Middle East Journal of Applied Science & Technology (MEJAST)
Volume 8, Issue 3, Pages 37-55, July-September 2025

Remote Sensing and GIS Applications in Managing Landslides along National Highways in India: A Focus on Himalayan Regions

Ritesh Kumar[1*], Gaurav Chakrabarty[2], Sanjay Kumar Roy[1], Kartik Varwade[1], Anand Singh[1], Manish Kumar[3] & Swapan Mahato[4]

[1]Scientist, CSIR-Central Institute of Mining & Fuel Research, Barwa Road, Dhanbad-826001, India. [2]M.Sc. Geo-informatics, Birla Institute of Technology, Mesra, Ranchi, India. [3]Senior Technical Officer, CSIR-Central Institute of Mining & Fuel Research, Barwa Road, Dhanbad-826001, India. [4]Technician, CSIR-Central Institute of Mining & Fuel Research, Barwa Road, Dhanbad-826001, India. Email: ritesh13@rediffmail.com[*]

DOI: https://doi.org/10.46431/MEJAST.2025.8303

Copyright © 2025 Ritesh Kumar et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Article Received: 09 May 2025 *Article Accepted: 22 July 2025* *Article Published: 26 July 2025*

ABSTRACT

This study presents a comprehensive review of landslides along National Highways in India, with a particular focus on the Himalayan Belt. By examining events over the past seven years, the paper delves into key drivers behind these frequent landslides and explores the efficacy of Remote Sensing (RS) and Geographic Information Systems (GIS) in landslide prediction and management. It is anticipated that the integration of these advanced tools will improve hazard assessments, enable precise interventions, and ultimately mitigate the socio-economic impacts of landslides.

The study draws on publicly available data and aims to uncover gaps in the existing research on Indian landslides. Emphasizing an innovative approach, the paper proposes enhanced prediction methods to mitigate both direct and indirect losses resulting from landslides. These suggestions are grounded in the socio-economic realities of the affected regions.

Keywords: Landslide; National Highway; Remote Sensing; Geographic Information Systems (GIS); Hazard; Prediction; Mitigation; Disaster Management; Himalayan Region; Landslide Susceptibility Map.

1. Introduction

Natural disasters, while unpredictable and devastating are an inevitable part of the Earth's dynamic processes. Among them, landslides pose a persistent threat to human life, infrastructure, and the environment, particularly in mountainous regions. India, with its diverse topography, is highly susceptible to such hazards. Landslides are not just geological phenomena but complex disasters with far-reaching consequences, including loss of life, economic disruption, and environmental degradation.

A landslide, as defined by Varnes (1984), is a form of mass movement caused by gravitational forces that result in the displacement of soil, rock, or debris down a slope. Landslides can be triggered by natural causes like heavy rainfall, earthquakes, and volcanic activity, or anthropogenic factors, such as deforestation, construction activities, and road building, which destabilize the slopes.

In India, approximately 12% of the landmass is vulnerable to landslides, with the most affected regions being the Western Ghats, Eastern Ghats, and the Himalayan Belt. The Himalayas, in particular, witness frequent landslides due to their fragile geology and high seismicity. According to the Geological Survey of India, over 300 people die annually due to landslides globally, with India contributing significantly to this toll (Geological Survey of India, n.d.; National Disaster Management Authority, 2019; Dutta, & Das, 2018; Bhasin et al., 2019).

Landslides are significant natural hazards that pose threats to both human lives and infrastructure, particularly in regions prone to geological instability. Figure 1 below which shows the landslide hazard map of India illustrates regions most susceptible to landslides. It can be seen that the country's mountainous and hilly terrains are particularly vulnerable (Landslide: NDMA GoI). The transportation network, often considered the backbone of society, can be severely disrupted by landslides, especially along highways. Such disruptions not only trouble daily life but also hinder economic activities and emergency responses (Sarkar & Kanungo, 2021). Landslides along national highways are a serious concern because they directly affect both travel safety and connectivity. This paper provides an extensive review of existing literature on landslides along national highways and explores innovative solutions to mitigate the associated risks, aiming to minimize the impact on infrastructure and human lives.

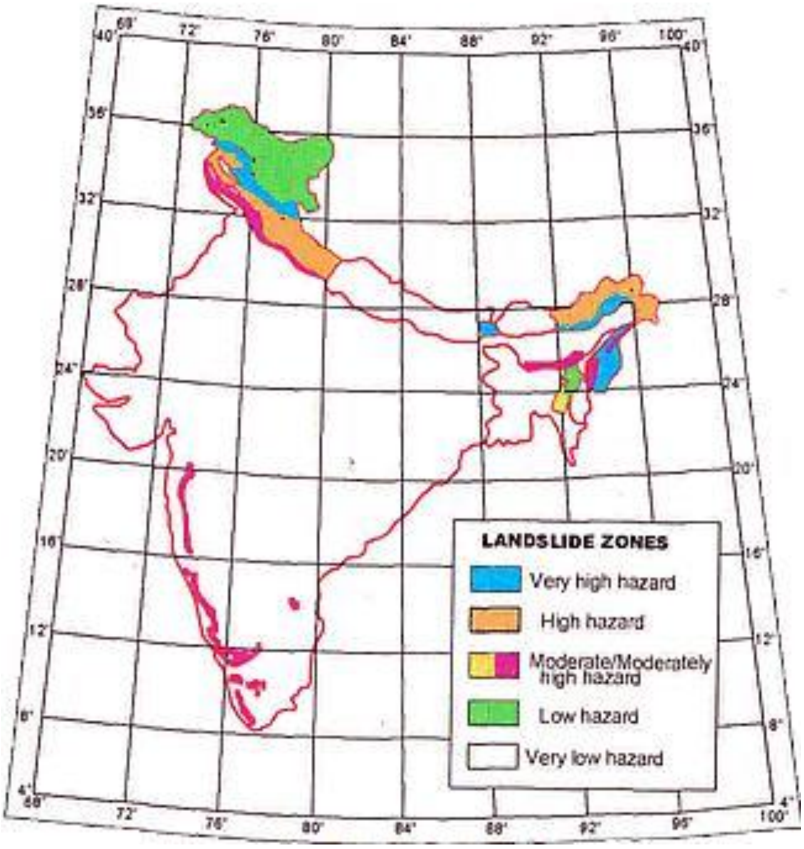


Figure 1. Landslide Hazard Map of India

1.1. Study Objectives

The present study was carried out with following objectives that are enumerated below:

1) To understand the cause and impacts of landslides along National Highways in India, with a focus on both natural triggers and anthropogenic factors.

2) To examine landslides through case studies of major landslides in the Himalayan region, including Jammu & Kashmir, Uttarakhand, Himachal Pradesh, and the North-Eastern states.

3) To analyse the role of Remote Sensing (RS) and Geographic Information System (GIS) in landslide prediction, monitoring, hazard mapping, and disaster management.

4) To identify effective and protective slope stabilization measures for landslide-prone highway corridors.

5) To explore innovations in landslide susceptibility mapping using geospatial techniques such as the bivariate frequency ratio model.

6) To evaluate policy and management strategies aimed at mitigating landslide risks while balancing infrastructure development and environmental stability.

2. A Review on Major Landslides

Landslides are a frequent natural hazard along several National Highways in India, particularly in the Himalayan region. These occurrences have become more prevalent in recent years, largely attributed to climate change and unsustainable human practices, including unregulated construction, deforestation, and infrastructure development. The states most vulnerable to landslides include Jammu and Kashmir, Uttarakhand, Himachal Pradesh, and Sikkim, where the steep and unstable slopes, coupled with anthropogenic pressures, exacerbate the risk (Kaur et al., 2020; Gupta & Joshi, 2019). Remote sensing and GIS technologies have emerged as critical tools for monitoring and managing landslides, offering enhanced capabilities for early warning systems and disaster management strategies (Sharma et al., 2021).

2.1. Landslides along the Jammu-Srinagar Highway

Landslides are a frequent natural hazard along several National Highways in India, particularly in the Himalayan region. These occurrences have become more prevalent in recent years, largely attributed to climate change and unsustainable human practices, including unregulated construction, deforestation, and infrastructure development. The states most vulnerable to landslides include Jammu and Kashmir, Uttarakhand, Himachal Pradesh, and Sikkim, where the steep and unstable slopes, coupled with anthropogenic pressures, exacerbate the risk (Kaur et al., 2020; Gupta & Joshi, 2019). Remote sensing and GIS technologies have emerged as critical tools for monitoring and managing landslides, offering enhanced capabilities for early warning systems and disaster management strategies (Sharma et al., 2021). Figure 2 shows some of the images of landslides incidents along Jammu-Srinagar Highway.

2.2. Landslides in Uttarakhand

Uttarakhand, situated in the North-Western Himalayas, is highly prone to landslides due to its vulnerable geological structure and significant rainfall patterns. The increasing frequency of cloudbursts and intense rainfall events has further intensified the landslide risk in recent years. These landslides not only result in substantial loss of life and property but also disrupt vital transportation and communication networks. A notable example is the 2013 Kedarnath disaster, which tragically led to the loss of over 4,000 lives and underscored the region's susceptibility to such hazards (Sharma, 2017; Singh et al., 2018; Bhandari & Bhatt, 2020). Remote sensing and GIS tools are increasingly being used to analyze such events and improve disaster preparedness in the region (Pandey et al., 2021).

Landslides are very common in this Himalayan state of Uttarakhand. In fact, of the North Himalayan states, including Himachal Pradesh and Jammu & Kashmir, Uttarakhand has the most amounts of landslide-prone or unstable zones (Kumar, 2016). Several incidence of landslide in 2019 is reported such as Uttarakhand’s Rudraprayag landslide due to falling of boulders from the hill. It killed as many as eight persons when the boulder hit a car and two motorcycles into a 500 meter deep gorge (Talwar, 2019; newindianexpress.com); Badrinath landslides that was triggered by rains blocked Badrinath National Highway (Jha, 2019); Pithoragarh-Tanakpur NH 125 that was the result of the human interference in the form of the ongoing work of the All Weather Road Project (July 05 2019: Uttarakhand: Traffic Jam……); A massive landslide wherein major portion of the hill came down on Badrinath National Highway in Chamoli, Uttarakhand; Landslides after cloudbursts kills many and cause extensive damage in Uttarakhand (Livehindustan.com: August 18, 2019); landslides disrupts normal life severely in Govind ghat area of Uttarakhand (ANI: September 7, 2019). Figure 3 shows some of the images of landslides incidents along the National Highway in Uttarakhand.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 2. Landslide along Jammu-Srinagar Highway (a) Landslides, snowfall witnessed at some places between Ramban and Panthal Areas; (b) An earthmover clears the landslide debris from the highway; (c) Jammu-Srinagar Highway Closed After Landslide, 2,000 Vehicles Stranded; (d) Multiple Landslides Disrupts Traffic on Jammu-Srinagar Highway; (e) Fresh landslide disrupts traffic on Jammu-Srinagar highway, clearance operation underway; (f) Multiple landslides disrupt traffic on Jammu-Srinagar highway.

(a)

(b)

Middle East Journal of Applied Science & Technology (MEJAST)
Volume 8, Issue 3, Pages 37-55, July-September 2025

(c)

(d)

Figure 3. Landslide along National Highway in Uttarakhand (a) Traffic Jam due to Landslides on Pithoragarh-Tanakpur National Highway 125; (b) A Massive landslide on Badrinath National Highway in Chamoli, Uttarakhand; (c) Landslide near Chandikhadar area of Rudraprayag district of Uttarakhand; (d) Cloudbursts followed by Landslide cause heavy damage in Uttarakhand.

2.3. Landslides in Himachal Pradesh

Himachal Pradesh is inherently prone to disasters, especially since it is part of the Himalayas. The state has a long history of natural disasters (Chandel and Brar, 2012). As per the Government of India (2003) report the state's 97% area is prone to landslide hazard. Himachal Pradesh, like Jammu & Kashmir, regularly experiences landslides along the National Highways that often causes disruption in the normal life of the people. In the year 2019 itself large number of landslides along the National Highways was reported that has always been of concern for the authorities. Huge man-power and machinery are deployed for clearing of the debris and restoring the highway for normal traffic movement. Landslide along NH-5 near KashangNala in Kinnaur (June 25, 2019); Gohar village of Chachyot Tehsil in Himachal Pradesh's Mandi district (August 17, 2019); Kalka-Shimla Highway (August 17, 2019); Marhi between Manali and Rohtang in Kullu district (August 21, 2019); etc. are some of the incidents to be reported. Below are few incidents of landslides along National Highway in Himachal Pradesh (Figure 4).

(a)

(b)

(c)

(d)

Figure 4. Landslide along National Highway in Himachal Pradesh (a) Incessant rains disrupted vehicular traffic and caused damage after Landslides in HP; (b) Trucks stranded after Manali-Leh road was closed due to landslides caused by heavy rains; (c) Heavy Rain Triggers Landslides in Himachal Pradesh, Several Roads Blocked; (d) Landslides triggered due to Heavy Rainfall caused extensive damage in HP (Mudgal, 2019).

2.4. Landslides in North-Eastern States

The North-Eastern states of India, including Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Tripura, and Sikkim, are situated in the eastern Himalayan ranges, making them particularly prone to frequent landslides. Much of this region consists of unstable geological zones, leading to regular landslide occurrences. Prolonged and intense rainfall is the primary trigger for landslides, significantly impacting the lives and livelihoods of the local population. Landslides have long been a major natural disaster in these states, with regions such as Manipur experiencing their devastating effects since ancient times (Das et al., 2019; Sharma & Singh, 2020). Remote sensing and GIS applications are increasingly being used to monitor these hazards and mitigate their impact (Bhattacharya & Das, 2021).

The earliest recorded catastrophic landslide in the North-Eastern states occurred on August 19, 1950, claiming over 500 lives and causing extensive destruction. This landslide was triggered by aftershocks from the Great Assam earthquake that struck on August 15, 1950. Since then, landslides have become frequent in the region, significantly impacting the lives and livelihoods of the local population (Nongmaithem, n.d.). Various factors contribute to these landslides, and addressing the issue requires a targeted approach that considers both individual triggers and a combination of factors to effectively mitigate the risks.

Several incidences of landslides were experienced in 2019. Some of the landslides incidences to be reported are multiple landslides in Sikkim block NH-31 (PTI, July 12, 2019); landslides in Sikkim block NH-10 (R. Choudhary, July 11, 2019); incessant rainfall trigerred landslides that affected NH-10 (connecting Siliguri and Sikkim), NH-31 (connecting Siliguri and Dooars in Jalpaiguri district) and NH-55 (Siliguri and Darjeeling); Kohima town cut-off by major landslides on NH-29 (uniindia: August 5, 2019); landslide cut-off NH-29 between Dimapur-Kohima. The stretch of NH-29 is a landslide prone area that has experienced landslides and subsidence of roads in the past too specially during the monsoon season (August 5, 2019; August 4, 2019); NH-44 was affected due to landslides near Assam-Meghalaya border (PTI: May 6, 2018); landslides on Imphal-Dimapur road caused heavy damage ((NT Online: October 27, 2019); landslides affected vehicular movements in Manipur (NT Online July 27, 2019); incessant rains reported landslides and heavy flooding in various parts of the State. Landslides led to the blocking major roads in Arunachal Pradesh. NH-415 was the worst hit (sentinelassam.com: July 13, 2019); landslides along

Imphal-Jiribam highway, NH-37 (August 3, 2019); landslides in north-east affected states like Arunachal Pradesh, Sikkim and Meghalaya, besides parts of Assam. Large parts of Arunachal Pradesh have been cut off because of heavy mudslides tearing apart roads, including highways (Hussain, 2019); landslides on Gangtok-Mangan road that disrupted vehicular traffic on road that connects Gangtok city with North Sikkim. Figure 5 shows some of the landslides incidents that have occurred in the past along the National Highway in North-Eastern states.

3. Discussion

Landslides are a frequent occurrence along the Himalayan mountain range, especially during and after the monsoon season. While many landslides are naturally triggered, there is growing evidence linking the increasing frequency of these events to anthropogenic activities in the region. Human interventions, such as the construction of roads and dams, contribute to slope destabilization, which in turn increases the likelihood of landslides. These activities exacerbate the natural vulnerabilities of the Himalayan terrain, further intensifying the landslide risk (Gupta & Kumar, 2020; Sharma et al., 2019).

Below is a brief description of the areas reviewed to better understand the causes and impacts of frequent landslides along the Himalayan belt:

(a) (b)

(c) (d)

(e) (f)

Middle East Journal of Applied Science & Technology (MEJAST)
Volume 8, Issue 3, Pages 37-55, July-September 2025

(g)

Figure 5. Landslides along National Highway in North-Eastern States (a) Multiple Landslides on NH-31 in Sikkim; (b) At least three blockages across NH-10 were reported following Landslide; (c) NH-29 affected due to Landslides in Kohima; (d) Landslide in Nagaland block NH-29; (e) Landslide in Mizoram; (f) Landslides along Jammu-Srinagar National Highway in Jajjar Kotli area of Jammu; (g) NH-29 connecting Kohima with Dimapur cut-off due to major Landslide.

3.1. Landslides along Jammu-Srinagar Highway

The Jammu-Srinagar Highway is particularly susceptible to landslides due to the challenging and unstable terrain it traverses. In recent years, landslides have frequently led to blockages, severely disrupting transportation along this critical route. Studies indicate that landslides are reported annually in large numbers, prompting growing concern among scientists and authorities across India. The most affected locations include Panthyal, Ramsoo, Anokhifal, Nashri, Maroog, Battery Cheshma, Kheri, and areas along the Bichleri stream in the Ramban and Udhampur districts. Remote sensing and GIS technologies have been instrumental in identifying and monitoring these landslide-prone zones, as depicted in satellite imagery of the Jammu-Srinagar region (Sharma et al., 2021; Bhat & Pandit, 2020; Singh et al., 2019). Figure 6 shows the satellite image of the Jammu-Srinagar area highlighting the landslides prone region.

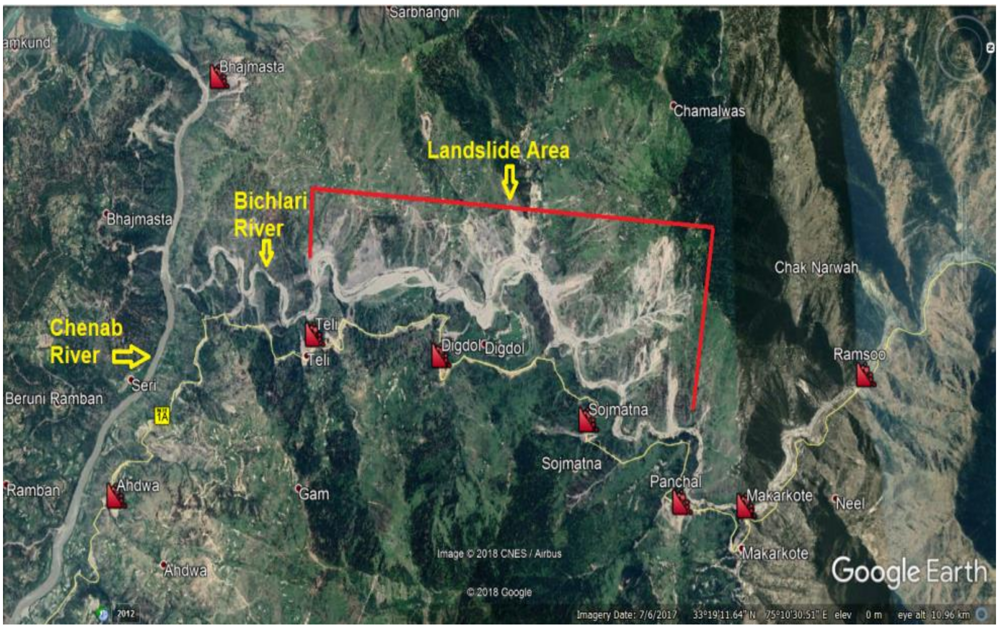


Figure 6. Landslides Prone Area along Ramban and Udham Districts in Jammu & Kashmir (Source: https://sandrp.in/2018/02/17/why-jammu-srinagar-highway-is-so-landslide-prone/)

Middle East Journal of Applied Science & Technology (MEJAST)
Volume 8, Issue 3, Pages 37-55, July-September 2025

Landslides along the National Highways in India are often triggered by heavy, continuous, and prolonged rainfall, which saturates the soil and destabilizes slopes. In addition to natural factors, anthropogenic activities, particularly those associated with highway expansion projects, have also been identified as significant contributors to landslide occurrences. Unplanned excavation and construction work at the base of steep slopes have further aggravated the issue by destabilizing the terrain. These landslides not only disrupt normal traffic flow but also impact local communities in various ways, both directly and indirectly (Kumar & Singh, 2020; Sharma & Thakur, 2019; Gupta et al., 2018).

3.2. Landslides along National Highways in Uttarakhand

The entire state of Uttarakhand is geologically fragile, making it highly susceptible to various geo-hazards, including landslides, earthquakes, and flash floods. Landslides occur annually, posing significant risks to those involved in development and infrastructure projects. In recent years, the state has experienced extreme climatic events, such as prolonged, low-intensity rainfall as well as short bursts of high-intensity rainfall. These weather patterns often trigger landslides, leading to substantial loss of life and property. A notable example is the 2013 Kedarnath disaster, often referred to as the "Himalayan Tsunami," which resulted in the loss of over 4,000 lives and caused widespread road blockages (Singh & Pandey, 2019; Sharma et al., 2020; Bhat et al., 2018**).** Figure 7 below shows the landslide hazard map of Uttarakhand.

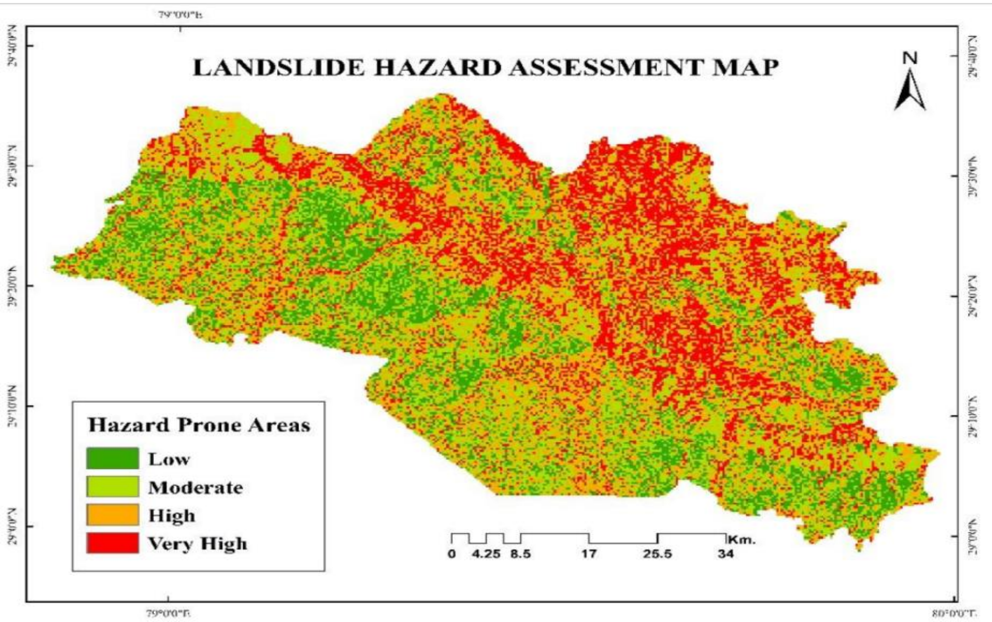


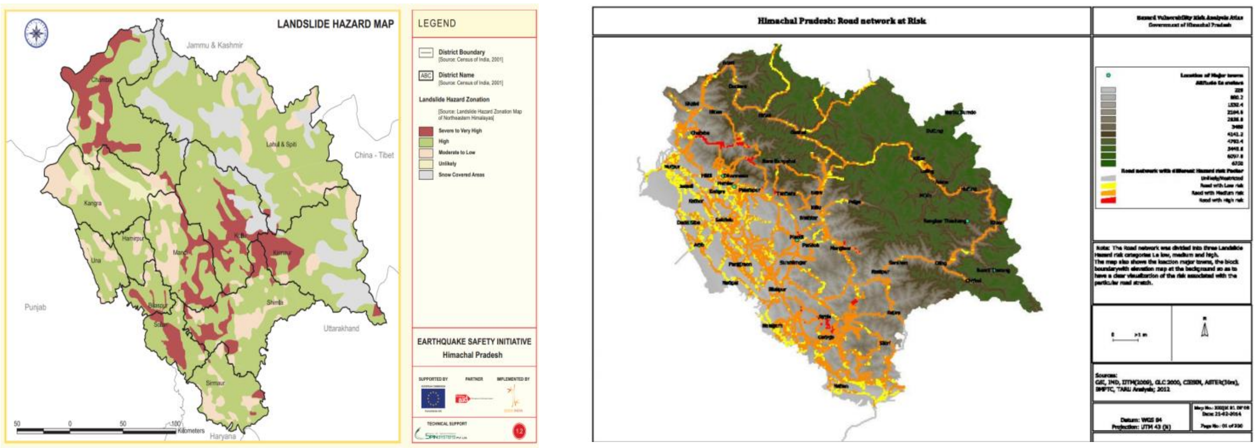
Figure 7. Landslide Zonation Map of Uttarakhand
(Source: Vaid et al., 2019)

As a newly formed state, Uttarakhand has witnessed rapid development, particularly in the expansion of roads and transportation infrastructure. However, this large-scale, unplanned development is believed to be causing significant harm to the region's mountainous terrain. Additionally, extensive dam construction projects have altered the land use patterns, further destabilizing the area's fragile slopes. It is evident that both prolonged rainfall and human activities are contributing factors to landslides along the National Highways in Uttarakhand. The consequences of these landslides include road blockages, disruptions to regular traffic, and the loss of life and property (Joshi & Kumar, 2020; Sharma & Singh, 2019; Pant et al., 2018). Figure 7 shows the landslide zonation map of Uttarakhand.

3.3. Landslides along National Highways in Himachal Pradesh

Landslides in Himachal Pradesh are widespread, although certain areas experience frequent and repeated slope failures. These high-risk zones include the Kalka-Shimla National Highway (NH-22), the Shimla-Rampur-Peo and Malling-Samdo stretch along the Hindustan-Tibet Highway, and the Swarghat-Bilaspur and Mandi-Aut patches on NH-21. Other vulnerable areas include the Kullu Valley, the Gumma-Jogindernagar-Palampur-Dharamsala Highway, the Bilaspur-Shimla Highway, as well as the Dalhousie-Chamba area, Bharmaur Valley, and Holi region of Chamba district (Singh & Thakur, 2019; Sharma et al., 2020; Chauhan & Negi, 2018).

Most of the landslides in Himachal is also the results of heavy and continuous rain that functioned as a triggering agent to landslides (ToI: July 22, 2013 & PNS: September 24, 2018). However, increasing anthropogenic intervention in the name of development cannot be ignored to the occurrence of landslides in the Himachal (Panwar, 2017). According to Kullu, J C Kuniyal a professor at GB Pant Institute of Himalayan Environment and Development in Mohal district "Himalayan rocks are sedimentary in nature and topographically fragile, because even road cuts cause landslide as upper portion of the mountain slides down automatically (ToI: July 22). The districts that most frequently experienced landslides and was affected during last five years are Shimla, Kangra, Kinnaur, Mandi and Kullu. So, rainfall, soft geology and human intervention all together contributes towards the landslides in Himachal states. Figure 8 below shows the landslide hazard zone and major roadways of Himachal Pradesh.

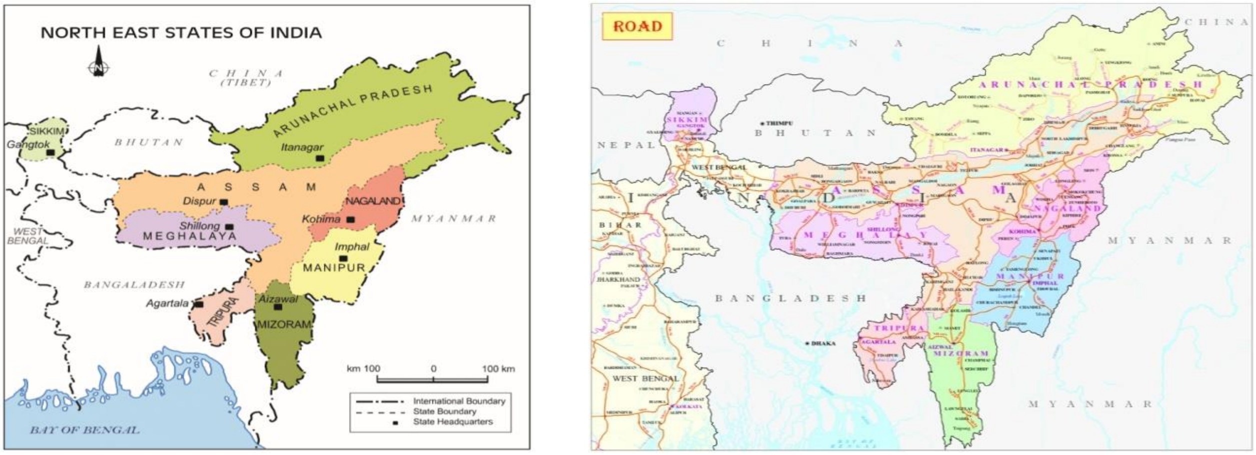


(a) (b)

Figure 8. Map showing landslide Hazard Zone and Major Roadways of Himachal Pradesh: (a) Landslide Hazard Map, and (b) Major Roadways under different Vulnerable Zone

3.4. Landslides along National Highway in North-Eastern States

Figure 9 shows the map of north eastern states and the roads along the National Highway (NH). The North-East Himalayas are characterized by weak geological formations, slope instability, and frequent seismic activity, making the region highly susceptible to natural hazards, particularly landslides and earthquakes. The area's vulnerability is partly due to natural causes, such as its fragile geology, and partly due to accelerated environmental degradation. In the north-eastern states of India, landslides are frequently triggered by heavy and prolonged rainfall. Additionally, human activities, including deforestation, construction, and unplanned development, have further exacerbated the occurrence of landslides in this region (Singh & Baruah, 2019; Sarkar et al., 2020; Das & Thapa, 2018).



(a) (b)

Figure 9. (a) Map showing North Eastern States; (b) Map showing North Eastern Region Road Map (only NH) (Source: https://mdoner.gov.in/infrastructure/road-map-only-nh-)

4. Protective Measures

The following protective measures can be implemented to stabilize slopes prone to landslides:

1. Excavated soil should be promptly removed from the site and not dumped along the slope, as this would increase the surcharge load on the slope and exacerbate instability.

2. Efforts should be made to preserve vegetation on the slope, particularly with deep-rooted trees, which help stabilize the area.

3. Jute geogrid can be utilized to support vegetation growth on slopes.

4. Crated masonry walls and R.C.C. cantilever retaining walls should be constructed at suitable locations, with ample weep holes to allow for drainage.

5. The area covered by the slide mass should be properly dressed and protected against water infiltration.

6. Open cracks in the slide zone should be sealed with cement mortar or other appropriate sealing materials to prevent further damage.

7. Side drains from new approach roads should be diverted away from the threatened area to reduce the risk of landslides (Kumar & Singh, 2020; Thakur & Verma, 2019; Gupta et al., 2018).

5. RS/GIS Strength in Addressing the Landslides Issue

In landslide studies, remote sensing (RS) and geographic information systems (GIS) are essential tools for identifying, tracking, mapping, and assessing the danger of landslides.

5.1. RS & GIS in Landslide Studies

Remote sensing techniques, including satellite and aerial imagery, have become essential tools in the study and management of landslides. These advanced technologies provide precise and reliable data, enhancing our understanding of landslide occurrences. By employing remote sensing, researchers can make significant advancements in the detection, monitoring, prediction, and management of landslides. Remote sensing data, when combined with deep learning techniques, plays a critical role in detecting landslides and contributes to the development of landslide susceptibility maps, which are crucial for effective disaster risk management. Furthermore, in the aftermath of landslides, remote sensing is vital for damage assessment and coordinating emergency response efforts (Singh & Gupta, 2020; Bhatia et al., 2019; Sharma & Verma, 2018).

Geographic Information System (GIS) is one of the most versatile tools for landslide modeling due to its capacity to process large volumes of data efficiently. GIS is widely used to analyze landslide-related variables, create landslide inventories, and generate susceptibility maps. Its ability to integrate various forms of spatial information—such as topography, soil type, land cover, and land use—facilitates comprehensive and detailed evaluations of landslide risk zonation in a given area. This integration allows for more efficient and in-depth landslide hazard zoning analyses (Kumar et al., 2021; Chauhan & Negi, 2020).

6. Innovations in Landslide Management

To mitigate the catastrophic impact of landslides, several key initiatives can be implemented:

1. Remote sensing (RS) data can be utilized to gather critical information and better understand the affected areas.

2. Landslide hazard analysis and mapping should be employed to address the issue, providing valuable insights for risk assessment and management.

3. In addition to these conventional approaches, the use of RS/GIS technologies can be further innovated, as suggested by the authors.

Landslide susceptibility mapping involves the incorporation of various input parameters, followed by specific processing steps and analytical techniques. Figure 10 shows a proposed flowchart for landslide susceptibility mapping using geospatial techniques models the process based on a bivariate frequency ratio, which enhances the accuracy of predictions and risk assessments (Sharma & Singh, 2020; Gupta et al., 2019; Thakur & Joshi, 2021).

7. Conclusion

In summary, it is evident that both natural and anthropogenic factors contribute to landslides along the National Highway, posing significant concerns as they disrupt the daily lives of local communities. The application of Remote Sensing (RS) and Geographic Information System (GIS) technologies can enhance the prediction and analysis of areas susceptible to landslides, allowing for timely interventions to mitigate impacts. The authors propose innovative strategies utilizing RS/GIS technology to effectively address landslide issues.

While it may not be possible to entirely prevent environmental catastrophes, we can take steps to prevent natural disasters from escalating into human-made crises due to ignorance and negligence. Landslides exemplify this risk, particularly as rainfall and weather patterns become increasingly erratic. Therefore, the need for proactive measures is more urgent than ever (Sharma & Gupta, 2021; Verma et al., 2020; Bhatia & Sethi, 2019).

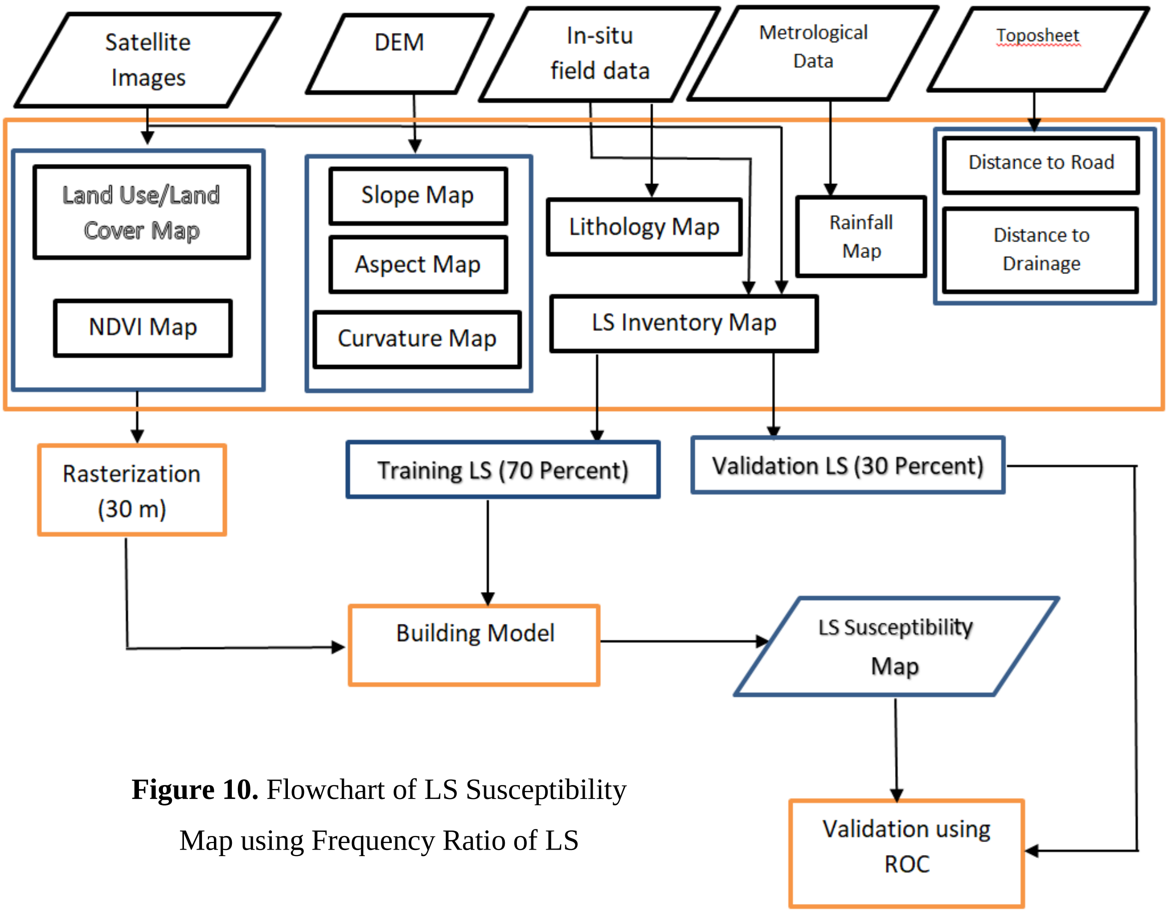


Figure 10. Flowchart of LS Susceptibility Map using Frequency Ratio of LS

8. Future Recommendations

Following points as listed below needs to be taken care of as part of future suggestion:

1. Use of RS/GIS based hazard analysis to identify high-risk zones in advance.
2. Integration of GIS for multi-parameter analysis (topography, soil, land cover, land use) to create hazard zonation maps.
3. Use of satellite/aerial imagery for landslide detection, monitoring, and damage assessment.
4. Incorporating hazard zonation maps in highway planning to minimize risks.
5. Establishing early warning systems using RS/GIS technology.
6. Training local communities in hazard preparedness and emergency response.

These suggestions combine technical measures (engineering & GIS/RS integration) with policy and community action, aiming to proactively reduce landslide risks along national highways.

Declarations

Source of Funding

This study received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

All the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Authors are willing to share data and material on request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

References

A landslide in Himachal Pradesh's Kinnaur blocks traffic on NH5 (2019). Retrieved from https://twitter.com/i/status/1143384794077782016.

ANI (2019). Landslides disrupt normal life in Govind Ghat, Uttarakhand. India Today. Retrieved from https://www.indiatoday.in.

Bhandari, R., & Bhatt, A. (2020). Impact of extreme rainfall events on landslides in Uttarakhand. Environmental Monitoring and Assessment, 192(3): 207–219.

Bhat, R., Singh, M., & Verma, A. (2018). The geological fragility of Uttarakhand: Understanding landslides and other geo-hazards. Journal of Mountain Science, 15(2): 103–114.

Bhatia, R., & Sethi, K. (2019). The impact of anthropogenic activities on landslide occurrence: A case study of Indian highways. Journal of Natural Hazards, 21(4): 321–335.

Bhatia, R., Singh, M., & Pandey, S. (2019). Remote sensing applications in landslide monitoring and disaster management. International Journal of Remote Sensing, 40(7): 2565–2580.

Bhattacharya, K., & Das, S. (2021). Remote sensing and GIS for landslide hazard assessment in the North-Eastern states of India. Geocarto International, 36(8): 952–965.

Chandel, V.B.S., & Brar, K.K. (2012). Himalayan Hazardscape: Risk & Vulnerability in Kullu District of Himachal Pradesh, India. The Deccan Geographer, 50(2): 1–15.

Chauhan, R., & Negi, S. (2018). Landslide susceptibility mapping in the Chamba district of Himachal Pradesh. Journal of Mountain Science, 15(1): 89–102.

Chauhan, R., & Negi, S. (2020). GIS-based landslide hazard zonation: A case study from the Indian Himalayas. Natural Hazards and Earth System Sciences, 10(1): 79–90.

Choudhary, R. (2019). National Highway 10 Blocked, Heavy Traffic Jam After Landslides In Sikkim. Retrieved from https://www.ndtv.com/india-news/national-highway-10-between-siliguri-west-bengal-gangtok-sikkim-blocked-after-multiple-landslides-2068002.

Das, A., & Thapa, P. (2018). The role of anthropogenic factors in landslides in North-East India. Environmental Monitoring and Assessment, 190(6): 351–365.

Das, A., Roy, S., & Thapa, P. (2019). Landslide susceptibility mapping in Arunachal Pradesh using GIS. Landslides, 16(3): 567–580.

Definition of Landslide (n.d.). Retrieved from https://www.merriam-webster.com/dictionary/landslide.

Eight Killed in Landslide in Uttarakhand (2019). Retrieved from https://www.newindianexpress.com/nation/2019/oct/20/eight-killed-in-landslide-in-uttarakhand-2050419.html.

Fresh Landslides shut Manali-Leh Highway (2019). Retrieved from http://newsonair.com/News?title=Himachal-Pradesh%3A-Fresh-landslides-block-Manali-Leh-Highway&id=370441.

Giri, P. (2019). Incessant rainfall triggers landslides in Darjeeling, Sikkim; Gangtok cut off from Siliguri. Retrieved from https://www.hindustantimes.com/india-news/incessant-rainfall-triggers-landslides-in-darjeeling-sikkim-gangtok-cut-off-from-siliguri/story-dsaf4kkmaobmkod36ocgqk.html.

Government of India (GOI) (2003). Landslide Hazard Zonation Atlas of India. New Delhi: Building Materials and Technology Promotion Council, Ministry of Urban Development and Poverty Alleviation.

Gupta, R., & Kumar, N. (2020). Impact of anthropogenic activities on landslides in the Himalayan region. Mountain Research and Development, 40(2): 135–145.

Gupta, R., Joshi, V., & Verma, S. (2018). The role of unplanned construction in triggering landslides along the Himalayan highways. International Journal of Geohazards and Environment, 6(2): 112–119.

Gupta, R., Sharma, P., & Singh, M. (2019). Remote sensing and GIS techniques for landslide hazard mapping in mountainous regions. Geospatial Information Journal, 14(2): 87–97.

Gupta, R., Sharma, P., & Thakur, N. (2018). Slope stabilization techniques for landslide-prone areas: Case studies from India. Geotechnical Engineering Journal, 45(2): 121–130.

Gupta, S., & Joshi, R. (2019). Landslide risk and management in the Himalayan region. Journal of Earth Science and Engineering, 8(3): 115–127.

Himachal Pradesh Vulnerability Atlas (n.d.). Retrieved from http://hp.gov.in/hpsdma/resourcelist/maps/vulnerabilityatlasstatehplow.pdf.

Hussain, S. (2019). Floods, landslides in northeast: More than a million displaced. Retrieved from https://www.theweek.in/news/india/2019/07/13/floods-landslides-in-northeast-more-than-a-million-displaced.html.

J & K highway closed due to landslide in Ramban, 3,000 vehicles stranded (2019). Retrieved from https://www.indiatoday.in/india/story/jammu-and-kashmir-highway-closed-due-to-landslide-in-ramban-3000-vehicles-stranded-1619344-2019-11-15.

Jammu-Srinagar Highway Again Blocked by Landslide, Clearance to Take 12 Hours (2019). Retrieved from https://www.news18.com/news/india/jammu-srinagar-highway-again-blocked-by-landslide-clearance-to-take-12-hrs-2381003.html.

Jammu-Srinagar Highway Closed After Landslide, 2,000 Vehicles Stranded (2019). Retrieved from https://www.ndtv.com/india-news/jammu-srinagar-national-highway-closed-after-landslide-2-000-vehicles-stranded-2153841.

Jammu-Srinagar National Highway cleared after remaining closed for over 42 hours (2019). Retrieved from https://www.ndtv.com/india-news/jammu-srinagar-national-highway-cleared-after-remaining-closed-for-over-42-hours-2153104.

Jammu-Srinagar National Highway Reopened Four Days After Landslides, Snowfall (2019). Retrieved from https://www.ndtv.com/india-news/jammu-srinagar-national-highway-reopened-four-days-after-landslides-snowfall-2149711.

Jha, P. (2019). Landslides block Badrinath National Highway, 40 other Rural Roads. Retrieved from https://timesofindia.indiatimes.com/city/dehradun/badrinath-highway-40-rural-roads-blocked-by-landslides-met-issues-yellow-alert/articleshow/71016248.cms.

Jha, S. (2019). Rains trigger Badrinath landslides, blocking highway. Hindustan Times. Retrieved from https://www.hindustantimes.com.

Joshi, R., & Kumar, A. (2020). Infrastructure development and its impact on mountain stability in Uttarakhand. Journal of Mountain Research, 12(3): 101–113.

Kaur, P., Singh, A., & Sharma, M. (2020). Remote sensing and GIS applications in landslide hazard zonation. International Journal of Disaster Risk Science, 11(2): 167–176.

Kohima town cut-off by road for major landslides on NH-29 (2019). Retrieved from http://www.uniindia.com/kohima-town-cut-off-by-road-for-major-landslides-on-nh-29/east/news/1689673.html.

Kumar, A., Sharma, P., & Verma, N. (2021). Role of GIS in landslide susceptibility mapping and risk management. Journal of Geospatial Science, 8(3): 98–108.

Kumar, P., & Singh, R. (2020). Human-induced factors in landslide occurrences along Indian highways. Geotechnical Engineering Journal, 45(3): 217–225.

Kumar, R. (2016). Landslide-prone areas in the North Himalayas. Journal of Himalayan Geology, 8(2): 34–42.

Kumar, Y. (2016). U'khand has Maximum Landslide Prone Areas among North Himalayan states, claim Min of Earth Sciences report. Retrieved from https://timesofindia.indiatimes.com/city/dehradun/Ukhand-has-maximum-landslide-prone-areas-among-north-Himalayan-states-claims-min-of-earth-sciences-report/articleshow/53512570.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst.

Landslide near Assam-Meghalaya border hits traffic on NH-44 (2018). Retrieved from https://www.business-standard.com/article/pti-stories/landslide-near-assam-meghalaya-border-hits-traffic-on-nh-44-118050600615_1.html.

Landslide occurs in Himachal Pradesh's Mandi (2019). Retrieved from https://timesofindia.indiatimes.com/videos/news/caught-on-cam-landslide-occurs-in-himachal-pradeshs-mandi/videoshow/70713476.cms.

Landslide on Imphal-Dimapur Road (2019). Retrieved from https://nagalandtoday.in/northeast/2019/10/landslide-on-imphal-dimapur-road/.

Landslide on Kalka-Shimla Highway in Himachal Pradesh (2019). Retrieved from https://www.youtube.com/watch?v=_ytixse0y_y.

Landslide triggered by incessant rain affects vehicular movements in Manipur (2019). Retrieved from https://nagalandtoday.in/northeast/2019/07/landslide-triggered-by-incessant-rain-affects-vehicular-movements-in-manipur/.

Landslides a cause of concern for HP (2013). Retrieved from https://reliefweb.int/report/india/landslides-cause-concern-hp.

Landslides Block Major Roads in Arunachal Pradesh (2019). Retrieved from https://www.sentinelassam.com/north-east-india-news/arunachal-news/landslides-block-major-roads-in-arunachal-pradesh/.

Landslides disrupt traffic on all major highways in Himachal Pradesh (2019). Retrieved from https://www.hindustantimes.com/india-news/over-800-roads-blocked-hundreds-stranded/story-zqj5eaynnnwxwwyjn5rlbl.html.

Landslide (n.d.). Retrieved from https://ndma.gov.in/Natural-Hazards/Landslide.

Landslides: Discovering Geology (n.d.). Retrieved from https://www.bgs.ac.uk.

Livehindustan (2019). Cloudburst and landslides cause deaths and damage in Uttarakhand. Live Hindustan. Retrieved from https://www.livehindustan.com.

Many People died in Cloudbursts and Landslide in Uttarakhand (2019). Retrieved from https://www.livehindustan.com/uttarakhand/story-many-people-died-in-cloudburst-and-landslide-in-uttarakhand-2695142.html.

Multiple Landslides disrupt Traffic on Jammu-Srinagar Highway (2019). Retrieved from outlookindia.com/newsscroll/multiple-landslides-disrupt-traffic-on-jammusrinagar-highway/1669468; https://timesofindia.indiatimes.com/india/multiple-landslides-disrupt-traffic-on-jammu-srinagar-highway/articleshow/72200430.cms.

Multiple Landslides disrupt Traffic on Jammu-Srinagar Highway (2019). Retrieved from outlookindia.com/newsscroll/multiple-landslides-disrupt-traffic-on-jammusrinagar-highway/1669468; https://timesofindia.indiatimes.com/india/multiple-landslides-disrupt-traffic-on-jammu-srinagar-highway/articleshow/72200430.cms.

Nagaland: Rains cause multiple landslides in Kohima (2019). Retrieved from https://morungexpress.com/nagaland-rains-cause-multiple-landslides-kohima.

NH-29 connecting Kohima with Dimapur cut-off due to major landslide (2019). Retrieved from https://thenortheasttoday.com/nh-29-connecting-kohima-with-dimapur-cut-off-due-to-major-landslide/.

Nongmaithem, H. (n.d.). Landslide disaster: Are Mitigation measures effective in context with North Eastern India. Retrieved from http://e-pao.net/epsubpageextractor.asp?src=education.science_and_technology.landslide_disaster_are_mitigation_measures_effective_by_herojit_nongmaithem.

Nongmaithem, T. (n.d.). Landslides in the North-East: Causes and impacts. E-Pao. Retrieved from https://epao.net.

Over 12% of Landmass in India prone to Landslides (2017). Retrieved from https://www.thehindubusinessline.com/news/national/over-12-of-landmass-in-india-prone-to-landslides/article9728811.ece.

Pandey, R., Sharma, D., & Tiwari, P. (2021). Use of remote sensing and GIS in understanding landslide dynamics in Uttarakhand. Journal of Mountain Science, 18(5): 1204–1215.

Pant, P., Rawat, B., & Singh, M. (2018). The role of dam construction in altering land use and triggering landslides in Uttarakhand. Environmental Geosciences, 25(4): 145–159.

Panwar, T.S. (2017). Unscientific Road Widening the Root Cause of landslides in Himachal. Retrieved from https://www.newsclick.in/unscientific-road-widening-root-cause-landslides-himachal.

Sarkar, S., & Kanungo, D.P. (2021). Roadside landslides in India: Risk management and mitigation strategies. Landslides, 18(2): 677–689. https://doi.org/10.1007/s10346-021-01612-y.

Sarkar, S., Bhattacharya, K., & Ray, R. (2020). Geological and anthropogenic influences on landslides in the North-East Himalayas. Natural Hazards, 102(3): 1201–1215.

Sharma, A., & Singh, K. (2020). Innovative use of remote sensing and GIS for landslide susceptibility mapping. Journal of Environmental Hazards, 25(3): 145–157.

Sharma, M., & Thakur, N. (2019). The impact of road construction on landslide frequency in the Himalayan region. Environmental Monitoring and Assessment, 191(5): 305–318.

Sharma, M., & Verma, S. (2018). Use of GIS and remote sensing for landslide risk assessment in mountainous regions. Disaster Risk Reduction Journal, 35: 145–159.

Sharma, M., Joshi, P., & Verma, R. (2020). Geospatial analysis of landslide-prone areas in Himachal Pradesh using remote sensing. International Journal of Disaster Risk Reduction, 42: 101292.

Sharma, N., Verma, P., & Bhatt, S. (2021). Integration of remote sensing and GIS for landslide susceptibility mapping in Uttarakhand. Natural Hazards, 106(4): 2731–2746.

Sharma, N. (2017). Frequent landslides in Uttarakhand worry scientists. Retrieved from https://www.hindustantimes.com/dehradun/frequent-landslides-in-uttarakhand-worry-scientists/story-nv9lgmesotk4e02f6dzjsm.html.

Sharma, P., & Gupta, R. (2021). The role of remote sensing and GIS in landslide risk management. Environmental Monitoring and Assessment, 193(2): 101–115.

Sharma, P., & Singh, L. (2019). Anthropogenic activities and landslide occurrences along the National Highways in Uttarakhand. Natural Hazards Review, 20(2): 04019003.

Sharma, P., & Singh, L. (2020). Climate change and landslide hazards in the eastern Himalayas. International Journal of Disaster Risk Reduction, 46: 101512.

Sharma, P., Joshi, V., & Gupta, N. (2020). Climatic events and landslide occurrences in Uttarakhand: The role of extreme rainfall. Natural Hazards and Earth System Sciences, 20(4): 1179–1190.

Sharma, P., Joshi, V., & Thakur, N. (2019). Influence of human activities on landslide susceptibility in the Himalayas. Natural Hazards, 95(4): 1093–1105.

Sikkim remains cut-off for 2nd day as multiple landslides block NH-31 (2019). Retrieved from https://www.indiatoday.in/india/story/sikkim-cut-off-2nd-day-landslides-block-nh31-1567945-2019-07-12.

Singh, M., Kumar, V., & Joshi, D. (2018). Landslides in the Kedarnath region: Causes and mitigation strategies. Natural Hazards and Earth System Sciences, 18(8): 2379–2392.

Singh, N., & Thakur, N. (2019). Landslide risk and mitigation strategies along National Highways in Himachal Pradesh. Natural Hazards Review, 20(3): 04019006.

Singh, R., & Baruah, P. (2019). Landslides in the North-East Himalayas: Causes and consequences. Journal of Himalayan Studies, 11(2): 97–108.

Singh, R., & Gupta, P. (2020). Integration of remote sensing and deep learning in landslide detection and management. Geoinformatics Journal, 12(4): 221–233.

Singh, R., & Pandey, S. (2019). The 2013 Kedarnath disaster: A case study of the Himalayan Tsunami. International Journal of Disaster Risk Science, 10(2): 213–224.

Talwar, G. (2019). Eight People killed in Landslide in Uttarakhand's Rudraprayag.

Talwar, R. (2019). Landslide in Rudraprayag kills eight. The New Indian Express. Retrieved from https://www.newindianexpress.com.

Thakur, M., & Verma, S. (2019). Vegetation and engineering solutions for slope stabilization. Journal of Mountain Environment, 9(3): 210–221.

Thakur, N., & Joshi, P. (2021). Landslide susceptibility analysis using bivariate frequency ratio model: A case study from the Himalayas. International Journal of Geoscience Applications, 19(1): 41–52.

Uttarakhand: Landslide disrupts normal life severely (2019). Retrieved from https://www.aninews.in/news/national/general-news/uttarakhand-landslide-disrupts-normal-life-severely20190907190801/.

Uttarakhand: Traffic Jam due to Landslides on Pithoragarh-Tanakpur NH 125 (2019). Retrieved from https://www.aninews.in/news/national/general-news/uttarakhand-traffic-jam-due-to-landslides-on-pithoragarh-tanakpur-nh-12520190705161720/.

Vaid, R., Chattoraj, S., Mishra, S., Kumar, P., & Ray, C. (2019). Landslide hazard zonation mapping and debris flow modelling in Nainital, Uttarakhand. Retrieved from https://www.researchgate.net/.

Varnes, D.J. (1984). Landslide Hazard Zonation: A Review of Principles and Practice. Paris: UNESCO.

Verma, S., Kumar, A., & Thakur, M. (2020). Innovative applications of remote sensing in landslide susceptibility analysis. Journal of Environmental Management, 264: 110427.