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Climate change induced disasters and highly vulnerable infrastructure in Uttarakhand, India: current status and way forward towards resilience and long-term sustainability

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ABSTRACT

The mountain state of Uttarakhand constitutes a part of the North-western Indian Himalayan region and is inherently vulnerable to natural disasters. It is witnessing faster melting of glaciers and increased occurrences of disasters like cloudbursts, flash floods, landslides, landslide/glacial lake outburst floods, rock–ice avalanches, and debris flows. This study provides a comprehensive assessment of the influence of changing climate on the occurrence of natural hazards. It assesses the status of two major rapidly developing infrastructures in the state (viz., hydropower plants and transportation network) under climate variability. Detailed causative analysis of two major disaster events (in Kedarnath and Chamoli in 2013 and 2021, respectively) and associated destruction is presented to understand the vulnerability of infrastructure and communities to hazards. Based on the challenges identified, a unique two-fold framework is proposed, and recommendations are articulated for building resilient and sustainable mountain infrastructures and communities in the region.

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Climate change; Indian Himalayas; natural hazards; resilience; sustainable mountain infrastructure

1. Background

The mountains and their ecosystems are global assets. The physical dynamics of the mountain ecosystem are highly responsive as compared to the flat terrains, which makes them highly sensitive to environmental changes (Beniston & Stoffel, 2014; Schlögel, Kofler, Gariano, et al., 2020). While their complexity, sensitivities, and significance have been extensively discussed in scholarly discourse, decision-makers tasked with guiding policy choices have not always been adequately informed by this information. Globally, 22% of the land surface area comprises mountains, and 13% of the global population lives here (Sharma, Molden, Rahman, et al., 2019). Mountains play a vital role in contributing to freshwater availability, food, timber and minerals, and energy generation. These bio-diversified regions often represent transboundary settings with cascading environmental systems (Gardner, 2015).

The Indian Himalayan Region (IHR) constitutes a significant landmass of the larger Hindu Kush Himalayas (HKH). Uttarakhand, the Himalayan mountain state of India, is characterized by fragile geology and lithology and complex and steep topography. The climate variability and change in the state, with particular effects on the cryosphere (Hock, et al., 2019) and highly active seismicity interplay, are leading to increased

exposure, vulnerability, and risk of the resident population and infrastructure to natural hazards and disasters. The high mountainous areas in the state are vulnerable to erosion and landslides, extreme rainfall or cloud burst-induced flash floods, hail storms, landslide/glacial lake outburst floods, rock–ice avalanches, mudflows, and debris floods (Aggarwal, Garg, Thakur, et al., 2019; Aher, Adinarayana, & Gorantiwar, 2014; Das, Ashrit, & Moncrieff, 2006; Kanungo & Sharma, 2014; Kumar et al., 2016; Maikhuri, Nautiyal, Jha, et al., 2017; Mathew, Babu, Kundu, et al., 2014; Norris, Carvalho, Jones, et al., 2017; Prasad & Pani, 2017; Vaidya, Shrestha, Nasabet al., 2019). The area is also undergoing rapid change due to various human-induced factors like economic expansion, globalization, infrastructural improvement, shifting land use patterns, migration, and urbanization (Wang, Wu, Kunze, et al., 2019). Thus, to combat the challenges mentioned above, intense efforts are required to preserve the high-mountain Himalayan ecosystem.

Uttarakhand state has abundant water resources in the form of Himalayan glaciers and two of the major river systems Ganga and Yamuna, originating and flowing through the region. These two river systems, majorly fed by glaciers, have a dense network of tributaries representing enormous hydropower potential. There has been

tremendous development to tap the hydropower potential in terms of the construction and operation of many hydropower projects in the region. The official website of Uttarakhand state hydropower organization (<https://ujvnl.com/hydro-power-projects-in-uttarakhand>) hosts the list of Hydro Power Projects in the state. Another major infrastructure type that has witnessed tremendous development recently is the state's transportation system (Dash & Punia, 2019). Rapid transportation infrastructure has been established by roads and bridges connecting remote villages in the mountains across all districts in Uttarakhand (Chopra, 2014).

The recently published IPCC- Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019) indicates that the cryosphere of High Mountain Asia (HMA) has undergone significant changes due to variations in precipitation volumes and intensities as well as an increase in surface temperature. These changes, which affect terrestrial and aquatic ecosystems as well as river runoff and geomorphology, significantly impact mountain social-ecological systems. The severity and frequency of natural hazards like landslides, avalanches, and flooding are expected to rise (Portner et al., 2022). Well-documented studies in the recent past confirm the occurrences of numerous extreme precipitation-based hazards ranging from flash floods, landslides, glacier lake outburst floods (GLOFs), landslide lake outburst floods (LLOFs), avalanches, and debris flows (Aher, Adinarayana, & Gorantiwar, 2014; Chawla, Osuri, Mujumdar, et al., 2018; Gariano & Guzzetti, 2016; Rajesh, Pattnaik, Rai, et al., 2016). Uttarakhand has been experiencing heavy precipitation or cloudburst-induced flash floods, especially in hilly districts (Singh & Pandey, 2021a). Additionally, coupled dangers and cascading hazards can become more probable. Therefore, the causes of natural disasters in Uttarakhand are not attributed to infrastructure development but are a combination of various factors, including climate change and human interventions like deforestation and land-use changes. It is important to mention that appropriate stability assessments are conducted before developing infrastructure in the region. However, even with these assessments, the construction of infrastructure can still have unintended consequences on the environment and, consequently, aggravate the severity and degree of damages caused during a natural disaster event (viz., landslides, flash floods, avalanches). Therefore, the significant evidence of changing climate in the region, an increase in the occurrences of natural disasters, along with human interventions pose serious challenges to the native communities in the region.

Therefore, exhaustive efforts are required to limit global warming in the region to less than 1.5°C by 2100 (Wester, Mishra, Mukherji, et al., 2019). But, the increased occurrences of disasters in the state have caused unimaginable destruction in terms of loss of life and infrastructural damage. Massive infrastructural damage has been inflicted on the state's hydropower infrastructure and transportation system. Thus, resilience is crucial as the region is highly vulnerable to geophysical and climate risks. There is an urgent demand for better risk governance in these areas, driven by these most recent increases in catastrophe susceptibility and risk due to intensifying stressors. There is an urgent need for innovative policy initiatives to strengthen the region's climate and infrastructure resilience. Therefore, it is necessary to examine various scenarios so that the scientific community, policymakers, local communities, and decision-makers come together and make the best governance decisions for long-term sustainability.

To build resilient infrastructures and communities, there is a need to pilot climate-related complexities and associated uncertainties in the ongoing and upcoming development. In Section 2, the paper presents a brief description of the study area with a particular emphasis on the topography and altitude-dependent climate setting. Section 3 assesses the influence of changing climate on the frequency and type of disasters as well as on the existing infrastructure. Section 4 presents the detailed status of the hydropower potential and vulnerable communities in Uttarakhand. Section 5 explores the way forward toward resilience and long-term sustainability of the infrastructure and mountain communities in the region. In this context, an approach is proposed to generate accurate and reliable flash flood susceptibility maps in the state using advanced machine learning-based algorithms. Additionally, the involvement of stakeholders and local communities is prospectively encouraging in creating a flash flood events inventory in the state. This solution addresses the '9th' and '11th' SDGs, which envisage building resilient infrastructure and making cities and human settlements inclusive, safe, resilient, and sustainable.

2. Study area

The study area focuses on Uttarakhand, which is a mountain state of India located in the northern portion of the Indian Himalayan Region (IHR). Uttarakhand sprawls over the southern slopes of the magnanimous Himalayas and has an area of 53,483 km², subdivided across 13 districts. It has a rich reserve of natural resources consisting of huge high-elevation glaciers which feed major rivers (Nandargi, Gaur, & Mulye, 2016) like Alaknanda, Bhagirathi, Ganga, Ramganga,

Kaliganga, and Yamuna. 45% of the total geographic area of the state is forested (ISFR, 2021), and the elevation in the region ranges from 185 to 7801 m. Figure 1 presents the location map of Uttarakhand, showing the elevation variation across the districts and the dense network of rivers. Most of the area is dominated by steep slopes with altitudes above 2000 m (Singh & Pandey, 2021a). The southwest monsoon is dominant in the region and is responsible for ~ 90% of the annual rainfall in just four months, i.e., June to September (Nandargi, Gaur, & Mulye, 2016).

Additionally, the state is one of India's most visited pilgrimage destinations. In the annually organized Char Dham Yatra, the devotees visit four highly regarded temples of Kedarnath, Badrinath, Gangotri, and Yamunotri. Also, Hemkund Sahib is another religious place where thousands of Sikhs and Hindus go for prayers and devotion every year. All the aforementioned holy temples and shrines are situated in very high-altitude locations. Apart from this, the state is known for its scenic beauty and picturesque destinations, which attract voluminous summer and winter tourists.

Furthermore, Uttarakhand is quite famous among the international scientific and disaster management communities, especially after two of the most dreadful natural disasters caused massive and widespread destruction. One is the Kedarnath disaster of 2013, and the other is the famous Chamoli disaster of 2021. The highly sensitive and undulated topography,

complex climate (Bharti, Singh, Ettema, et al., 2016), and climate change variations in the region instigate and accelerate soil erosion and debris removal when rivers and streams carry fast-moving water beyond their carrying capacities (Ghosh, Jakobsen, Joshi, et al., 2019), resulting in significant human and financial losses.

Figure 2(a) shows the coefficient of variation of annual rainfall across the state, with the coefficient of variation (CV) values ranging between 8% and 70%. Figures 2(b–e) depict the spatial distribution of the variability of seasonal rainfall across Uttarakhand during the pre-monsoon season (March to May), southwest monsoon season (June to September), post-monsoon season (October and November), and winter season (December to February), respectively. The pre-monsoon season shows CV values ranging from 40% to 200%, with the extreme south-eastern part and some portion in the western part of the state exhibiting the highest variability (between 130% and 200%). In comparison, the northern region and a smaller portion of the southwest region exhibit the least variability with CV less than 70%. During the southwest monsoon season, CV values range from 15% to 90%, with the highest variability observed in a small part of Udham Singh Nagar and Nainital districts (CV ranging between 60% and 80%), and the least variability observed (CV ranging from 10% to 30%) in a large portion of the northern region and some parts of the

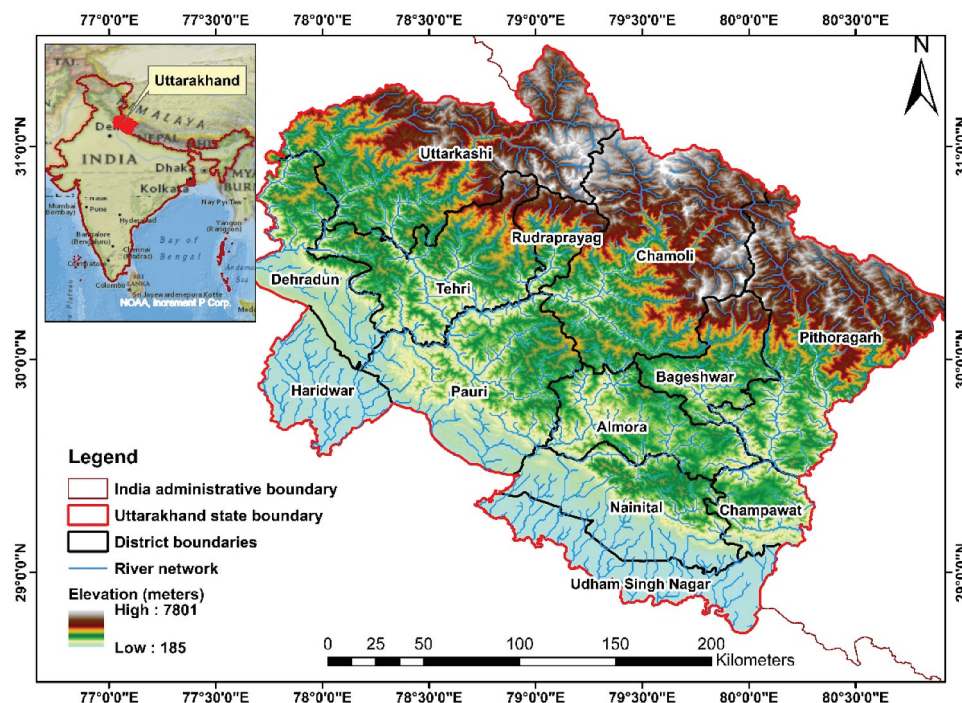


Figure 1. Location map of Uttarakhand showing the elevation variation across the districts.

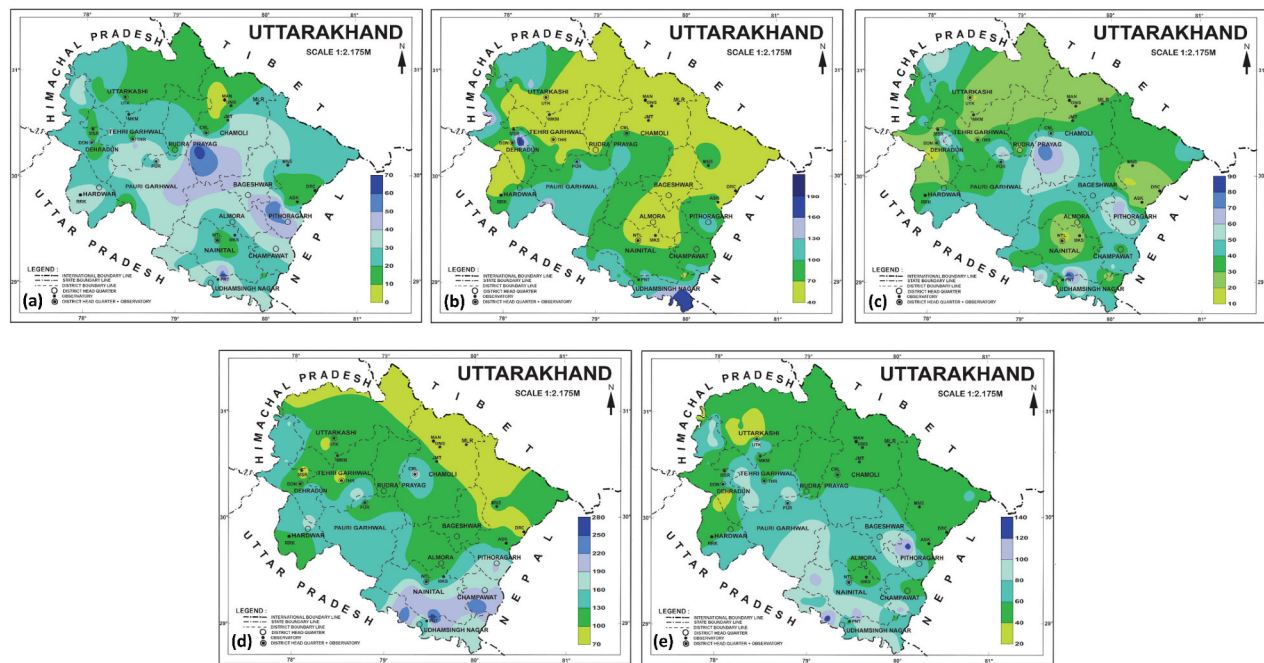


Figure 2. Spatial distribution of the variability of rainfall across Uttarakhand (a) annual; (b) pre-monsoon season; (c) southwest monsoon season; (d) post monsoon season; (e) winter season. [source: Climate of Uttarakhand Report (2014) issued by the office of the Additional Director General of Meteorology, IMD]

western, eastern, and southern regions. In the post-monsoon season, CV values range from 78% to 280%, with the highest variability observed in a small part of Udham Singh Nagar, Champawat, and Nainital districts and the least variability observed in the northeast region of the state and small pockets in Tehri Garhwal and Dehradun districts. During the winter season, CV values range from 20% to 140%, with the highest variability observed in a smaller portion of the southernmost Udham Singh Nagar and eastern Pithoragarh districts and the least variability observed in some part of Uttarkashi district in the northwest sector and small parts of the west sector.

The contribution of southwest monsoon rainfall to the annual rainfall is generally maximum over Uttarakhand because the variability of annual and southwest monsoon rainfall is relatively low compared to the other three seasons, where the rainfall variability is very high with CV values exceeding 100% in some parts of the state.

The map in Figure 3 shows areas in the state under each climate pattern. This broad classification is based on annual and monthly means of precipitation in cm and temperature in °C.

The map in Figure 4 is obtained from the WorldCover 2020 global land cover dataset (<https://esa-worldcover.org/>) generated by the European Space Agency at 10 m spatial resolution. This product is derived from Sentinel-1 and Sentinel-2 data and classifies the earth's surface features

into 11 land cover classes aligned with UN-FAO's Land Cover Classification System (Zanaga, Van De Kerchove, De Keersmaecker, et al., 2021).

3. Influence of changing climate on occurrences of disasters and infrastructure

Mountains uniquely play an essential role in the development of the regional climate. They obstruct the moving air masses, forming different climatic levels and landscapes with changes in the elevations and slopes (Figure 5a). The mountains are responsible for precipitation due to the orographic effect causing more precipitation on the windward side and warm/dry conditions on the leeward side (Figure 5b). Climate change has led to extreme consequences for the communities residing in the mountains (Kumar, Jain, & Singh, 2010; Dore, 2005). To understand this, mountain regions can be divided into four zones: valleys and mountain plains, foothills, high mountain zone, and glacier zone from lower elevation (bottom) to high elevation (top). Changing climate is accelerating the melting of glaciers in the topmost zone (Portner, Roberts, Adams, et al., 2022). The high mountain zone and the foothills are experiencing increased heavy precipitation events, snowfall, avalanches, landslides, GLOFs/LLOFs (Singh & Pandey, 2022), and the bottom-most zone of valleys and mountain plains are experiencing droughts (Pörtner, Roberts, Adams, et al., 2022).

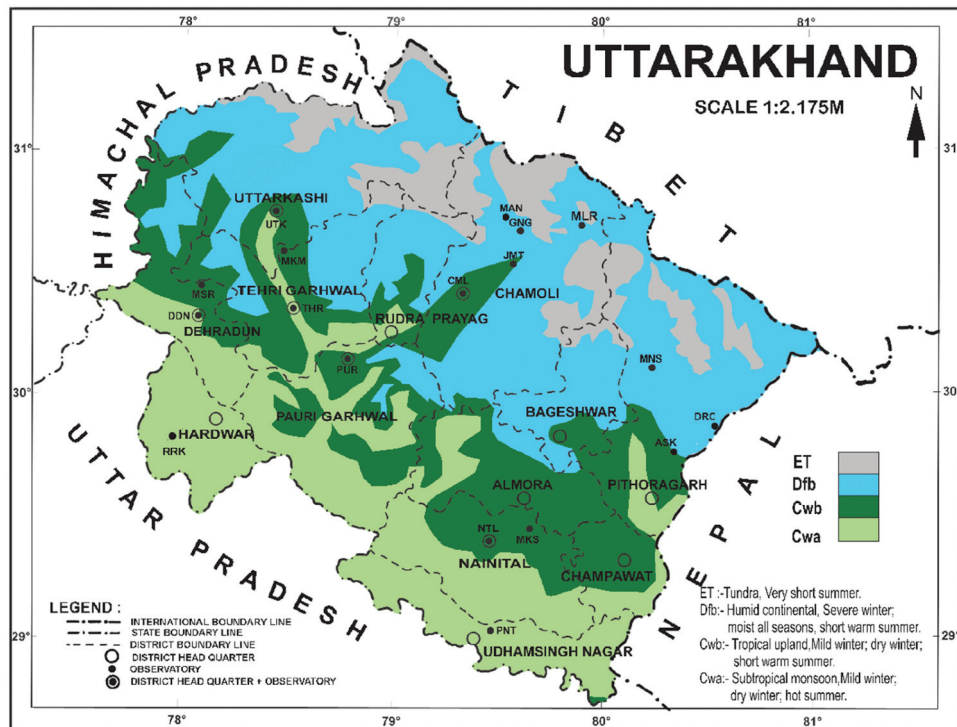


Figure 3. Koppen climatic classification of Uttarakhand (source: Climate of Uttarakhand report (2014) issued by the office of the Additional Director General of Meteorology, IMD).

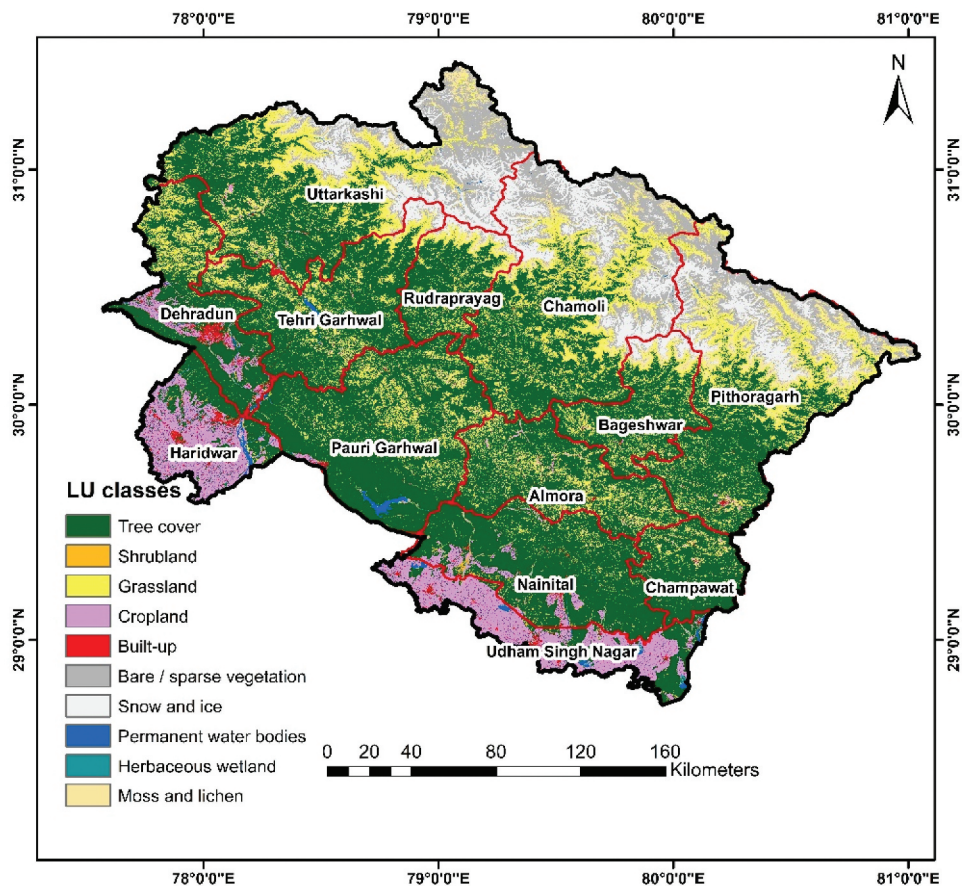
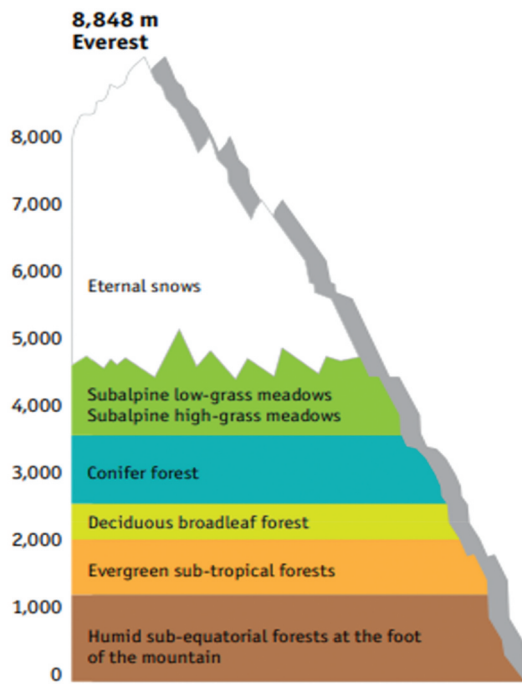
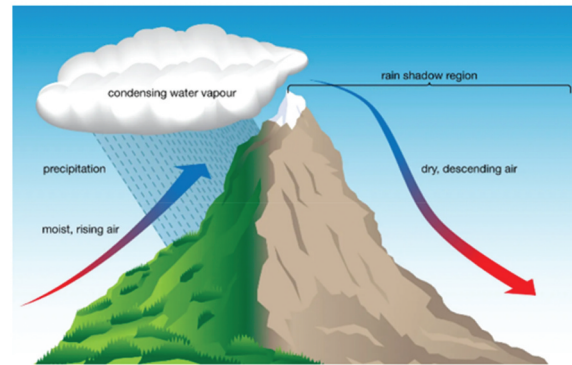


Figure 4. Land use map of Uttarakhand.



(a) Elevation zones in the Himalayas

Source: <https://climate-box.com/>

(b) Orographic precipitation

Source <https://www.britannica.com/science/>**Figure 5.** Elevation zones in the Himalayas and orographic precipitation.

Limited studies have been found focussing on the rainfall trend over the Himalayan Region (Vinodhkumar, Jose, Rao, et al., 2022) due to the poor network of rain gauges and radars. However, according to the statistics maintained by the International Disaster Database, in the past 3–4 decades, the western Himalayan region has experienced an apparent increase in extreme weather events (<http://www.emdat.be>). Extreme weather events refer to weather phenomena that are significantly outside the normal range of weather patterns or weather conditions typically experienced in a particular geographic region. These events are often characterized by their intensity, duration, and frequency and can lead to significant disruptions to human activities, infrastructure, and natural ecosystems. A complementing study (Sen Roy & Balling, 2004) reported that between 1910 and 2000, the rainfall intensity increased in Uttarakhand and surrounding states in the western Himalayan region. This pattern may be ascribed to the current acceleration of global warming (Wang, Liu, Kim, et al., 2012). Consequently, in the past few decades, there have been frequent rainfall-induced natural disasters (Chawla, Osuri, Mujumdar, et al., 2018; Gupta & Uniyal, 2012; Kirschbaum, Kapnick, Stanley, et al., 2020; Rajesh, Pattnaik, Rai, et al., 2016; Singh & Pandey, 2021a) in the region, leading to massive destruction of human

settlements, transportation systems disruptions, infrastructure damage, and loss of life. Also, a recent study (Vinodhkumar, Jose, Rao, et al., 2022) provides critical inputs to better comprehend the future climate extreme occurrences in Uttarakhand. The high-resolution ($0.25^\circ \times 0.25^\circ$) NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) data were analyzed for the climate change scenarios (RCP 4.5 & 8.5) in the near and future time frames, i.e., (2021–2050) & (2070–2099) respectively. According to the findings, both representative concentration pathway scenarios predicted an increase in the short and long terms. In the near future, the multi-model mean showed a rise of 13% and 16% in RCP 4.5 & 8.5 scenarios, respectively. In contrast, compared to the precipitation in the baseline period (1976–2005) from the multi-model mean, rainfall has significantly increased by 23% and 36% in RCP 4.5 & 8.5 scenarios for the far future. Additionally, the RCP 8.5 scenario shows more increase in the highest 1-day and 5-day precipitation than that shown for the RCP 4.5 scenario. This may be attributed to the reason for the extreme precipitation events that have been occurring in the Uttarakhand region. Similar patterns under global warming scenarios have indicated an increase in precipitation extremes in the future (Rao, Kulkarni, Patwardhan, et al., 2020; Kulkarni, Sabin, Chowdary, et al., 2020).

Tyagi, Jayal, Singh, et al. (2022) evaluated the observed and future climate change projections for Uttarakhand. The spatial resolution of the datasets (CORDEX-SA RCMs) utilized in this study was $0.5^\circ \times 0.5^\circ$. However, downscaling technique, i.e., the Delta method, was employed to enhance the quality of the datasets. As a result, the spatial resolution of the datasets was improved to $0.25^\circ \times 0.25^\circ$. The analysis revealed that the maximum temperature may rise from 0.42°C to 3.07°C under RCP 4.5 scenario and from 0.83°C to 5.49°C under RCP 8.5 scenario from mid-century (2021–2050) to end-century (2070–2099) respectively.

Additionally, the lowest temperature may rise from 0.80°C to 3.25°C under RCP 4.5 scenario and 0.30°C to 5.86°C under RCP 8.5 scenario from mid-century to end-century. While it is true that the changes in precipitation extremes observed in Uttarakhand may be similar to those observed in other regions, we believe that the uniqueness of the studies conducted by Vinodhkumar, Jose, Rao, et al. (2022) and Tyagi, Jayal, Singh, et al. (2022) lies in the specific focus on the Uttarakhand region. These studies provide valuable insights into the future changes in precipitation extremes that may be specific to this region, and such information is essential for decision-makers and policy-makers in the region to formulate effective strategies for adaptation and mitigation. Moreover, these studies report thorough analyses of the changes in precipitation extremes in Uttarakhand, including the trends and patterns, and these results are based on robust methodologies. Therefore, the results from the two studies mentioned above strongly suggest that climate change-driven future projections indicate rise in temperature and extreme rainfall in Uttarakhand. Consequently, this provides evidence of a probable increase in natural disasters and accelerated glacier retreats in the future.

More importantly, climate change is causing a severe impact on the water cycle, consequently making water availability less predictable, which contributes to increased atmospheric water vapor concentrations (Allan, Barlow, Byrne, et al., 2020). This justifies the occurrence of heavy rainstorms in certain areas, while other regions may experience more severe drought conditions, particularly during the summers.

3.1. Disasters

IPCC AR6 (WG-1) highlights that the globe has warmed 1.1 degrees more than during 1850–1900. Moreover, the 1.5 degrees mark is likely to be reached in another two decades, indicating a clear indication of longer warm seasons and more heat waves. Some severe warnings

have also been documented for the High Mountain Asia region with a high confidence level. In the twenty-first century, snow-covered areas and snow volumes will shrink, snowline heights will rise, and glacier mass will probably drop with more dramatic mass loss in scenarios with higher greenhouse gas emissions. Rising precipitation and temperature can increase the frequency of landslides over moraine-dammed lakes and glacial lake outburst floods. These warnings can be validated, especially in the Uttarakhand state, with the region experiencing increased circumstances of short duration very heavy precipitation events, flash floods, and landslides, especially in the last 20 years (Singh & Pandey, 2022).

Moreover, the state has experienced a considerable number of heavy precipitation or cloudburst-induced flash floods, especially in the last 2 decades. A list of some major events is compiled in Table 1.

The data in Table 1 is compiled from the following references (Aggarwal, Garg, Thakur, et al., 2019; Lindell, Arlikatti, & Huang, 2019; Kumar et al., 2015; Singh & Pandey, 2021a). Thus, it is evident that climate change is playing its role in causing natural disasters in Uttarakhand. Therefore, two major disaster events have been discussed hereafter to understand the large-scale impacts caused and their prospective association with changing climate.

In June 2013, extreme rainfall and the lake burst of the Chorabari glacial lake, which was blocked by a moraine, led to catastrophic flooding of the Mandakini River and its tributaries in the Uttarakhand Himalayas. Flash floods caused damage to several downstream towns, including Kedarnath, Rambara, and Gaurikund, located at 3546 m, 2740 m, and 1990 m above sea level (Bhambri, Mehta, Dobhal, et al., 2016). Numerous studies assessed and analyzed the Kedarnath disaster and its likely causes (Dobhal, Gupta, Manish, et al., 2013; Rautela, 2013), the rationale behind the very heavy extreme rainfall pattern and orography (Dubey,

Table 1. A few major flash flood events in past 20 years in Uttarakhand.

Cloudbursts-induced flash floods		Monsoon-related extreme rain events	
Place	Year	Place	Year
Ketgaon	2002	Chamoli	2004
Ranikhet	2004	Pithoragarh	2009
Bastari, Pithoragarh)	2007	Almora	2010
Kapkot, Bageshwar	2010	Uttarkashi	2012
Almora	2010		
Ukhimath, Rudraprayag	2012		
Kedarnath and multiple downstream towns	2013		
Kapkot, Bageshwar	2013		
Singhali, Pithoragarh	2016		
Bijrani, Almora	2017		

Shukla, Ningreihon, et al., 2013; IMD, 2013; Kotal, Roy, & Bhowmik, 2014), hydrological as well as hydrodynamic simulation of the event (Rao, Rao, Dadhwal, et al., 2014), and assessment of landslides triggered during the event (Martha, Roy, Govindharaj, et al., 2015). The Mandakini catchment area experienced extremely heavy and continuous precipitation between June 15 & 16, 2013 (Dobhal, Gupta, Manish, et al., 2013; Rautela, 2013). The key learning from these studies on the Kedarnath disaster is that it was caused by a combination of natural and anthropogenic factors specifically attributed to global warming, because of which glacial lakes are being formed in the Himalayas. The extreme rainfall and orography of the region, combined with anthropogenic activities such as deforestation, uncontrolled construction, and encroachment of riverbanks, led to disastrous consequences. The studies also highlighted the need for improved disaster management and mitigation strategies, including early warning systems, better land-use planning, construction guidelines, and a more comprehensive scientific understanding of such extreme events and their impacts. Additionally, the studies emphasized the importance of community participation and engagement in disaster management and preparedness efforts.

Consequently, the massive destruction witnessed in the Kedarnath valley on the 16th and 17th of June was attributed to two events (Bhambri, Mehta, Dobhal, et al., 2016; Petley, 2013). One was the flooded river Saraswati, that brought in excessive volumes of water and hit Kedarnath town. The other was a massive volume of water gushing down after the collapse of the moraine-dammed Chorabari lake (1 km upstream from the Kedarnath settlement), washing away everything in its way. The glacial lake had no outlet; excessive rainfall and snowmelt increased the lake's water level to about 15 to 19 meters. This excess volume of water exerted massive pressure on the natural moraine wall leading to the dam breach from the left embankment of the lake. This led to unimaginably high volumes of water overflowing through the Mandakini and Saraswati rivers and downstream, causing massive devastation. The rivers in the entire Kedarnath valley carried massive discharges well beyond the carrying capacities generating tremendous velocity and momentum, thereby destroying all the infrastructure and natural features in its path (Dowling & Santi, 2014; Hungr, Leroueil, & Picarelli, 2014). Additionally, the entire catchment area reported many landslides along the river banks.

In theory, it is highly challenging to attribute or link the occurrence of the Kedarnath disaster to alterations in

the climate system (Allen, Rastner, Arora, et al., 2016). However, the evidence of changing climate in the region in terms of increasing temperature, glacier ice loss (Kääb, Berthier, Nuth, et al., 2012), as well as a rise in the number of extreme precipitation events during the Indian Summer Monsoon enhanced the likelihood of the occurrence of Kedarnath disaster (Singh et al., 2014). In recent years, irregularities in the onset of monsoons have been observed. The potentially fatal combination of extremely heavy monsoon rains with spring snowmelt leading to very high flows in the river systems has been projected in the twenty-first century due to an earlier start to the South Asian monsoon and more severe related precipitation forecast (Christensen, Kanikicharla, Aldrian, et al., 2013).

The Himalayan catchments will become increasingly dependent on rainfall as the overall area covered by glaciers continues to shrink (Bolch, Kulkarni, Kääb, et al., 2012; Collins, Davenport, & Stoffel, 2013). This provides optimum conditions for the formation of new glacial lakes. Consequently, leftover sediment deposits will remain exposed, thereby increasing damage causing potential in the downstream areas during an extreme hydrometeorological event. As a result, the Kedarnath disaster might be a precursor to the kinds of repercussions that the Himalayan states can anticipate happening more frequently due to the changing climate.

The 7th February 2021, Chamoli disaster was a unique and first-of-its-kind cascade hazard in Uttarakhand (Shugar, Jacquemart, Shean, et al., 2021; Singh, Rawat, & Pandey, 2023). A huge rock-ice mass (~26.4 million m³) dislodged from the Raunthi peak and initiated a sequence of hazards leading to an unprecedented level of debris flow and destructive flash floods in the Raunthi Gadhera, Rishiganga, and Dhauliganga river valleys in the Chamoli district (Shugar, Jacquemart, Shean, et al., 2021; Singh, Rawat, & Pandey, 2023). Due to the fast-flowing nature of the moving rock-ice mass downhill from an altitude of 5474 m to 3732 m covering almost 2.9 km of descent (Martha, Roy, Jain, et al., 2021), massive momentum and velocity were attained. After touch down at the impact point in the Raunthi Gadhera, the debris moved downstream. It formed a lake due to the accumulation of excessive debris at the confluence of the channel with the Rishiganga river (Pandey, Chauhan, Bhatt, et al., 2021). The energy generated by this impact favored snow and ice melting, and the rock mass broke into multi-size boulders and debris (Meena, Bhuyan, Chauhan, et al., 2021; Shugar, Jacquemart, Shean, et al., 2021). The impact also created an air blast that followed the debris and uprooted trees in the downstream valleys (Meena, Bhuyan, Chauhan, et al., 2021).

This event, triggered by rock-ice mass failure, has been linked to changing climate as it plays a significant role in permafrost dynamics and slope stability (Pandey, Kumar, Singh, et al., 2022). The rock-ice mass detachment zone can be linked to long-term temperature instabilities and climate change, which might have significantly predisposed the permafrost layer and glacier ice (Mao et al., 2022). Moreover, the Uttarakhand region has experienced 14 major hydrometeorological disasters (Sati, 2022), rendering the communities and infrastructure more vulnerable. Therefore, the critical concern is landscape degradation in the region due to the extensive infrastructural development in the wake of global warming and the exploitation of natural resources.

3.2. Infrastructure

The mountain ecosystem's instability caused by climate change is increasingly threatening the mountain infrastructure, like dams, reservoirs, roads, bridges, and residential pockets. These instabilities directly designate the occurrences of glacier collapses (Kääb, Jacquemart, Gilbert, et al., 2021), rock-ice avalanches (Cook, Rekapalli, Dietze, et al., 2021; Sain, Kumar, Mehta, et al., 2021; Shugar, Jacquemart, Shean, et al., 2021), permafrost thaw, and related landslides (Gruber, Fleiner, Guegan, et al., 2017), debris flows (Ding, Mu, Wu, et al., 2021), extreme lake outburst floods (Nie, Pritchard, Liu, et al., 2021), higher erosion rates (Koppes & Montgomery, 2009), and cloudburst or heavy precipitation induced flash floods (Singh & Pandey, 2021a, 2022).

In February 2021, a rock-ice avalanche in the Chamoli district of Uttarakhand caused a debris flood that devastated two hydroelectric power projects (HPP), including an under-construction project. As a result, 204 people died or were missing, including 190 HPP employees/workers (Sain, Kumar, Mehta, et al., 2021; Shugar, Jacquemart, Shean, et al., 2021). Also, the extreme rainfall and snowmelt were the driving factors behind the June 2013 Kedarnath disaster, leading to a sequence of hazards that included a lake outburst, consequent flash floods, landslides, and debris flows. These devastating catastrophes culminated in the destruction of several HPPs (Li, Lu, Walling, et al., 2022). The associated human casualties highlight the rising dangers to hydropower infrastructure and community safety in the Himalayan mountain valleys of Uttarakhand (Allen, Rastner, Arora, et al., 2016; Bhambri, Mehta, Dobhal, et al., 2016; Schwanghart, Ryan, & Korup, 2018; Schwanghart, Worni, Huggel, et al., 2016).

The 2013 flash flooding in the Kedarnath valley engulfed the entire Kedarnath settlement, causing

partial damage to the Kedarnath temple (Bhambri, Mehta, Dobhal, et al., 2016). Several villages and townships viz. Rambada, Gorikund, Sonprayag, Kund, Chandrapur, Bhiri, Agastyamuni (Vijaynagar), Silli, and Tilwada downstream were washed away (Sati & Gahalaut, 2013). The fury of these floods caused widespread damage to the settlements further downstream in the major towns situated at the confluence points of all major tributaries of the river Ganga. Sati & Gahalaut, (2013) carried out a damage assessment in the affected region, indicating that the under-construction hydropower projects aggravated and magnified the degree of devastation in the lower reaches of the valleys. The mismanaged disposal of muck produced by these hydro projects contributed to amplifying the destructive potential of the flooding considerably.

Tentatively, the 330 MW Srinagar hydropower project generated 800,000 cubic meters of debris and muck (Sati & Gahalaut, 2013). Approximately 60% of this volume of muck was deposited along the channel during this event, causing widespread devastation to the residential infrastructure in Srinagar town. About 70 hydropower schemes were sanctioned on different rivers in the state. Besides, the construction of hydropower infrastructure involves heavy explosives making the mountain rocks fragile and susceptible to landslides. A study on mapping landslides in Uttarakhand triggered by the June 2013 extreme rainfall event (Martha, Roy, Govindharaj, et al., 2015) employed high-resolution satellite data and identified 6013 landslides (Martha, Roy, Govindharaj, et al., 2015). 3472 of these landslides were classified as those initiated due to the extreme rainfall during the disaster. According to the India Disaster Report 2013, compiled by Singh, Horton, Tsiang, et al. (2014) and published by the National Institute of Disaster Management, a total of 169 people died, and over 4021 people were reported missing (presumed to be dead). Also, a total of 4200 villages were affected, 11091 livestock were lost, and 2513 houses were fully damaged. Additionally, the transportation network in the region was severely interrupted as multiple bridges were washed off, and many road sections experienced heavy damage rendering them unserviceable. This left around 100,000 pilgrims and tourists stranded in the valleys during the disaster, which the Indian Defence Forces later rescued with the help of other civic authorities (Martha, Roy, Govindharaj, et al., 2015).

The 2021 disaster event created an air blast starting at the impact point, which followed the debris and uprooted trees in the downstream valleys. This event damaged the 13 MW Rishiganga hydropower station

(near Raini village), a road bridge (near Raini village), 520 MW NTPC Tapovan HPP, and two other suspension bridges (Nainwal, Shankar, Mishra, et al., 2022). There had been a significant life loss of the construction workers at the hydroelectric project site in Tapovan. Sedimentation severely damaged this under-construction HPP (Nainwal, Shankar, Mishra, et al., 2022).

Another major infrastructure in the mountain state which faces the brunt of changing climate and associated extreme events is the transportation network, i.e., roads. Slope stability has been a prime concern associated with the roads in the high-elevation mountainous terrain of Uttarakhand (Komadja, Pradhan, Oluwasegun, et al., 2021). The Himalayan region has witnessed significant temperature changes since the 20th century (Bajracharya, Mool, & Shrestha, 2008). Increased occurrences of forest fires in recent years have been yet another significant climate change-induced natural hazard in Uttarakhand. The incidents are responsible for weakening the soil cohesiveness (due to heat-induced dryness) and, in turn, contribute towards increasing incidences of cloud bursts (soot acting as cloud condensation nuclides) (Sharma, Sati, Sundriyal, et al., 2021), and others cascade into landslides and flash floods. A huge road widening project in Uttarakhand called the Char Dham Project (CDP) is under the aegis of the Government of India. Approximately 825 km of roads are being widened in the hilly districts of the state. Interestingly no environmental clearance was required before the start of this project despite the area being geologically fragile and ecologically sensitive (Sharma, Sati, Sundriyal, et al., 2021). As per the official mandate, Environment Impact Assessment (EIA) is carried out for road development projects of 100 km or more. The CDP was fragmented into 53 segments, each having a length of less than 100 km, for which EIA was

not mandatory (Sharma, Sati, Sundriyal, et al., 2021). Therefore, the project is quite delicate regarding disaster resilience and environmental degradation. Without addressing the ecological and environmental stability of the geologically/geomorphologically fragile slopes riddled with chronic landslides, achieving the desired objective of providing sustainable disaster-resilient roads would be difficult. The entire state falls under seismic zone IV and V and experiences numerous earthquakes of varying magnitudes (Joshi, Ghildiyal, & Rautela, 2019). This renders the region highly vulnerable to slope instability and landslides. Every year several incidents of landslides and consequential disruption of road infrastructure are experienced in almost all of the hilly districts in the state.

4. Hydropower potential and vulnerable communities

Uttarakhand state has a hydropower potential of approximately 20,000 MW (AHEC, 2011). Table 2 shows the district-wise estimated hydropower potential and the total number of operational and under-development projects (HPP) in the state.

The information is compiled using the data available on Uttarakhand Jal Vidyut Nigam Limited-UJVNL (<https://ujvnl.com/hydro-power-projects-in-uttarakhand>). This is a solely owned Corporation of the Government of Uttarakhand responsible for the operation and maintenance of hydropower projects. In summary, per the data shared by the state government in the public domain, 37 operational HPPs are generating 3971 MW of power. Additionally, there are a total of 87 HPPs in the development stage (the projects are being carried out by UJVNL, Central Public CPSU, accounting for 9885.6 MW of hydropower potential.

Table 2. District-wise hydropower potential (in Mega Watts) in Uttarakhand.

District	Number of Projects				Estimated Hydropower Potential (MW)			
	Operational	In development stage			Operational	In development stage		
		UJVNL	CPSU	IPP		UJVNL	CPSU	IPP
Almora								
Bageshwar	3			3	30.3			34
Chamoli	7	6	7	7	447	788.8	1610	414.3
Champawat	1				120			
Dehradun	6	2			477.75	420		
Haridwar	2				29.7			
Nainital								
Pauri	4	1	2		673.5	1.5	850	
Pithoragarh	3	7	7	5	290	382	1845	392.3
Rudraprayag		3		3		23.5		251
Tehri	4	3	2	4	1425.5	72	1195	27.5
Udham Singh Nagar	1				41.4			
Uttarkashi	6	10	4	11	435.85	1036	301	241.7
Total	37	32	22	33	3971	2723.8	5801	1360.8

UJVNL-Uttarakhand Jal Vidyut Nigam Limited; CPSU-Central Public Sector Undertakings.
IPP-Independent Power Producer.

Therefore, the state is currently in the process of generating 13,856.6 MW of hydropower.

As per the national census of 2011, which is conducted every ten years across the country for demographic assessment, 10,086,292 people reside in Uttarakhand, of which 5,137,773 and 4,948,519 are males and females, respectively [The census of 2021 was postponed owing to the COVID-19 pandemic and has not been conducted yet]. The total population growth from 2001 to 2011 was 18.81%. Most mountain people depend on land and forests for their livelihood, agriculture being the primary occupation in the hilly landscapes. On the one hand, these mountain communities face the wrath of increasing disasters and are forced to adapt to government rules, procedures, and market forces. Both these scenarios create a severe impact on the resilience of the local landscapes of the mountain state. The evident examples of these scenarios have been discussed in detail, viz., the government's increased efforts to develop hydropower and transportation infrastructure. A small sector of individuals comprising environmental activists and conservationists always oppose these developments in the mountain state. The sole reason is the unsustainable repercussions experienced in terms of deadly devastation due to increasing regional disasters.

5. Towards resilience and long-term sustainability

5.1. Global awareness and efforts for resilience and sustainability

The influence of changing climate on occurrences of disasters and its destructive impacts on mountain infrastructure (particularly the rapid development of hydropower projects and road networks) has accelerated global awareness of mountains, mountain ecosystems, and mountain communities. Impactful international scientific meetings, committees, forums, and interactions like the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, the Sendai Framework for Disaster Risk Reduction 2015, the Paris Agreement 2015 of the United Nations Framework Convention on Climate Change, the Sustainable Development Goals (SDGs) and Targets 2030 are making efforts to make things better in terms of resilience and long-term sustainability for the Himalayan region.

The UNDRR has been doing exceptional work to create global awareness of the concepts and significance of vulnerability, resilience, and disaster risk reduction. It defines resilience as: 'The ability of a system, community or society exposed to hazards to resist, absorb,

accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management (UNDRR, 2020).

5.2. Gap analysis: spatial prediction of flash floods in Uttarakhand

Based on a detailed analysis of the current status of disasters and vulnerable infrastructure and communities in the Himalayan state of Uttarakhand, this review paper has highlighted a significant gap that hinders the pathway to resilience. Currently, there is a lack of accurate spatial prediction of flash floods (the most frequently occurring natural disaster in the state), which is crucial for identifying areas probable to be affected due to extreme events like continuous high-intensity rainfall or cloud bursts.

Flash floods in the mountains can destroy every infrastructure in the region, viz. built-up infrastructure like residential buildings, schools, colleges, hotels, restaurants, roads, bridges, electricity infrastructure, and water supply infrastructure. Moreover, monsoon-dominated weather-based events like cloud bursts and extreme rainfall, which depend on the topography and atmospheric conditions, are highly dynamic (in terms of place and time of occurrence). As of date, only one study has been carried out addressing this problem in the region (Singh & Pandey, 2022), which employed hybrid ensemble models based on bivariate statistics due to a scarcity of data points. Flash flood susceptibility (FFS) assessment is the most effective evaluation mode for developing preventive measures to minimize the effects of such disasters. FFS concept works on the principle of the likelihood of flash flood occurrence in an area considering the influence of local terrain and geographical and hydrometeorological factors (Singh & Pandey, 2022). Literature suggests that FFS studies in India (Chakraborty, Chandra Pal, Rezaie, et al., 2022; Chowdhuri, Pal, & Chakraborty, 2020) have largely excluded the Himalayan region of Uttarakhand.

Consequently, there is no input from the decision-makers and stakeholders regarding which areas are most susceptible to flash floods. This inadequacy leads to significant casualties and infrastructural damage in this region during extreme events. Machine learning techniques have proved to be very effective in (Khosravi, Shahabi, Pham, et al., 2019; Janizadeh, Avand, Jaafari, et al., 2019; Band, Janizadeh, Chandra Pal, et al., 2020; Costache, Pham, Sharifi, et al., 2020a, 2020b) identifying the most susceptible flash flood-prone areas. A significant challenge in the study area is that no flash flood

inventory database is available in the public domain as of date (Singh & Pandey, 2021a, 2022).

5.3. Addressing the gap: Towards accurate flash flood susceptibility mapping

Flash flood susceptibility maps can be a valuable resource for planners and stakeholders by providing the spatial extent of critical areas (Singh & Pandey, 2022). It can be an essential resource to ensure multi-infrastructure resilience in the region. Therefore, this section presents a way forward toward resilience and long-term sustainability. An approach is proposed to generate accurate and reliable flash flood susceptibility maps in the state using state-of-the-art advanced machine learning-based algorithms. Preparing a database of historical flash flood locations and making efforts to record the locations of current and future flash flood disasters can serve a great deal in predicting future flash flood locations by susceptibility modeling.

Keeping the aforementioned gap in context, a two-fold solution is proposed which can be applied as a framework (Figure 6) addressing the '11th' SDG, which envisages making cities and human settlements inclusive, safe, resilient, and sustainable. It also aims to contribute towards disaster risk reduction aiming at 'target 13.1' of SDGs to strengthen resilience and adaptive capacity to climate-related hazards. Based on a recent study conducted by (Singh & Pandey, 2022) on hybrid ensemble modeling for flash flood potential assessment and susceptibility analysis in the Mandakini River Basin of Uttarakhand and an extensive literature survey, the

proposed solution (practically feasible) has been illustrated below:

- A mobile-based application: This application aspires creation of a flash flood inventory. This can prove to be an advantageous asset for ensuring Disaster Resilient Infrastructure in the region. Since no such platform exists in Uttarakhand that maintains a dedicated database for flash floods, this application can play a pivotal role in encouraging further research work based on the collected database (Singh & Pandey, 2021a, 2022). More importantly, the application demands the involvement of the residents (stakeholders). Therefore, as flash floods are frequent in the region, local people are expected to get involved actively.
- Flash flood susceptibility maps for vulnerable river basins of the state: These maps aim to categorize the entire area into five susceptibility zones: very high, high, medium, low, and very low. Machine Learning algorithms (viz. Artificial Neural Networks (ANN), Logistic Regression, Support Vector Machines (SVM), eXtreme Gradient Boosting (XGBoost), K Nearest Neighbour (KNN), Naïve Bayes (NB), Random Forest (RF), and many more) being one of the most sought after and data-intensive modern-day technologies can be employed to identify the most accurate flash flood susceptibility model for each river basin (Chakraborty, Chandra Pal, Rezaie, et al., 2022; Khosravi, Pham, Chapi, et al., 2018; Nandi, Mandal, Wilson, et al., 2016; Tehrany, Pradhan, Mansor, et al., 2015). These algorithms follow a

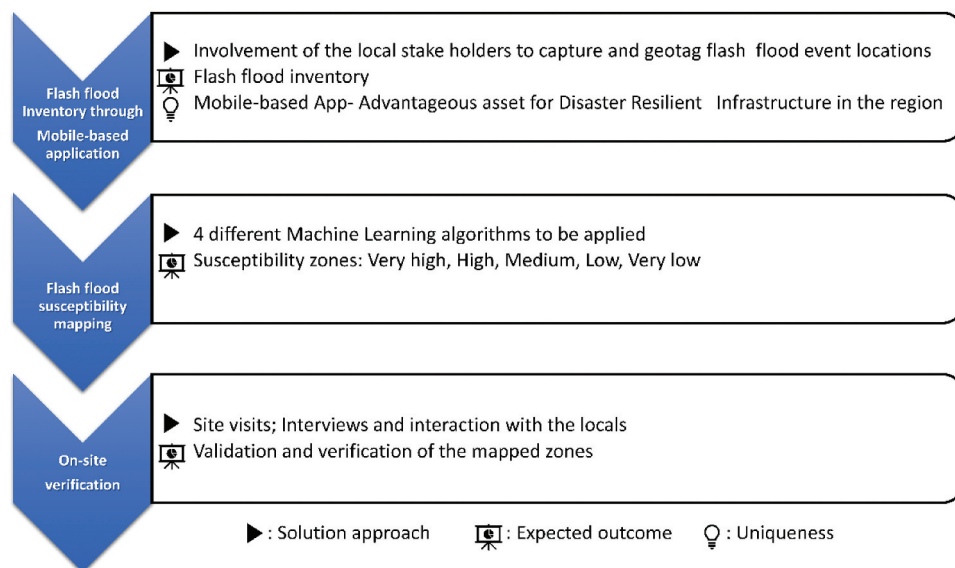


Figure 6. Proposed solution.

typical workflow using a set of flash flood event locations for model training and thereafter testing it on the remaining set of locations. Finally, a comparison is made to evaluate the effectiveness of the chosen model. The generated map must be verified through site visits and local interviews.

Most importantly, the above-presented solutions aim to reduce disaster mortality and the number of affected people. Additionally, the proposed solutions may significantly reduce natural disaster economic loss by reducing damage to critical infrastructure and disrupting essential services.

The detailed methodology (Figure 7) involves the following tasks:

- Literature review for preparing historical flash flood event locations database.
- Development of a mobile application for preparing flash flood inventory for the current year and onwards.
- Site visits and awareness programs among the local community for using the developed application.
- Partitioning the inventory points into two parts for training and validation: The cross-validation technique can be used for the split, which involves dividing a dataset into n subsets, or folds, and then repeatedly combining the folds in different ways to create training and testing sets. Each cross-validation iteration involves using one-fold as the test set and the remaining $n-1$ folds as the training set. This process is repeated for each of the n folds so that each fold is used as the test set once, while the rest of the folds are used as the training set. In practice, tenfold cross-validation has been used in flash flood susceptibility studies (Costache, Pham, Sharifi, et al., 2020a), where the dataset is divided into ten subsets. Although cross-validation is useful for evaluating model performance, it is computationally more expensive than simply dividing the data into training and test sets (Liu & Cocea, 2017).

Alternatively, the splitting can also be done several times (for example, 100 times) to obtain many results which are not influenced by the first partition. Then, the subsequent analyses (i.e., application of ML techniques) should be repeated for each partition to get a wide range of results, among which the best and average results can be selected. To achieve this, the optimum, average, and minimum values for each variable obtained in the output will have to be calculated. Standard deviations and other relevant statistics will also be calculated to provide a more comprehensive analysis of the

models' performance. This approach ensures that the model performance is not influenced by random training and testing set selection.

Performing the random partitioning multiple times and averaging the results will provide a more robust analysis, reducing the impact of any particular data partition on the overall analysis. This approach will also allow the quantification of the variability in the models' performance and provide more confidence in the obtained results.

- Data acquisition: high-resolution digital elevation model (DEM)
- Preparation of flash flood conditioning factor layers (Band, Janizadeh, Chandra Pal, et al., 2020; Janizadeh, Avand, Jaafari, et al., 2019; Pham, Phong, Nguyen, et al., 2020; Singh & Pandey, 2022).
- Predictive ability analysis of flash flood conditioning factors and their selection (Singh & Pandey, 2022).
- Application of ML techniques for estimating flash flood potential index (FFPI)
- Mitigating false alarms is critical for developing accurate and effective machine-learning models for flash flood susceptibility assessment. It can be achieved through various approaches:

Feature selection: Selecting relevant input features is critical in reducing false alarms. By using only the most important features, machine learning models can be trained to focus on the critical factors that contribute to flash floods. This can help to eliminate extraneous noise and reduce the likelihood of false alarms. In the proposed methodology, the estimation of variance inflation factor (VIF) and tolerance (TOL) has been included to select the most relevant factors for the susceptibility assessment (Singh & Pandey, 2022).

Ensemble modeling: It involves combining multiple machine learning models to produce a more accurate prediction (Islam, Talukdar, Mahato, et al., 2021). This can help reduce false alarms by increasing the model's robustness and reducing its susceptibility to overfitting.

Post-processing techniques: Post-processing techniques such as clustering and outlier detection can be used to refine the machine learning model results and eliminate false alarms (Zhang, Chen, Zhang, et al., 2022). These techniques can help identify patterns and anomalies in the data that may indicate false alarms.

- Generation of flash flood susceptibility (FFS) maps: Regarding zoning for flash flood susceptibility assessment, a statistical classification method can be employed to identify the limits for various

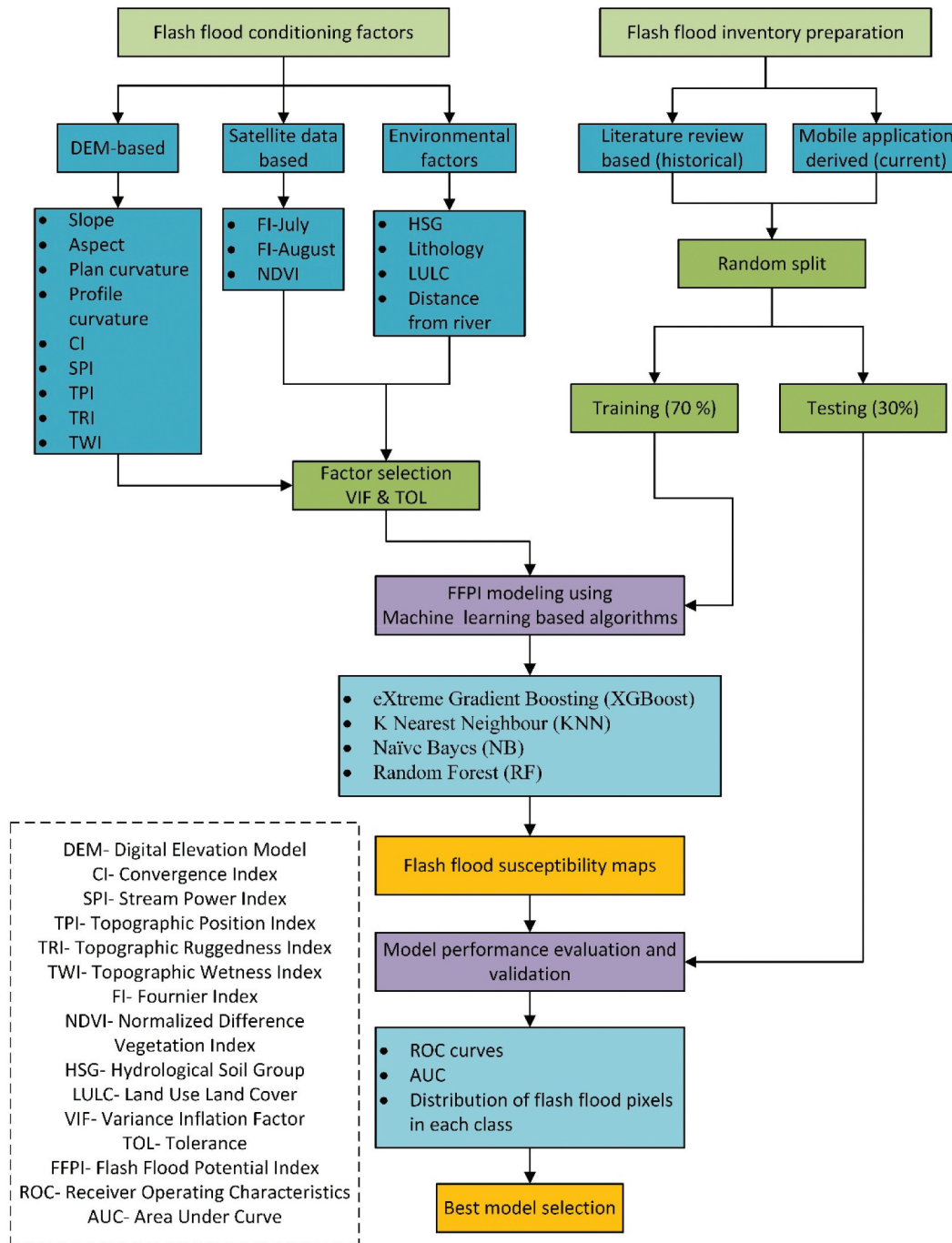


Figure 7. Detailed methodology flowchart.

zones, viz., very low, low, medium, high, and very high. Four popular classification approaches – natural breaks (NB), quantile (Q), equal interval (EI), and geometric interval (GI) – are commonly used. A systematic analysis of flash flood locations in each susceptibility class should be conducted to determine the most effective approach, as outlined by Costache and Zaharia (2017). The percentage of training and validating flash flood event locations for each ML approach should be estimated across different susceptibility classes for all four

classification methods. The approach with the highest percentage of flash flood events (training and validation) in the high and very high susceptibility zones should be selected for zoning (Singh & Pandey, 2022).

- Result validation using receiver operating characteristics (ROC) curves.
- Model performance evaluation.
- Model explanation: To address the ‘black box’ nature of machine learning models for flash flood susceptibility assessment, it is required to

understand how the models make predictions, identify potential sources of bias, and increase trust in the model predictions. Explainable AI (XAI) techniques can be employed to provide transparency into the models' decision-making process, improve the interpretability of the model predictions, and increase confidence in the models' results (Ekmekcioğlu, Koc, Özger, et al., 2022).

The explainability of the models exhibits the contribution of conditioning factors to the overall predicted results, their interdependencies, and relationships which further provides insights into how the ML model evaluates flash flood susceptibility (Aydin & Iban, 2022). XAI techniques can be broadly categorized into global and local approaches. Global explanations provide information about the essential conditioning factors and their impact on average predictions. Examples of global approaches include permutation feature importance, mean decrease impurity, and information gain (IG). In contrast, local explanations allow analysts to identify the conditioning factors that are most influential in individual predictions, as well as how these factors affect specific samples. Emerging local techniques in XAI include SHapley Additive exPlanations (SHAP) and Local Interpretable Model-Agnostic Explanations (LIME) (Iban & Sekertekin, 2022; Kim & Kim, 2022).

Given the predictions of a substantial increase in rainfall frequency in the future (IPCC, 2022), accurate identification of flash flood-susceptible areas is essential. Therefore, understanding the mechanism of flash flood genesis and employing advanced state-of-the-art techniques is crucial in achieving highly accurate and objective results.

5.4. Implementation and impact of proposed solutions

The susceptibility maps can be used by the stakeholders (residents), village authorities (gram panchayats), district administrators, disaster management officers, and decision-makers to plan ongoing and future infrastructure development in the region. The high and very high susceptibility zones should be judiciously planned for any significant infrastructure development. On the contrary, the low and very low susceptibility zones should be considered for future development. Another challenge against accurately conducting such studies is the absence of readily available flash flood events data. The proposed mobile application directly addresses this issue.

Moreover, this application is a one-time investment and a permanent solution to address this gap. The application will serve as a highly effective flash flood

event locations database. The proposed solution's impact may be directly quantified in terms of the population residing in the region. Finally, concrete recommendations will be proposed for the direct and indirect stakeholders for on-ground implementation based on the results. The above submission is an attempt and a prospective contribution towards introducing and initiating resilience to the mountain communities and infrastructure in Uttarakhand. The basis of the proposed approach is believed to be very beneficial for society.

5.5. Existing disaster management efforts and considerations

It is noteworthy to discuss the efforts made by the central government and the Uttarakhand state government towards effective disaster management. The Disaster Management Act, of 2005 provides a framework for integrating measures for the prevention of disasters and mitigation into the development plans and projects, as per the guidelines of the National Disaster Management Authority (NDMA). Further, NDMA prepared the National Disaster Management Plan (NDMP) in 2016 and revised it in 2019. This Plan includes measures to mitigate disaster risks, including those in the Himalayan region. Under the National Disaster Management Plan (NDMA, 2019), disasters such as earthquakes (due to the high seismicity of the Himalayan regions), cold waves & frost, landslides, cloudbursts and hailstorms, Glacial Lake Outburst Flood (GLOF), forest fires, etc. are covered, of which the Himalayan region is prone to. In India, disaster management is evolving from being reactive to proactive with a focus on mainstreaming disaster management into development and planning (Madan & Routray, 2015). The plan covers all phases of disaster management, viz., prevention, mitigation, response and recovery. It focuses on the horizontal and vertical integration among all the agencies and departments of the government. It has clearly defined the roles and responsibilities of all levels of the Government. The plan has introduced coherence and mutual reinforcement of the post-2015 global frameworks like SFDRR, SDGs.

Furthermore, the Indian government strives to promote a national resolve to mitigate the damage and destruction caused by natural and man-made disasters, through sustained and collective efforts of all Government agencies, Non-Governmental Organizations and people's participation. Active efforts are being made to accomplish this by adopting a Technology-Driven, Pro-Active, Multi-Hazard and Multi-Sectoral strategy for building a Safer,

Disaster Resilient and Dynamic India. Despite these efforts there are some challenges concerning disaster risk management in the Uttarakhand state:

- (i) Monitoring, forecasting and early warning: Regular monitoring of high-altitude lakes and areas prone to avalanches is a challenge. High precision numerical weather forecasting models are required. Also, there is a need for robust, reliable, and redundant warning generation and dissemination infrastructure.
- (ii) Policy & planning: There is a need for conducting detailed risk assessment incorporating the climate change driven extreme events. The diversification of assets is a challenge and can be considered as a policy. Moreover, planning hydropower and other mega projects in the state needs to be judiciously considered.
- (iii) Capacity building & awareness: There is a need to train and prepare a cadre of DRR professionals. Also, prompt and effective communication before, during, and after disaster event can play a vital role in reducing disaster impacts.
- (iv) Lack of objective and uniform disaster database and lack of risk assessment and communication (Rautela, 2016).

To address the above listed challenges, the Uttarakhand State Disaster Management Authority has taken major initiatives for DRM viz.,

- (i) Developing a Decision Support System (DSS) focused on creation of an integrated geospatial database platform, framing evacuation instructions, collection and reporting of damage information, lifesaving, monitoring shelter establishment, road traffic control, reporting, and announcements.
- (ii) Early Warning Systems development through accurate weather forecasting, issuing flood and earthquake warnings. The central and state government is working on strengthening the meteorological network with high-end hydro-meteorological sensors like automated rain/snow gauges, automated weather stations, field observatories, Doppler weather radars. Also, Uttarakhand State Disaster Management Authority (USDMA) is working on installation of sirens in densely populated areas.
- (iii) USDMA has a State Emergency Operations Centre (SEOC) which is responsible for conducting trainings of DRR professionals on the Incident Response System (IRS)

- (iv) The state government has recently invested in advanced data capturing technologies like drones and Unmanned Aerial Vehicles (UAVs).
- (v) Since the mountain state is highly vulnerable to landslides which often initiate cascading hazards, a dedicated division 'Landslide Mitigation and Management Centre' has been established for mapping and monitoring landslides.
- (vi) Efforts are being made to strengthen satellite communication in remote areas.
- (vii) The government also has an operational resettlement and rehabilitation mechanism.

Additionally, the state disaster management plan (volume 1) (<https://usdma.uk.gov.in/uttarakhand-state-disaster-management-plan-2020-21-1332.aspx>) framed by the State Disaster Management Authority (SDMA) Uttarakhand has considered six types of disasters viz. earthquakes, floods, landslides & avalanches, drought, industrial disasters, and forest fires. Hazard-wise responsibility matrices for DRR and mitigation are well-defined and documented. Also, the disaster management plan documents the state institutional framework, their significant tasks, and responsibilities during and after a disaster. Proper response mechanism in evacuation planning, emergency contacts, operations, recovery process, and reconstruction is very well chalked out. However, there seems to be a gap in the flood risk mitigation matrix and vulnerability zonation, as there is no provision for flash flood susceptibility mapping which is a highly critical problem for the mountain communities of the state as highlighted in this study. Therefore, the proposed two-fold solution can be instrumental in addressing this issue.

In the context of developing resilient hydropower infrastructure projects, primarily in the Himalayan region, there is a need to analyze resilience in terms of the variability in rainfall due to climate change. Additionally, the safety aspect is always a huge concern, especially in the wake of the detailed discussion on the two devastating disasters witnessed by the state. The cascading calamity of 2021 highlights the necessity and significance of planning for climate-resilient development. Infrastructural development in risky flood-prone mountainous terrain should be planned with the utmost care to ensure climate resilience. In the absence of high-tech and sophisticated instrumentation to monitor dynamic atmospheric developments and weather conditions, a community-based flood early warning system can be an efficient solution.

5.6. Disaster risk financing

Panwar, Sen, and Shaw (2022) conducted a study on disaster risk financing (DRF) wherein they conducted an exhaustive survey and interacted with key stakeholders from both government/non-government entities to identify the gaps and scope in disaster prevention and management policies. The study highlighted the reactive nature of existing financial arrangements against disaster risks in India. The current financial arrangements for disasters in India primarily rely on post-disaster funding through national and state disaster response funds. These funds are typically used for emergency response and recovery after a disaster. The findings suggest that these funding sources are insufficient to address the full scope of disaster risks and their associated financial consequences. The study also identifies a perception among government stakeholders that post-disaster funding through national and state disaster response funds is adequate. However, pre-disaster funding transfers are perceived as inadequate. This suggests a need to shift towards proactive disaster risk financing (DRF) solutions that can provide funding before a disaster occurs to support preparedness, prevention, and risk reduction efforts. Therefore, a diversified approach, including proactive and reactive measures, can help protect human and economic assets, manage fiscal consequences, and minimize developmental losses caused by disasters.

Furthermore, the increasing trends in disaster-induced loss and fiscal pressure on the government are acknowledged by government stakeholders. The study (Panwar, Sen, & Shaw, 2022) also identifies challenges such as lack of initiative, low-risk perception, lack of coordination, lack of awareness, lack of business case, low-risk investment, and lack of fiscal incentives. The funding needs of the government depend on the severity of the disaster events, timing of funding requirements, and capacity of the funding sources. Therefore, it is recommended to have a mix of ex-ante and ex-post disaster risk financing instruments, utilizing tools such as reserve funds, contingent credit, catastrophe insurance, and catastrophe bonds. There is a need to raise awareness about proactive disaster risk financing (DRF) solutions among key stakeholders, including policy-makers, government officials, and the general public. This can be done through awareness campaigns, capacity-building programs, and educational initiatives highlighting the benefits and importance of proactive risk financing. Comprehensive risk assessments and mapping exercises to identify high-risk areas and vulnerable populations can help prioritize resources and investments in disaster prevention and preparedness measures.

5.7. Possible extension of the methodology over the whole Himalayan region

Flash floods are a significant hazard in the Himalayan region, and their occurrence is increasing due to climatic and anthropogenic changes. The region is particularly prone to flash floods due to its complex terrain, heavy rainfall, and melting snow. Flash flood susceptibility assessment is crucial for disaster risk reduction and management. Advanced machine learning models have shown promising results in flash flood susceptibility assessment in various regions (Singh & Pandey, 2021b). Several steps need to be taken to extend the application of these models to the Himalayan region. Firstly, a comprehensive dataset that includes various environmental, meteorological, and topographical factors that contribute to flash flood occurrence in the Himalayan region needs to be collected. This dataset can be obtained from multiple sources, such as remote sensing data, ground-based sensors, and historical records. More importantly, developing a flash flood inventory is a must for the region. Secondly, suitable machine learning models need to be selected and trained on the collected dataset. Various machine learning models such as artificial neural networks (ANNs), decision trees, random forests, support vector machines (SVMs), and gradient boosting machines (GBMs) have been used for flash flood susceptibility assessment in other regions and have shown promising results. Using the collected dataset, these models can be fine-tuned and optimized for the Himalayan region. Post the training and validation of the models, and susceptibility maps can be generated. The resulting maps will provide valuable information for disaster risk reduction and management in the Himalayan region.

6. Conclusions

The Himalayan mountain state of Uttarakhand is vulnerable to a wide range of natural calamities under the influence of climate variations due to the fragile geology, complex and steep topography, and increased occurrences of heavy precipitation events in the region. During the monsoon season, landslides and floods occur frequently. Every year, the infrastructure in the area is subjected to massive destruction, and the mountain communities witness the deaths of hundreds of people and disruption in their livelihoods. These disasters may be natural, but their impacts can be significantly reduced with apt preparation. However, inadequate planning and a lack of resilience at the local level lead to a significant, preventable loss of life every year. The

preceding review of the influence of changing climate on occurrences of disasters provides insights into the classification of altitude-dependent climate zones in the Himalayas and concepts of orographic precipitation. Findings from the latest IPPC AR6, Special Report on the Ocean and Cryosphere in a Changing Climate and the Hindu Kush Himalaya Assessment were analyzed to understand the impacts of changing climate on the nature and type of disasters in the region. A detailed assessment of the two major disaster events is presented to understand the differences and similarities in terms of causes and effects. A comprehensive assessment of mountain infrastructure (particularly hydropower and road infrastructure) is discussed to understand their vulnerability and exposure.

Hydropower potential development and road infrastructure development in the state have been critically analyzed to understand their impact on damage-causing potential in the state. Finally, perspectives on the resilience of infrastructures and communities for long-term sustainability are discussed. This quest proposes an approach to generate accurate and reliable flash flood susceptibility maps in the state using state-of-the-art advanced machine learning-based algorithms. This approach is presented as a 'next-level' development strategy based on a recent study on flash flood susceptibility conducted by (Singh & Pandey, 2022). The susceptibility maps can be used by the stakeholders (residents), village authorities (gram panchayats), district administrators, disaster management officers, and decision-makers to plan ongoing and future infrastructure development in the region. The high and very high susceptibility zones should be judiciously planned for any significant infrastructure development.

On the contrary, the low and very low susceptibility zones should be taken into consideration for future development. The proposed solution also floated the idea of developing a mobile application that can be effectively used to create an inventory of flash flood events in the state. Moreover, this application can prove to be one-time-life-long solution to address this gap of non-availability of flash flood event locations data in the public domain. The application will serve as a highly effective flash flood event locations database. The proposed solution is an attempt and a prospective contribution towards introducing and initiating resilience to the mountain communities and infrastructure in Uttarakhand. Finally, an overview of government initiatives toward managing disasters and minimizing their impacts on vulnerable infrastructures and communities is presented.

The following conclusions and recommendations are suggested from the present study:

- To create resilience against disasters in the state, it is necessary to consider the impacts of climate change and occurrences of natural hazards on both mountain infrastructure and mountain communities. This can be achieved by identifying the vulnerable elements of the available infrastructure. Consequently, adaption and mitigation strategies can be prioritized according to how likely they are to fail.
- Before starting any infrastructure development project, conducting EIA of the terrain must be made mandatory. This would considerably aid in building environmentally friendly and disaster-resistant infrastructures in the ecologically sensitive and delicate Himalayan state.
- In a multi-hazard context (like the 2021 Chamoli disaster), cascading events can prove to be excessively destructive and difficult to predict in advance. Therefore, there is a need to strengthen the institutional mechanisms and capacities to handle multi-hazard environments and cascading disasters.
- There is a need for a proactive system involving the scientists, engineers, planners, and decision makers along with the stakeholders, i.e., mountain communities, to develop approaches to Identifying, documenting, storing, evaluating, and sharing local knowledge of hazards and disaster risk reduction strategies.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the manuscript in the form of tables.

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