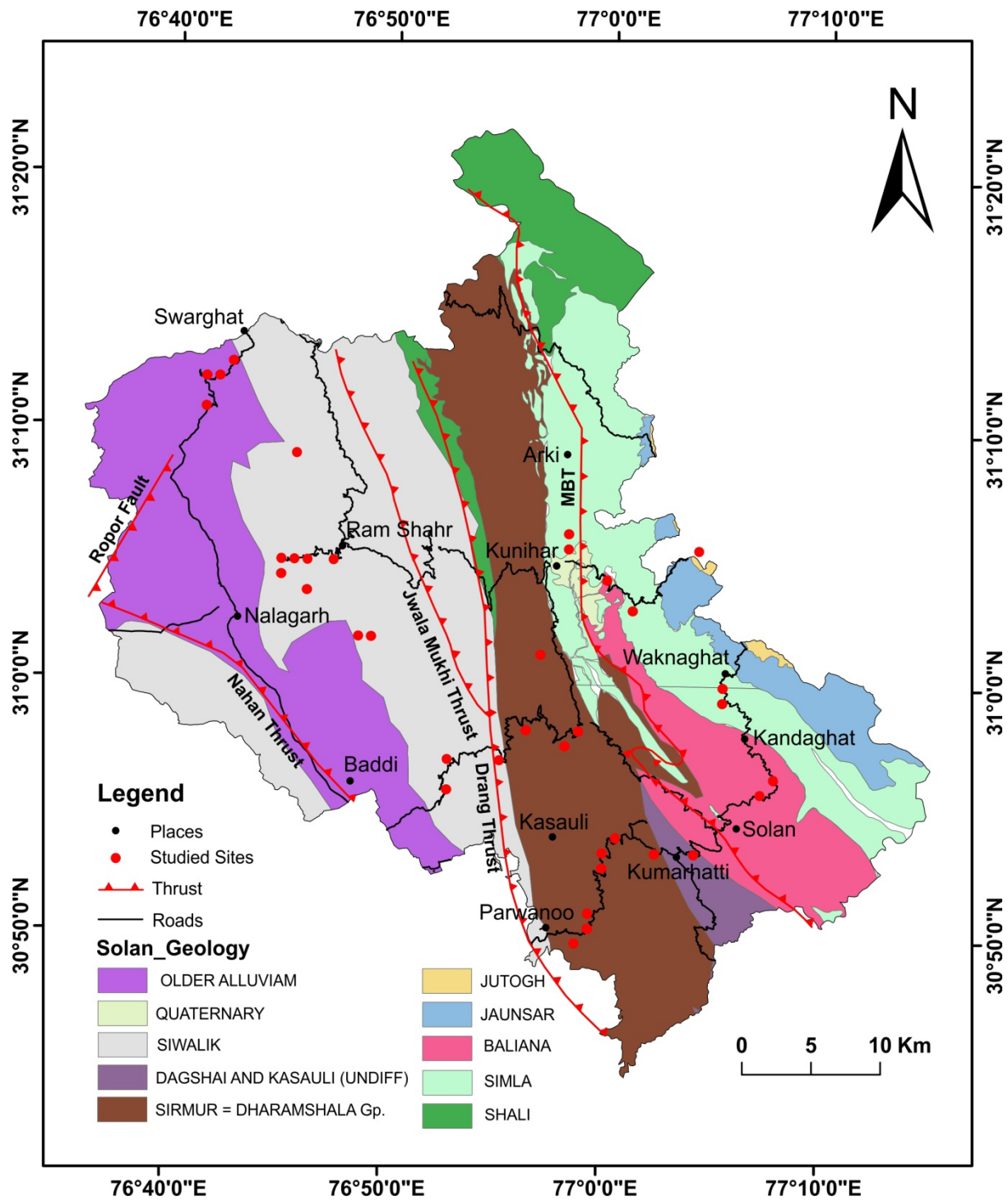
The geomorphology of the Solan district primarily consists of moderate to highly dissected hills. Additionally, scree materials were marked on the escarpment of slopes. The terrain of this area is rugged, with relief ranging from 234 m to 2220 m above sea level (asl). Further, to find a deeper comprehension of the geomorphological control on landslides in the Solan district, we have extracted five catchments within the district, designated as watersheds-1 (WS-1) to -5 (WS-5) (**Fig. 4A**). The steepness index of each watershed/catchment is calculated for

determining the areas with steeper slopes. This index allows for mapping spatial changes in fluvial incision capacity along rivers. Overall, the steepness index is a valuable tool in geomorphology for assessing river profiles, bedrock erodibility and landscape evolution.

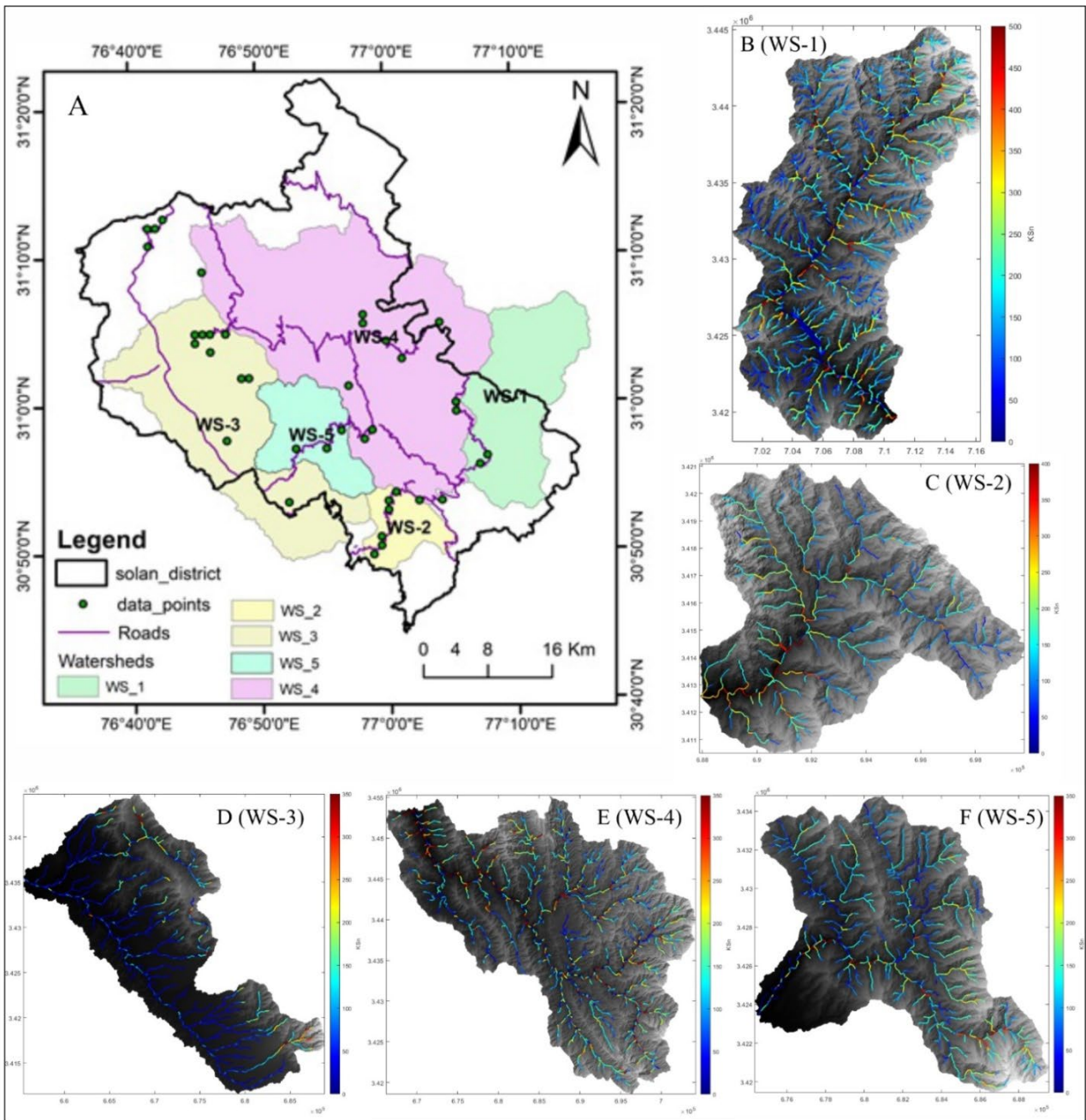
The WS-1 and WS-2 lie in the transect-1 (Kalka to Kandaghat: National Highway-5) (**Fig. 4B & 4C**). The steepness index in this transect is relatively high (300-500), and it has been observed that the number of landslides and related damages is also significantly high. The WS-3 has relatively lower values of steepness index (up to 300) and lies in a relatively flat area. The transect-5 (Nalagarh – Bawasni) (**Fig. 4D**) has been taken in this watershed. However, there have been some disastrous landslides in this watershed's upper reaches, as shown by the higher steepness index values (~350). WS-4 and WS-5 lie in transect-2 (Baddi – Arki: State Highway (SH) - 9), where the Ksn values are relatively low (up to - 300) (**Fig. 4E & 4F**). However, a large number of landslides (~12) were documented in this area, which is due to highly weathered and altered slopes, i.e., debris material. These debris materials fell due to excessive rainfall in this area. It has been observed that rugged topography, steep slopes, and high hills have made slope failures more severe in Solan areas.

## **5. Extreme rainfall events**

The Indian Meteorological Department (IMD) Shimla stations have reported that in July month of 2023, Himachal Pradesh received 437.5 mm cumulative rainfall. This amount is approximately 71% higher than the average precipitation typically obtained in July month for this region (**Fig. 5**). In June 2023, four active episodes of westerlies led to widespread precipitation across the Himachal Pradesh state. Consequently, Himachal Pradesh received 20% excess rainfall and Solan district recorded the highest of 252.6 mm, i.e., ~56% departure from the average. Since 2010, the highest recorded rainfall for July month was 285.4 mm in 2021. But, this monsoon year, in July 2023, the Solan district of Himachal Pradesh received approximately 735.7 mm of rainfall, surpassing the district's average by approximately 143% (**Fig. 5**). From 7<sup>th</sup> to 10<sup>th</sup> July 2023, vigorous monsoon conditions resulted in heavy rainfall across the state. The state received 223 mm of rainfall in just four days, i.e., a ~436% deviation from the average. Solan district, during this event, recorded an ~809% departure from the average with 472.6 mm of rainfall. Specifically, on July 7<sup>th</sup>, 9<sup>th</sup>, and 11<sup>th</sup>, 2023, the Kasauli weather station recorded 80 mm, 172 mm, and 198 mm of precipitation, respectively.

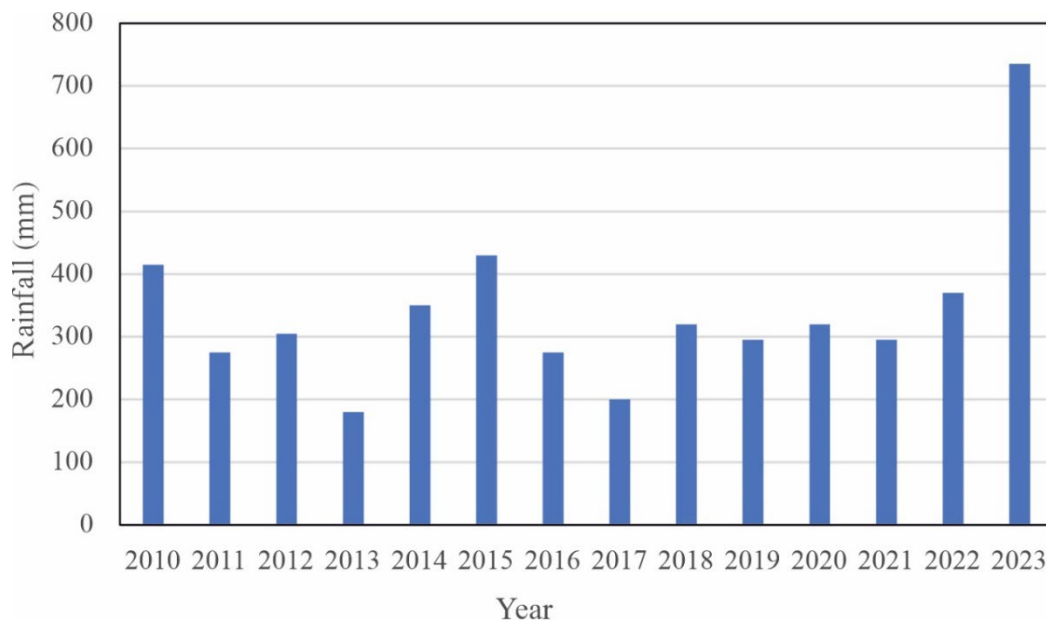


**Fig. 3** The geological map of Solan District (after Geological Survey of India, BHUKOSH) with major thrusts (solid red lines) and studied landslide sites (red circles) marked.



**Fig. 4** (A) Five different watersheds in Solan district named WS-1 to WS-5 with the studied landslide sites (green circle). (B) to (F) represent the steepness index (Ksn) map of the individual watershed WS-1, WS-2, WS-3, WS-4, and WS-5, respectively. The higher the steepness values, the higher the erodibility of the terrain.

The Arki weather station received 150 mm and 170 mm of rainfall on July 10th and 11th, 2023, respectively. In August 2023, the state experienced widespread rainfall, with extreme rainfall recorded on 14<sup>th</sup> and 23<sup>rd</sup> August. Several districts, including Bilaspur, Hamirpur, Mandi, Shimla, and Solan, received excessive rainfall. Solan district recorded 466.1 mm of rainfall, i.e., a ~62% deviation from the average. According to the Shimla station of India Meteorological Department (IMD), in the month of September 2023, Solan district, along with Bilaspur, Hamirpur, Kullu, Mandi, and Shimla districts, recorded an excess yearly cumulative precipitation (+60% or more).



**Fig. 5** Rainfall histogram for July month of Solan district, Himachal Pradesh (Year 2010 – 2023) (Data from IMD Shimla Station).

The unpredictable intense rainfall events in the Himalayan region are perceptible and are a matter of debate. Several studies have suggested that changes in wind patterns across the Himalayan region result in variations in the hydrological response to climate change and warming (Immerzeel et al., 2012; Gupta et al., 2024). The variability in downpours of water in the Himalayan region is also controlled by the changes in the mid-latitude westerlies. During 2023, Himachal Pradesh, particularly the Solan district experienced significant rainfall deviations. The state had more frequent and intense westerlies in 2023, which significantly contributed to the state's record-breaking rainfall amounts. The extreme rainfall events led to significant departures from average precipitation levels, particularly in the Solan district, which

consistently recorded the highest rainfall throughout the monsoon season. The excessive rainfall event in this region has triggered multiple landslide occurrences by reducing the shear strength of slope-forming material. The water has also percolated into joints and fractures of the rocks and generated excessive pore water pressure against the discontinuity. The heavy rainfall event in 2023 highlights the need for planned infrastructure development and mitigation measures to minimize the impacts of such extreme weather events in the future.

## **6. Field assessment of landslide occurrence**

The field visit was done to accomplish the objective of a preliminary report for landslide and land subsidence occurrences in Solan district in Himachal Pradesh. Data of landslide sites are plotted in **Fig. 6**, and the preliminary data of field investigation along five transects are discussed below:

### **(i) Parwanoo – Kandaghat transect**

The field visit was done between Parwanoo and Kandaghat along the national highway NH5 in Solan district to identify different landslide sites. It was found that this transect is the most vulnerable section in the Solan district of Himachal Pradesh, and data on the twelve most vulnerable sites were collected. Photographs of some debris slide sites and their damages along this route are given in **Fig. 7**.

The rock slope failure at L-1 (Site-1) has occurred due to a highly fractured rock mass having three sets of joints. The bedrock composed of mudstone is weathered and overlain by altered loose mass-like debris material along the slope face, forming rock cum debris slide. At sites L-2 and L-3, the landslide is structurally controlled where failure occurred along the prominent joint plane. The road-cut slope has an angle of almost 70-80°, which also assists slope failure. At site L-4 (Important location), the slope consists of an alternate bed of sandstone and a thin mudstone bed, where weathering is prominent in thinly bedded mudstone and prone to failure. Three sets of joints are commonly identified, where fine-grained material is deposited in the joint spacing. At site L-5, a large area of almost 300-400 m in length along the roadside has been affected due to a landslide that occurred at the site, Chakki mod (Important location) (**Fig. 8**). The bedrock is mudstone and siltstone in which three sets of joints (Attitude- J1: 55/265, J2: 46/23, J3: 26/330) are commonly found with spacing varying from 4 to 60 cm. The rocks are weathered and altered, whereas mudstone is prominent in weathering. A thick deposit of

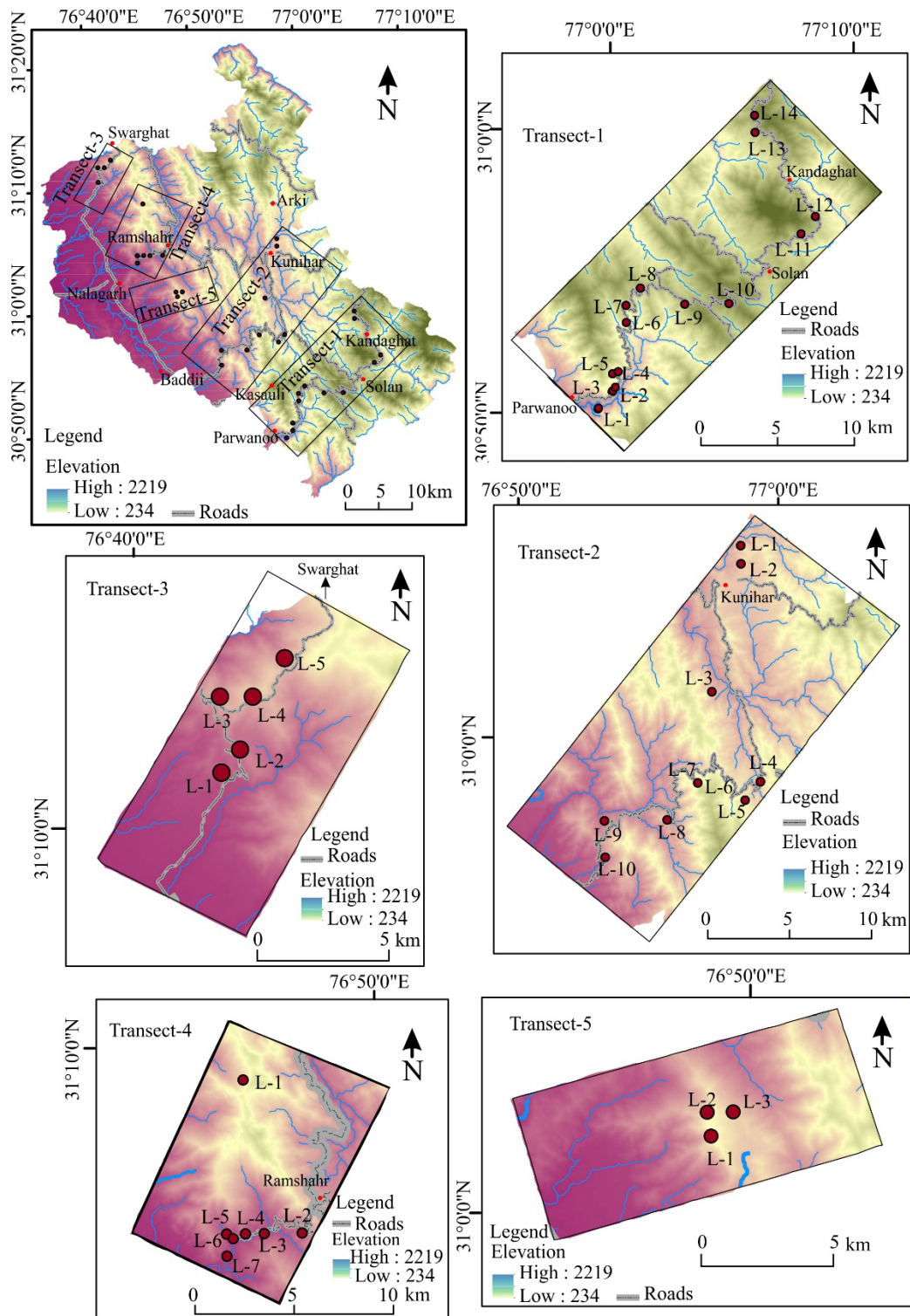
debris materials over the bedrock of mudstone and siltstone, forming debris cum rock slide. The cracks on the crown of the slope are also observed during the field visit. The average slope angle is found here at almost  $65^\circ$ .

At the site, L-6 (Important location), ~150 m, L-7, and L-8, ~ 400 m road section has been affected due to the landslide. Rocks are observed here with highly fractured alternate layers of mudstone, sandstone, and shale. Three sets of joints are found here, and the spacing of joints varies between 10-60 cm with an average spacing of about 60 cm. Shale and mudstone are highly weathered and altered at some locations, forming debris-like material. Heavy settlement has also been marked at several locations on the top of the hill slope causing passive load on the highly fractured and weathered rock mass and susceptible to failure. At sites L-9 and L-10, ~300 to 350 m road section was affected due to landslide events. Some houses and hotels are being damaged as said by local people. The bedrocks are siltstone, sandstone and claystone rock types, where rocks are very low in strength due to highly weathered and fractured rock mass. The loose material has been slumped down along the circular plane due to heavy load as weathered rock mass mixes with the rainfall water.

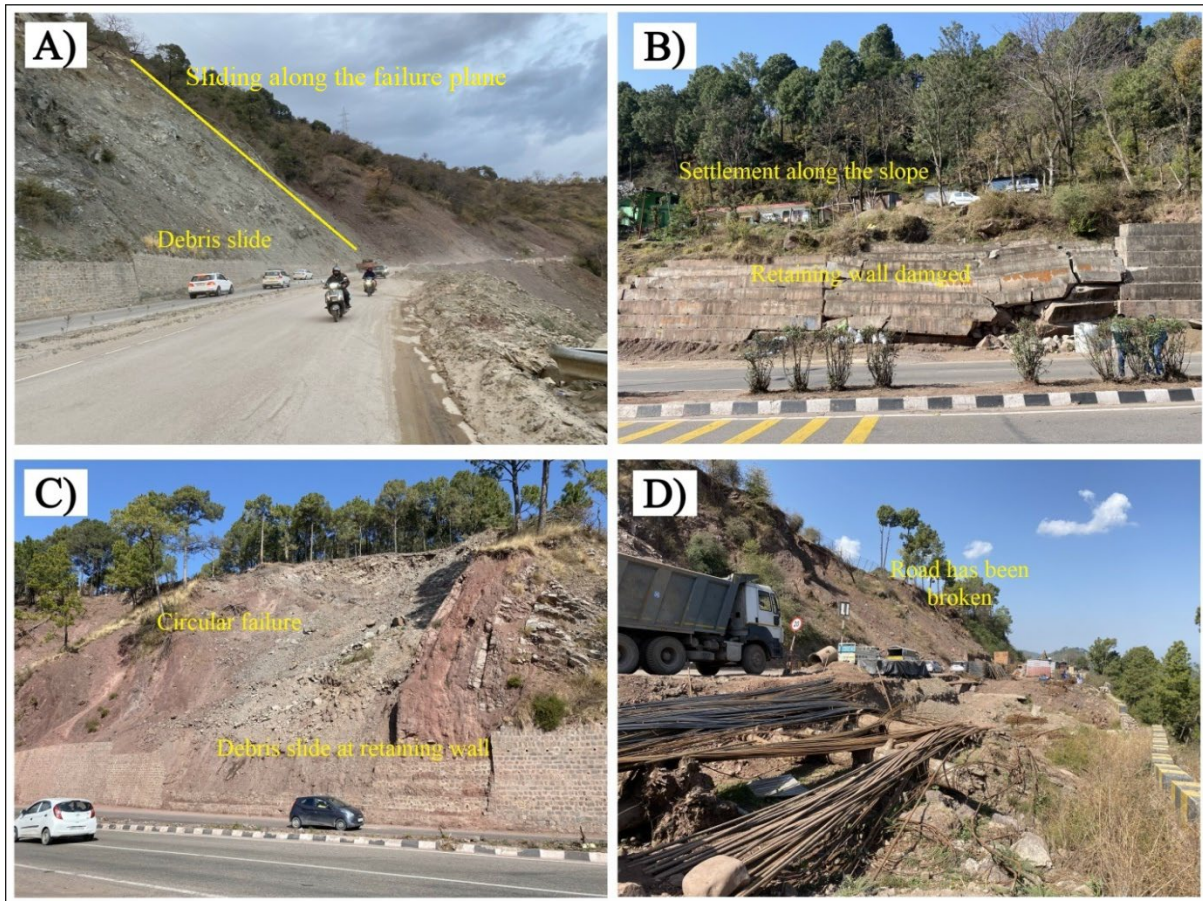
At site L-11 (Important location), slope failure has occurred in the highly fractured and weathered dolomitic and limestone rock. The outcrop has a steep slope ( $\sim 75^\circ$ ) and shows three sets of joints (Attitude of joints- J1: 79/138, J2: 84/89, J3: 10/293), where the spacing of joints varies from 30 to 60 cm. The rocks here at many points along the roadside are cut in an un-engineered manner, which is observed during the field visit. At site L-12, landslides have occurred here in highly fractured sandstone, siltstone, and shale rock. The site has a steep angle ( $65^\circ$ ), having three sets of joints. The low-strength material and highly jointed steep cut slope overloaded with loose altered material have created a huge risk for large landslide events. Further, on the top, the settlement has been observed, which is also imposing uncertainty.

## **(ii) Arki – Baddi transect**

The Arki to Baddi transect, along the state highway SH 9, was also affected due to landslides in the recent rainy season (2023), where more than 10 sites were marked. The rocks are shale, slate, and sandstone, which are highly fractured and consist of two and three sets of joints. The spacing of joints is varied. The rocks are of mostly low strength and show prominent weathering along the slope face.



**Fig 6** Topographic map shows all the studied sites and transects.



**Fig 7** Some photographs of debris slide and damage along the Parwanoo – Kandaghat transect.



**Fig. 8** - A panoramic view of debris slide at Chakki Mod.

Further, the thin-bedded shale exhibits noticeable weathering, which increases the overall slope propensity to failure. Most of the sites have highly altered rock material, forming debris material and slumped or failed due to heavy rain. Fluvial deposits have been marked at some sites along the slope face or top of the slope. These deposits have very little cohesion, which contributes to the slope's nature towards failure. At many sites, the low-strength debris material failed along the concave path, resulting in circular-type failure. Where, the roads have been damaged and debris slide has been extended towards the valley side (L6 & L7). At site L6, a big Nala has been marked. A large area is being affected along the roadside due to debris failure at site L10 (~ 300 m length along the road section). In between Arki and Baddi, site L1 near the bridge has been marked as an important site where a huge landslide has occurred. The predominant rock types are sandstone and thinly bedded shale. The rocks are extensively fractured and have three sets of joints (Attitude of joints - J1: 47/117, J2: 80/235, J3: 80/294). Prominent weathering is found in the shale and having crushed-like material imposing more threatened to failure. This is another instance where the unplanned cut slope increases the chance of vulnerability. The other side of the bridge has also witnessed the landslide event, where highly fractured slate and sandstone (more than three sets of joints) caused more vulnerability (**Fig. 9**). The slate at this site is highly jointed and highly weathered making it more susceptible to failure. The valley width is found to be almost 50 m and is partially blocked due to the landslide. This site is also prone to further landslides, which may blockade the river channel completely, and storage of water may create significant problems in the future. Apart from these, there are several spots where slope failure has occurred, but they are of low risk, as these slopes are gentle and have low heights.

### **(iii) Nalagarh – Swarghat transect**

The data has been collected between Nalagarh and Swarghat along the NH21 section. This route is also affected and five prominent landslide sites were marked as the most vulnerable sites. The bedrock along this route are mainly, sandstone and mudstone, which are highly fractured. Three sets of joints are commonly found in the rock mass, and rocks are also weathered and, at some sites, altered to debris material. At sites L-1 and L-2 in this transect, highly fractured sandstone rock has failed, and almost 100 m length along the road section has been affected. At site L-3, cracks of 10-15 cm are marked on the road and along the valley side, which is causing the upcoming failure. A temple and some settlements have been marked on the top of this slope, which is affected, and some damage has also been marked. Thin mudstone bed is found laminated between highly fractured sandstone beds and the rocks are mostly of

low strength. The site L4 site is a significant debris slide site along this route, where a big landslide has occurred, and an almost 100 m road section is affected (**Fig. 10**). The valley side is also affected due to this landslide. Here also, on the top of the slope, a Temple and other settlements are marked, and there is also thick vegetation on the top portion, imposing extra load for failure. The slope is more than 100 m in height and gentle in nature. The failed debris material, having a boulder size of a few centimeters to 2.5 m, is deposited along the lower portion of the slope and bulges in convex form. Some cracks are also observed towards the upper portion of the slope, depicting a progressive failure in the upward direction.



**Fig. 9** Landslide happened on both sides of the river near the bridge at site L1 (Between Kunihar and Arki).

#### **(iv) Swarghat – Ramshehar – Nalagarh transect**

The fieldwork has been done between Swarghat to Ramshehar and then Ramshehar to Nalagarh along the state highways to find out the different vulnerable sites. Seven sites were marked where debris slides have occurred, and almost 100 to 200 m road section is affected. In between Swarghat and Ramshehar, thick vegetation on the slope and gentle dipping sites reduce the slope instability issue in this area.



**Fig. 10** The debris slide, the slide is also growing towards the upside (progressive slide).

An important site (L7) where a huge debris slide has occurred near Sheri Khad, where a ~300 m road section has been completely damaged. The river channel is blocked here and a small lake is formed as a result of landslide damming (**Fig. 11**). The rock type is sandstone, which is highly fractured. The boulder size ranges up to 5 m, and one big dry Nala is also marked on the other side of this event. The area is thick in vegetation, and due to the slide, fallen trees can be seen here. Although the slope is gentle, due to the cloud burst tragedy at this site, the highly fractured rock mass with a large volume has slide along the slip surface.

#### **(v) Nalagarh – Bawasni transect**

Fieldwork was also conducted along this local route between Nalagarh and Bawasani. Three sites are mainly identified as vulnerable, where landslides have been marked. At sites L1 and L2, almost 150 to 200 m length of road section was affected due to this natural calamity. The rocks at these sites are mainly sandstone, which are highly fractured having two and three sets

of joints. Average boulder size varied from 1.5 m to 5 m, and boulders were seen dislodged towards the valley side. There is also a significant site L3 along this route, where a huge landslide has occurred (**Fig. 12**). The rock type here is sandstone, which is highly fractured, having three sets of joints (Attitude of joints – J1: 44/57, J2: 76/241, J3: 89/342) and the boulders of size up to 5 to 8 m are seen here. Below the highly fractured sandstone bed, marl deposits of moderate to low strength are found, on which large volumes of fractured blocky sandstones slide due to heavy rainfall. The field visit witnessed that around 500 to 600 m of road and up to 250 m of valley side were affected by this landslide, and several houses were damaged.



**Fig. 11** Small Lake has been formed due to landslide damming.

### **Conclusions and recommendations**

A team of WIHG has carried out fieldwork in Solan district, Himachal Pradesh to collect the data for preliminary investigation of the landslide. The team surveyed the five transects along highways and roads, namely (1) Parwanoo – Kandaghat, (2) Baddi – Arki, (3) Nalagarh – Swarghat, (4) Swarghat – Ramshehar, and (5) Nalagarh – Bawasni. There are almost 40 landslide sites (rockfall and debris slide) for which, preliminary data regarding the slope

failures are collected. Of which, 8-10 sites are found as significant in different transect, which have been discussed in different transects (i.e., transects-1, -2 and -5).



**Fig. 12** Highly fractured sandstone bed moved along the slip surface of the marl bed.

The steepness index ( $K_{sn}$ ) values in the transects 1 & 2 shows higher values and suggest susceptible to erode. These transects were severely affected due to landslide events, which is also confirmed in the field. The landslides in this area are generally geologically and structurally controlled and occur mostly at places where highly fractured and low-strength sandstone, siltstone, claystone, mudstone, sandstone, and slate rock types are present. The rocks are mostly more than two sets of joints, which increases mass instability and results in planar, wedge, and toppling failure. Prominent weathering in mudstone and claystone rocks has been identified that has also increased the susceptibility to failure. Several debris slide zones are marked in this region and occurred on the scarp of circular failure following the shallow translational slides due to loose material or very weak rock mass. Geomorphologically, steep slopes, deep v-shaped valleys, and high relief again increase the possibility of slope failure. Further, various anthropogenic activities such as the widening of roads, human

settlement, various types of constructions and heavy tourism have changed the natural pattern of the hilly terrain. The steep slopes because of road widening is a big problem in these hilly terrains. The orientation of the joints exposed to surface processes makes the terrain more vulnerable. Additionally, long-duration, heavy rains caused water to infiltrate into debris material and joints of fractured rock mass which lowered the safety factor and made the critical locations for collapse. Therefore, geology, structurally controlled weak rock mass, weathering in predominant rock types, topography, and considerable rainfall during the most recent rainy season (2023) have all combined to result in slope failures at various locations in the Solan district of Himachal Pradesh.

As the area is highly critical for landslide occurrences, a detailed investigation is further recommended for the most vulnerable locations. A detailed study is required to understand the engineering characteristics of slope-forming materials, the mechanism behind slope failure, the impact of discontinuity parameters, and rainwater infiltration. Such investigation and their suggestive measures can mitigate and minimize the risk of slope failures.

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### **References**

- Chauhan, C., Bisht, G., Thakur, K.N., 2023. Floods in Himachal leave trail of destruction. Hindustan Times, July 13, 2023.
- Cruden, D.M., Varnes, D.J., 1996. Landslide types and processes, special report Transp. Res. Board, Natl. Acad. Sci., 247, pp. 36-75
- Geological Survey of India, 2024. Bhukosh. Geological Survey of India. <https://bhukosh.gsi.gov.in/Bhukosh/Public> (accessed March 24, 2024)
- Gupta, V., Syed, B., Pathania, A., Raaj, S., Nanda, A., Awasthi, S. and Shukla, D.P., 2024. Hydrometeorological analysis of July-2023 floods in Himachal Pradesh, India. *Natural Hazards*, pp.1-26.
- Hindustan Times., 2023. Himachal rain, Kalka Shimla road at NH-5, closed after landslide in Solan. Hindustan Times, August 11, 2023.

IMD., 2023. Government of India Ministry of Earth Sciences (MoES) India Meteorological Department Meteorological Centre, Shimla.

Immerzeel, W.W., Van Beek, L.P.H., Konz, M., Shrestha, A.B. and Bierkens, M.F.P., 2012. Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climatic change*, 110, pp.721-736.

India Today., 2023. Himachal Pradesh rains cloudburst Shimla temple landslides images of destruction, August 14, 2023

Kumar, V., Gupta, V. and Jamir, I., 2018. Hazard evaluation of progressive Pawari landslide zone, Satluj valley, Himachal Pradesh, India. *Natural Hazards*, 93, pp.1029-1047.

The Free Press Journal., 2023. Highway washed away after landslide near Solan district in Himachal Pradesh, August 2, 2023

The Indian Express., 2023. Himachal counts losses: 31 dead, 40 bridges damaged, 1,300 roads closed. The Indian Express, July 13, 2023.

The Tribune News., 2023. The Tribune Himachal scary visuals of flash flood from Mandis Thunag in Himachal Pradesh cloudburst triggers major landslide in Solans Chewa village, July 10, 2023

The New Indian Express., 2023. Landslides kill 13 more people in rain hit Himachal Uttarakhand, July 12, 2023

Sinha, A.K., 1981. Geology and Tectonics of the Himalayan Region of Ladakh, Himachal, Garwhal-Kumaun and Arunachal Pradesh: A Review. *Zagros Hindu Kush Himalaya Geodynamic Evolution*, 3, pp.122-148.

Srikantia, S.V. and Bhargava, O.N., 2021. Geology of Himachal Pradesh. GSI Publications, 2(1).

Valdiya, K.S., 1983. Lesser Himalayan geology: crucial problems and controversies. *Current science*, pp.839-857.