Chapter 16
Climate-Induced and Geophysical Disasters and Risk Reduction Management in Mountains Regions

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Abstract Mountains, being fragile, act as a vital repository for water and biodiversity. The Himalaya, in specific, the "roof of the world" is endowed with a magnificent and scenic view with temperate green forests, alpine meadows, agricultural fields, gorges, waterfalls, cascades of river valleys, and a human settlement in the unstable slopes or at the perennial streams of major rivers. The vulnerability of mountain ecosystems is being disproportionately influenced by climate change-induced disasters and is poorly understood as well. Cascading effect of temperature change can melt the snow and ice, thereby exhibiting a noticeable impact on the availability of water, biodiversity, boundary shift in ecosystem, agriculture, and on human well-being. Furthermore, several climate-induced disasters, like flash floods, mass movements, debris flows, and landslides, have occurred in the Himalayas. Specifically, this has happened a lot in the recent past, resulting in numerous deaths and property damage. This insecurity is due to the region's unplanned, unscientific and unregulated practices as well as a massive rise in population. This underlines the necessity for a Mountain Specific Risk Management Framework (MSMRMF) and the incorporation of spatial specificities for risk reduction. The three dimensions of vulnerability, namely, adaptive capacity, exposure, and sensitivity, are greatly governed by livelihood strategies, access to water, food, and hygiene. The best available research on disaster risk reduction (DRR) and climate change adaptation must be incorporated in deciding disaster resilience. This chapter sheds light on various climate-induced and geological disasters in mountain regions, their impact,

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S. Sharma et al. (eds.), *Climate Change Adaptation, Risk Management and Sustainable Practices in the Himalaya*,
https://doi.org/10.1007/978-3-031-24659-3_16

and risk management strategies. The significance of regional climate models, development of alternative technologies, people's understanding regarding the social construction of risk, the role of local stakeholders, and enhancing the governance capacity and participation to manage the disaster risk is as well briefly discussed.

Keywords Climate change · Geophysical disaster · Risk reduction · Management · Himalayas

1 Introduction

The Himalayas, the world's tallest, youngest, and most active continental mountain range, have a variety of remarkable geological and tectonic features that began to emerge some 50 million years ago and are still evolving now. The Himalayas are a massive crescent-shaped mountain range that stretches over 2500 km from the Indus Valley's southern end, Nanga Parbat in the west, to Namcha Barwa in the east. The breadth of the range varies from 350 km in the west to 150 km in the east. The beautiful mountain ranges with considerable southerly convexity forms a wall that runs the length of the Indian subcontinent's northern boundary. The Himalayas' rising height, capped with several of the world's prime snow-covered summits, including 10 of the world's 14 above 8000 m peaks, is the Himalayas' most distinctive geomorphological characteristic (Roy & Purohit, 2018). The mountain range is at the crossroads of four different zoogeographic zones (Xu et al., 2009; Kotru et al., 2020). Climate change, along with a diverse range of habitats occupied by animals and plants from many worlds, has resulted in a global biodiversity hotspot (Myers et al., 2000; Wambulwa et al., 2021). The region is prone to natural catastrophes due to strong monsoon rains and occasional earthquakes (Vaidya et al., 2019), which has been worsened by recent human pressures, including deforestation and land-use changes (Sharma et al., 2007; Pandit et al., 2014; Paudel et al., 2020; Dhimal et al., 2021). Grassland makes up around 39% of the HKH, whereas woodland makes up 20%, shrubland makes up 15%, and agricultural land makes up 5%. Other forms of land use, such as barren terrain, rock outcrops, built-up regions, snow cover, and water bodies, account for the remaining 21%. The HKH's elevation zones range from tropical (500 m) to alpine ice-snow (>6000 m), with temperate broadleaf deciduous or mixed forest, temperate coniferous forest, and tropical and subtropical rainforest, as well as high-altitude cold shrub or steppe and cold desert, as the primary vertical vegetation regimes (Pei, 1995; Chettri et al., 2007). The climate ranges from subtropical to very cold. The market-led logic of growth through economic integration states that marginalized communities in India's border zones require infrastructure, particularly electricity grids and transportation networks, to connect them to fast-growing regions. On the other hand, anthropogenic intervention with the Himalayan slopes has been a major cause for disasters. For instance, Uttarakhand is home to various holy places, beautiful landscapes, and a diverse environment, attracting a large number of visitors and pilgrims. The central government has proposed a plan to enhance the Char Dham pilgrimage route, which connects Badrinath, Kedarnath, Yamunotri, and Gangotri. In late 2017, excavation for the project began in small portions along National Highway (NH)-58. The roads in such dangerous terrain are under a lot of strain. Large-scale excavations that alter equilibrium circumstances might result in catastrophic calamities in the near future (Siddique & Pradhan, 2019). Apart from this, climate-related calamities are also widespread in the Himalayan area. It is very vulnerable to climate change and calamity. It is characterized by terrain fragility, instability, tectonic activity, and seismic sensitivity. The severity of the climatic calamity was amplified by monsoon rain. The fast retreat of Himalayan glaciers has ramifications for water-related risks, such as glacier lake outburst floods, and water stress, as freshwater supplies diminish during the lean season (Sati & Litt, 2011; Mir et al., 2021). Rapid environmental and social changes are affecting the HKH region's landscapes and communities at the same time. Identification and understanding of essential biological and socio-economic aspects of mountain ecosystems, especially their sensitivity to and susceptibility to climate change (Yadav et al., 2021), has become critical for environmental management and sustainable development of mountain regions and downstream areas.

2 Climate Change in Mountain Regions

Mountain is a powerful system, which maintains the ecological balance and climate related weather pattern. It accounts for 26.5% of the world's total continental land surface and are highly susceptible to change in climatic conditions (Khan & Qureshi, 2019; Shugar et al., 2021). The major mountain regions like Himalayan region, Andes, and European Alps and the mountainous parts of Africa and Central Asia are prone to various climate-induced and geophysical disasters. It includes earthquakes, landslides, glacial lake, outburst floods, subsidence, snow avalanches, heat extremes, droughts and wildfires (Carrivick & Tweed, 2016). In recent years, climate-induced and geophysical disasters have increased in the Himalayan regions, including northern zone, central zone, and western zone, making it one of the world's most vulnerable and fragile locations. The Himalayas are sensitive to even minor changes in the climate due to geologically young and fragile nature (Maikhuri et al., 2017).

In Himalayan region, increased disaster occurrence was mostly related to climate-induced and geophysical changes (Fig. 16.1). Flood disasters accounted for 52.6% of disasters in the Himalayan region, while mass movements, such as landslides and avalanches, account for 28.5% and storm disasters account for roughly 13%. Moreover, during the monsoon season, heavy rainfall caused landslides, glacial lake outburst floods, and soil erosion throughout the region (Stäubli et al., 2018).

According to the IPCC AR6 report (2021), the following projected changes over Himalayan mountain region were reported

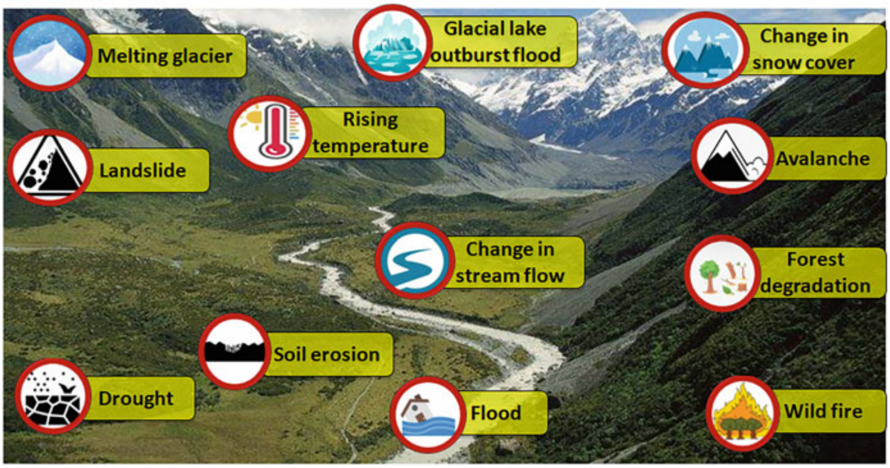

Fig. 16.1 Climate-induced and geophysical disasters in Himalayan mountain region

- Since 1970s, snow cover has decreased and glaciers have thinned and lost mass, though the Karakoram glaciers have marginally gained mass or in a balanced state.
- During the twenty-first century, snow-covered areas and volumes will decrease, snowline heights will rise, and glacier mass will likely drop with larger mass loss due to higher greenhouse gas (GHGs) emission.
- The glacial lake outburst floods and landslides have occurred over moraine-dammed lakes, which may increase with the rise in temperature and precipitation.
- In the twenty-first century, a general wetting of the Himalaya is expected with increase in heavy precipitation.

2.1 Climate-Induced Disasters

The annual mean temperature trends in the Hindu Kush Himalayas showed broad agreement with worldwide land surface temperature trends, with minor differences. Between 1901 and 2020, it was anticipated that the annual mean warming rates would be 0.19 °C per decade; however, it was observed to increase by 0.20 °C per decade during 1951–2014 (Ren et al., 2017; Sun et al., 2017). According to Global Circulation Model (GCM) simulations, a 1.5 °C global temperature increase at the end of twenty-first century would result in a temperature increase of 1.8 ± 0.4 °C averaged over the whole Hindu Kush Himalayan (HKH) areas. At high mountain ranges, it would result in temperature increase of 2.2 ± 0.4, 2.0 ± 0.5, and 2.0 ± 0.5 °C, respectively for the Karakoram, central Himalaya, and south-eastern Himalaya (Krishnan et al., 2019). At higher elevation of mountain regions, the air and surface temperatures have been rising at higher rate (Krishnan et al., 2020).

The climate change-mediated Himalayan glacier shrinkage is increasing throughout the region, ultimately resulting in drastic alteration in the underlying rock's hydrology and thermal regimes (Maurer et al., 2019). High-mountain glaciers with steep slopes and perennially frozen glaciers were extremely vulnerable to climate change (Hock et al., 2019). The regional climate and related cryospheric change interacted with the geology and topography caused huge slope failures. Changes in rock temperature and mechanical properties would have resulted in snow avalanches (Gruber & Haeberli, 2007; Hock et al., 2019). Temperatures in permafrost are rising over the world, especially in cold permafrost, causing long-term thermal anomalies as well as permafrost degradation (Noetzli et al., 2020).

Increased temperatures in the Himalayas will result in higher glacier melting, glacier contraction, and a reduction in summer runoff (Sorg et al., 2014). As a result of continuous glacier retreat in the Himalaya-Karakoram areas, several new lakes are expected to form (Linsbauer et al., 2016). The eroding nature of permafrost with decreasing slope stability, the risk of glacial lake outburst floods (GLOFs), and also landslides into moraine-dammed lakes are increasing. In Hindu Kush Himalayas, there are 204 glacial lakes that could break at any time (Narama et al., 2018; Wang et al., 2020). Glacier runoff in Asia's high mountain regions will increase until 2050, after which runoff would likely decline due to the glacier loss (Huss & Hock, 2018). In the next century, glacier mass and area will continue to decline in North Asia, High Mountains of Asia, Caucuses, and the Middle East. Glacier loss slowed under RCP2.6, but accelerates under RCP8.5, and peak in the mid- to late-twentieth century. According to GlacierMIP (Glacier Model Intercomparison Project) forecasts, glaciers in Asia's High Mountains will lose 42.5%, 56.4%, and 71.2% of their mass (at 2015) by the end of the century for RCP of 4.5, 6.0, and 8.5 scenarios, respectively (Rounce et al., 2020).

The altitudinal shift is projected to be ~20–80 m/decade in the eastern Himalaya based on the projections of temperature increase of 0.01–0.04 °C per year (Hussain et al., 2021; Liu & Rasul, 2007). Under the RCP8.5 scenario, snowline elevations in the Indus basins, Ganges, and Brahmaputra basins are expected to rise between 400 and 900 m, i.e., 4.4–10.0 m year^{-1} by 2100 (Viste & Sorteberg, 2015). There was no significant interannual variation in snow cover in Eurasia between 2000 and 2016 (Sun & Zhou, 2020). Since 1970s, there have been considerable seasonal changes of Eurasian snow cover extent (particularly for faster spring snowmelt), and these changes are projected to continue in the future (Zhong et al., 2021).

The amount of precipitation did not vary much in the eastern Himalaya, but the number of rainy days reduced, resulting in more rainfall in a shorter period of time. In the eastern Himalaya and mountainous places, this intense rain may trigger flash floods and landslides (Syed & Al Amin, 2016). High-resolution climate model projections showed that the variations of the western disturbances might increase the winter rain over the Karakoram and Western Himalayas (Forsythe et al., 2017). Flood occurring more frequently at higher altitudes might hasten glacier melting and flood events, posing considerable disaster risks in the region (Dalezios et al., 2017). During the last several decades, the Himalayan regions have seen a dramatic increase in the extreme rain events (Krishnan et al., 2019). A western disturbance is denoted as extratropical storm that originates in the Mediterranean region that would cause heavy wintertime precipitation to the Indian subcontinent especially around north-western regions (Krishnan et al., 2019).

Droughts are caused by an imbalance in precipitation pattern, duration, and frequency, thereby creating an irreversible damage to society and are directly related to climate change (Wilhite et al., 2014). Precipitation variability and drought monitoring have been observed over many regions; however, the interrelationship between the climate change and droughts has received little attention due to its slow onset (Ahmed et al., 2019; Keshavarz et al., 2013; Nikravesh et al., 2020). In Himalayan region, low precipitation was noticed in Karakoram compared to the Hindukush region (Khan et al., 2020).

Forests are more prone to fires as a result of global warming caused by increased climate variability. Remote sensing studies also showed the occurrence of forest fire due to extended dry winter period and rising mean temperature (Sannigrahi et al., 2020). In the Himalayas, wildfire season varied from November to May, with a peak in March to April. Approximately, 69% of the forest area was susceptible to forest fire in Uttarakhand, followed by 50% in Himachal Pradesh and 40% in Jammu and Kashmir and Sikkim (Sharma et al., 2014). Forest fires in the Himalayan regions are becoming more common due to rising temperatures, decreasing precipitation, and drought (Abrha & Adhana, 2019). The majority of forest fires in Himalayan regions are linked to meteorological parameters, such as temperature, dryness, rainfall, and humidity (Wang et al., 2021).

2.2 Geophysical Disasters

Geologically, Himalayan mountain ranges are broadly classified into four regions across its length: (1) Foothill/Outer Himalaya, (2) Lesser Himalaya, (3) Higher Himalaya, and (4) Trans-Himalaya (Chakrabarti, 2016). Climate change is attributed to long-term patterns of increasing slope collapse occurrence in mountain areas. Mountain locations are prone to mass movements due to steep slopes, considerable topographic relief, and seismic activity, which are intensified by the sensitivity of glaciers and permafrost (Gruber et al., 2017).

The Himalayan mountain range is tectonically active and prone to earthquakes and landslides (Sastry & Mondal, 2013; Velayudham et al., 2021). Landslides can occur both in Lesser and Higher Himalayas as well as in cold desert regions (Sastry & Mondal, 2013). Intense landslide activity is influenced by undeveloped geology of the Himalayan region, fragile geological structures and uneven topography, as well as the pressures generated by an earthquake. Some of the key attributes in the geology of the failed rocks are the following: (a) the failed mass detached and cut by several directions of planar weakness; (b) the rock mass located near a major thrust fault contains several local shear fractures, which would have aided in chemical weathering; and (c) the unweathered rock types, i.e., schist and gneiss contains soft, platy, and minerals like phyllosilicates and kyanite; further, weathering of these rocks will be more weakened, and making them to disintegrate into fine material would enhance the mass flow mobility (Shugar et al., 2021).

The major rivers, Indus, Ganges, and their respective tributaries are originated from the Himalayan regions. Hazard cascades, in which an initial incident triggered a downstream chain reaction, can have far-reaching consequences, especially when a huge quantity of water is involved (Kirschbaum et al., 2019). Moreover, rainfall-induced landslides are high risk in the Western Himalayan region due to excessive rainfall during the monsoon season (June to September) that would moisten the terrain by 77.7% (Dikshit et al., 2020).

The majority of the landslides seen in the field around 65% fell into the debris slide category. This clearly demonstrates that the overburden or debris material was saturated by extended heavy rains causing catastropic landslides. A steep, glacierized north-facing slope triggered the rock-ice avalanche in Chamoli region, Uttarakhand, during February, 2021, causing debris flow (Mergili et al., 2021). Moreover, Chamoli event might be viewed in the circumstance of a shift in geo-morphological sensitivity due to continuous global warming events in recent days (Shugar et al., 2021).

2.3 Implications on Environment

Disasters in the mountain areas affect the wildlife and human society by declining water resources, wild food resources, fuel wood, and biodiversity. Furthermore, changes in land use patterns caused by climate change have an equal impact on animal and human environment (Khanduri et al., 2018). Climate change impact with signs of phenological changes and reduced agricultural productivity in the Himalayan regions progressed during recent decades (Hart et al., 2014; Krishnan et al., 2020).

Changes in temperature and precipitation over the mountain regions could have significant implications on biodiversity, ecosystem goods, and services (Chettri & Sharma, 2016). High evaporation will cause wetlands to diminish, which will be aggravated by the spread of towns and human activities. Water bodies are becoming more suited as habitats for invading species, which competes with native species and endangers native life. As the temperature rises, more evaporation occurs, resulting in an increase in atmospheric moisture content, and, as a result, future geographical and temporal precipitation patterns will shift. Due to the region's diverse topography, localized weather phenomena, such as cloudbursts, flash floods, and landslides, may increase, eventually leading to greater risk (Hussain et al., 2021).

The MODIS satellite results showed that the significant decline in wintertime snow across the HKH region in present decade affects the river flow regimes and water resource availability (Maskey et al., 2011). Heavy rains and rapid ice melting in high-mountain glaciated areas have increased the risk of dammed lake outburst floods, which have harmed the human population and infrastructure (Khanduri et al., 2018; Mergili et al., 2021). The occurrence of disasters, like floods and landslides on a regular basis, changes the distribution of groundwater recharge and runoff, which controls the soil moisture indirectly (Pangali Sharma et al., 2020).

Rapid loss of forest to fires can aggravate the extent and magnitude of socio-ecological consequences, including degradation of ecosystem services, shortage of fuel wood, and displacement of people (Han & Han, 2020). Forest fires destroyed the endemic forest plants and species and devastated the dead vegetation and detritus, thereby exposing the top soil to erosion (Wang et al., 2021). This results in massive amounts of carbon dioxide released into the atmosphere and enhancing the effect of global warming (Hanson & Ranganathan, 2017). Due to biomass burning and forest fires, almost 100 million tons of smoke aerosols and black carbon are released into the atmosphere, and an increase in surface albedo and water runoff were observed (Fearnside, 2019). On the other hand, absorbing aerosols at high elevations enhanced the warming rate on snow, indirectly amplifying the melting of glaciers.

3 Occurrence of Climate-Induced and Geophysical Disasters in Himalayan Regions

3.1 Earthquakes

The Himalayan region is known for the maximum seismic activity in southern Asia, where multiple massive earthquakes have caused thousands of deaths in the past (Table 16.1). The geodetic strain build-up rate and the stress release rate through earthquakes are two important factors in determining a seismogenic area's energy budget. As a result, the comparison of geodetic rate and seismic moments along the Himalaya can be viewed as a main predictor of seismic hazard. It was projected that the rate of geodetic moment varied from 1.7×10^{18} to 10.2×10^{18} Nm per year, while the rate of seismic moment ranged from 3.7×10^{16} to 5.1×10^{19} Nm per year (Sharma et al., 2020). This difference in geodetic and seismic moment rates was equal to a moment deficit rate ranging from $\sim 1.15 \times 10^{17}$ to 7.97×10^{18} throughout the northwest to northeast Himalaya, which corresponds to a magnitude of 5.7–8.2 earthquake potential. Even though the regions of Kashmir and Kathmandu are thought to have low seismic potential, the northeast half of Himalaya have a larger earthquake potential ($Mw \geq 8.0$) (Bilham, 2019).

3.2 Landslides

The landslide, being one of the primary disasters in the steep and hilly region, is a downward movement of dislodged rocks, debris, and earth materials caused by gravity and one of the most destructive geo-hazards (Mandal & Maiti, 2015). In Asia, over 66 million people live in landslide-prone zones (Tien Bui et al., 2019).

Table 16.1 Occurrence of earthquake in Himalayan mountain regions

Region	Year of occurrence	Place	Casualties	Richter magnitude	Impact	References
Northwest Himalayan region	November, 1997	Bangladesh	23	5.8	Infrastructure damage and property loss	Islam et al. (2011)
	October, 2005	Muzaffarabad, Kashmir	>80,000	7.7	Life loss and infrastructure damage	Kamp et al. (2008)
	January, 2016	Manipur	–	6.7	Infrastructure damage and transport system collapsed	Gahalaut and Kundu (2016)
	January, 2017	Ambasa earthquake, Tripura	10	5.7	Infrastructure damage	Halder et al. (2021)
	June, 2020	Mizoram earthquake	–	5.5	Transport system collapsed	
Western Himalayan region	October, 1991	Uttarakhand	2000	7.0	Infrastructure damaged and human life loss	Chopra et al. (2012)
	March, 1999	Uttarakhand (Chamoli)	110	6.8	Infrastructure damage, property loss, and transport system collapsed	
	December, 2005	Uttarakhand	–	5.4	Transport system collapsed	Mittal et al. (2019)
Eastern Himalayan region	September, 2011	Sikkim	97	6.8	Transport system collapsed	Halder et al. (2021)
	April, 2015	Gorkha, Nepal	8964	7.8	Life loss, infrastructure damage, and property loss	
	May, 2015	Nepal	218	7.3	Property loss, infrastructure damage, and transport system collapsed	
	April, 2021	Assam	2	6.0	Property loss and infrastructure damage	
Southeast Himalayan region	August, 2016	India and Myanmar region	11	6.7	Infrastructure damage	Aung et al. (2019)

According to the Geological Survey of India (GSI), landslides threaten 4,20,000 km^2 or 12.6% of India's entire geographical land area. Rainfall and earthquakes are the two most common causes of landslides in Himalayan terrain (Table 16.2). India, as a monsoon-affected country, experiences the majority of landslides during the monsoon season, notably from June to August (Mondal & Mandal, 2020). Rain-induced landslides, contributing for nearly 76% of landslide events, occur during or after the monsoon season (Ghosh et al., 2020), whereas earthquake-induced landslides happen right after the earthquake (Dikshit et al., 2020; Kumar et al., 2021). The Himalayan region accounts for roughly 30% of all landslide occurrences worldwide, while 42% of India's landslide occurred around north-west Himalayas, including the Darjeeling-Sikkim Himalayas (Dikshit et al., 2018).

Across Goriganga valley, Kumaun Himalaya region, ~20–25% of the area along the Goriganga river and the Lesser Himalaya lies in the high and very high landslide susceptible zones, whereas ~50–63% of the areas located in the Higher Himalaya and Tethys Himalaya lies in the low and very low susceptible zone (Kumar & Gupta, 2021). Across Mussoorie Township and around Lesser Himalaya, ~44% of the area are prone to very high landslide susceptible zones while ~56% of the area comes under the low susceptible zones (Ram et al., 2020).

3.3 Flood

Intense precipitation events enhance the risk of disasters that can cause unexpected events like flooding and flood-related disasters (Aryal et al., 2020; Zhao et al., 2019). Continuous and varied precipitation eventually leads to an intense river flow to exceed a threshold, causing flood by breaching the river bank or previously constructed flood restoration regions (Aryal et al., 2020; Dulal et al., 2007).

With warming rate higher in Himalayan region than in other parts of the world, the availability of water vapor increases, eventually leading to intense precipitation resulting in increased risk of flooding (IPCC, 2021; Simmons et al., 2010). Nearly 63% of basins under the zone of Sikkim–Darjeeling and Bhutanese Himalayas falls under high to very high flash flood risk, whereas 28% comes under medium and only 9% in the low categories of flash flood risk (Karmokar & De, 2020). Furthermore, nearly 29% area of Himalayan foothills of Jalpaiguri district lies under a high threat level (Roy et al., 2021). Recent flood events over Himalayan mountain regions are detailed in Table 16.3.

3.4 Glacial Lake Outburst Flood (GLOF)

Due to climate change and the acceleration of glacier melt in recent decades, glacial lakes in the Himalayas are rapidly increasing (Khadka et al., 2018). Glacial lakes are considered as an important source of water reservoirs that would highly vary in

Table 16.2 Occurrence of landslides in Himalayan mountain regions

Region	Factors	Year of occurrence	Place	Casualties	Economic loss	References
Northeastern Himalayan region	Cloudburst-landslide	August, 1993	Nagaland (Kohima)	500	Infrastructure damage and transport system collapsed	Nokendangba Chang et al. (2021)
	Earthquake-induced landslide	May, 1995	Mizoram (Aizawl)	25	Transport system collapsed	Vinoth et al. (2022)
	Flood-induced landslide	June, 2017	Bangladesh	152	Life loss	Uddin et al. (2021)
	Rainfall-induced landslide	July, 2020	Manipur (Noney, Mao Town, and Senapati District)	–	Infrastructure damage	Geological survey of India (2020)
Western Himalayan region	Rainfall-induced landslide	July, 1970	Belakuchi, Uttarakhand	–	Infrastructure damage	Parkash (2015)
		July, 1990	Uttarakhand	25	Property loss	Dikshit et al. (2019)
	Landslide-flash flood	July, 1991	Himachal Pradesh	300	Human life losses and transport system collapsed	Meena and Mishra (2018)
	Cloudburst-landslide	June, 1993	Himachal Pradesh	–	Transport system collapsed	Haritashya et al. (2006)
	Rainfall-induced landslide	September, 1995	Himachal Pradesh (Kullu)	65	Property loss and transport system collapsed	Meena and Mishra (2018)
		August, 1998	Uttarakhand (Malpa)	380	Human life loss and transport system collapsed	Onagh et al. (2012)
		March, 1999	Uttarakhand (Chamoli)	–	Infrastructure damage	Gupta et al. (2021)
		August, 2002	Tehri, Uttarakhand	29	Transport system collapsed	Parkash et al. (2015)

(continued)

Table 16.2 (continued)

Region	Factors	Year of occurrence	Place	Casualties	Economic loss	References
		July, 2003	West Bengal	11	Human life loss, infrastructure damage	
			Kullu, Himachal Pradesh	–	Transport system collapsed	Dubey et al. (2013)
		September, 2003	Uttarkashi, Uttarakhand	–	Infrastructure damage	Parkash et al. (2015)
	Earthquake-induced landslide	October, 2005	Kashmir (Muzaffarabad)	26,500	Human life loss, transport system collapsed, and property loss	Mahmood et al. (2015)
	Cloudburst-landslide	July, 2007	Uttarakhand	28	Infrastructure damage and transport system collapsed	Kumar et al. (2017)
	Avalanche-induced landslide	February, 2008	Jammu and Kashmir	25	Infrastructure damage and transport system collapsed	Parkash et al. (2015)
	Rainfall-induced landslide	September, 2008	Shimla, Himachal Pradesh	42	Infrastructure damage and transport system collapsed	Parkash et al. (2015)
		June, 2009	Munsiyari, Uttarakhand	–	Transport system collapsed	Sati (2020)
	Avalanche-induced landslide	February, 2010	Jammu and Kashmir	17	Transport system collapsed	Banerjee and Dimri (2019)
	Cloudburst-landslide	July, 2011	Jammu and Kashmir	3	Transport system collapsed	Parkash et al. (2015)
	Flood-induced landslide	June, 2013	Uttarakhand and Himachal Pradesh	4094	Transport system collapsed and property loss	Shekhar et al. (2015)
	Rainfall-induced landslide	August, 2021	Uttarakhand (Pithoragarh)	2	Transport system collapsed	ECHO (2021)
		October, 2021	Uttarakhand	52	Life loss and transport system collapsed	

Eastern Himalayan region	Rainfall-induced landslide	August, 1948	Assam	500	Infrastructure damage	Parkash (2015)
	Landslide and subsidence zone	August, 1984	Gangtok, Sikkim	9	Transport system collapsed	Murgese et al. (2015)
	Rainfall-induced landslide	August, 1993	West Bengal (Kalimpong)	40	Infrastructure damage and life loss	Roy et al. (2019a, b)
		July, 1993	Arunachal Pradesh (Itanagar)	25	Property loss	Rupa (2015)
		June, 1997	Gangtok City, Sikkim	–	Transport system collapsed	Ramanathan et al. (2020)
		September, 2003	Sikkim	4	Human life loss and transport system collapsed	
		August, 2005	Assam	12	Human life loss, property loss, and infrastructure damage	Parkash et al. (2015)
		September, 2005	Sikkim	7	Human life loss and property loss	
		July–September, 2007	Sikkim, Darjeeling	–	Transport system collapsed	Mondal and Mandal (2018)
		May, 2009	Kurseong, Darjeeling	27	Property loss	Parkash et al. (2015)
		September, 2010	Dhemaji, Golaghat, and Bongaigaon, Assam	2	Infrastructure damage and property loss	
		June, 2011	Sikkim	16	Transport system collapsed and infrastructure damage	Sridharan and Gopalan (2019)
		May, 2020	Sikkim	–	Transport system collapsed	Geological survey of India (2020)
			Meghalaya	–	Transport system collapsed	

(continued)

Table 16.2 (continued)

Region	Factors	Year of occurrence	Place	Casualties	Economic loss	References
		June, 2020	Assam	29	Transport system collapsed, life loss, and property loss	
		July, 2020	Arunachal Pradesh (Papum Pare)	–	Transport system collapsed	
		October, 2021	Nepal	88	Life loss and transport system collapsed	ECHO (2021)
Southeast Himalayan region	Rainfall-induced landslide	July, 2019	Myanmar	75	Infrastructure damage	Panday and Dong (2021)
		August, 2019	Myanmar (Kpakant)	115	Infrastructure damage and property loss	

Table 16.3 Occurrence of flood events in Himalayan mountain regions

Region	Factors	Year of occurrence	Place	Casualties	Impact	References
Western Himalayan region	Cloudburst-flash flood	September, 1988	Himachal Pradesh	65	Property loss and infrastructure damage	Prasad et al. (2016)
		August, 1997	Himachal Pradesh (Chirgaon)	–	Property loss	
		June, 2000	Uttarakhand (Gangotri Glacier)	–	Property loss	Kumar et al. (2018)
		July, 2003	Kullu, Himachal Pradesh	40	Infrastructure damage and transport system collapsed	Prasad et al. (2016)
		June, 2005	Himachal Pradesh (Sutlej Valley)	19	Property loss and transport system collapsed	Pandey et al. (2015)
		June, 2005–August, 2009	Jammu and Kashmir	–	Infrastructure damage and transport system collapsed	Kumar et al. (2018)
		August, 2010	Leh, Jammu and Kashmir	25	Transport system collapsed, life loss, and property loss	
	Rainfall-induced flash flood	August, 2010	Uttarakhand	65	Property loss	
		August, 2011	Uttarakhand (Dokriani Glacier)	–	Property loss	Khanduri (2020)
	Cloudburst-flash flood	September, 2012	Uttarakhand	–	Property loss and infrastructure damage	
	Uttarakhand floods	August–September, 2012	Uttarkashi, Rudraprayag, and Bageshwar	52	Property loss and infrastructure damage	Parkash et al. (2015)
	Cloudburst-flash flood	September, 2012	Uttarakhand (Asi ganga, Uttarkashi)	–	Transport system collapsed	

(continued)

Table 16.3 (continued)

Region	Factors	Year of occurrence	Place	Casualties	Impact	References
		June, 2013	Uttarakhand (Kedarnath)	5000	Transport system collapsed and property loss	Singh et al. (2016)
			Uttarakhand (Gangotri Glacier)	–	Transport system collapsed and property loss	Kumar et al. (2018)
			Himachal Pradesh (Kinnaur)	23	Property loss, life loss, and infrastructure damage	Pandey et al. (2015)
	Floods	October, 2014	Jammu and Kashmir	8	Infrastructure damage and transport system collapsed	Bhatt et al. (2020)
	Cloudburst-flash flood	July, 2016	Uttarakhand (Bastadi Narula)	–	Transport system collapsed	Kumar et al. (2018)
	Avalanche-flash flood	February, 2021	Uttarakhand	200	Property loss and infrastructure damage	Pandey et al. (2021)
Eastern Himalayan region	Cloudburst-flash flood	July, 2016	Assam	28	Life loss, property loss, infrastructure damage, and transport system collapsed	Paik (2018)
		May, 2020	Assam	149	Property loss, infrastructure damage, and transport system collapsed	Sachdev and Kumar (2021)

number, size, and volume with respect to climate change. Glacial lake outburst floods (GLOF) occur when significant quantities of water from glacial lakes are released suddenly, either by dam failure, self-destruction, ice/rock avalanche, or excessive precipitation into the lake (Harrison et al., 2018).

Dam self-destruction was responsible for more than two-fifth of GLOF incidents in the Himalayan region (Emmer & Cochachin, 2013). Across 38 cases of GLOF events assessed over Himalayas, 34% was due to ice avalanche falling into the lake, 20% by hydrostatic pressure mediated water level rise, and 14% by melting of dead ice (Falátková, 2016). According to Mal et al. (2021), Jammu and Kashmir regions have higher number of lakes at high risk ($n = 556$), followed by Arunachal Pradesh (388) and Sikkim (219). The top three triggering mechanisms of 21 historical GLOF episodes in Bhutan were glacier ice falling into the lake (44%), glacier calving (33%), and ice deformation (10%) (Komori et al., 2012). Furthermore, 36 out of 329 glacial lakes analyzed were vulnerable to snow avalanche, and 23 glacial lakes were found to be very high-risk lakes and 50 as high-risk lakes in Indian Himalayas (Dubey & Goyal, 2020). The historical glacial lake outburst flood events over Himalayan mountain regions are given in Table 16.4.

3.5 Snow Avalanche

Avalanches are a common hazard in snow-covered mountainous area all over the world. Two union territories and three states in the Indian Himalaya are more prone to avalanches: Jammu and Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, and Sikkim (Singh et al., 2020a, b). Greater number of snow avalanches occurred in Asia's high mountains, such as the Himalaya, Karakoram, Pamir, Hindu Kush, Tien Shan, and Dazu Shan of India, China, Pakistan, and Nepal (McClung, 2016). Due to its unique terrain, snow characteristics, and seismic activity, the Karakoram Mountains in the north-western Himalaya experiences earthquake-induced and delayed-action avalanches throughout the year (Singh & Ganju, 2002; Kumar et al., 2019; Singh et al., 2021a, b, c). In general, the zone heights of hazardous avalanche slopes in the Upper Himalayan zone are around 5000 m or greater. About 33% of snow avalanche paths have slope angles of 32°–40°, and majority of its track faces north-west (Kanna et al., 2018). The details of snow avalanche occurred over Himalayan mountain regions are described in Table 16.5.

3.6 Subsidence

Himalayan terrain is more prone to ground subsidence due to its seismic activity and soil erosion. The river Kali constantly accumulated sediments by depositing mass from the north to down regions of Garbyang basin. Moreover, the stream passed through stabilized landslide mass, and water percolated through the destabilized

Table 16.4 Occurrence of glacial lake outburst flood events in Himalayan mountain regions

Region	Glacier	Year	Location	Casualties	Impact	References
Northern Himalayan region	Ghulkin Glacial lake	2008	Pakistan	–	Property loss and transport system collapsed	Nie et al. (2018)
Central Himalayan region	Cirenmaco	1964	Central Himalaya (Zhangzangbo valley)	–	Property loss and transport system collapsed	Gurang et al. (2017a, b)
	Lahaul Valley	1979	India	200	Life loss and infrastructure damage	Gurang et al. (2017a, b)
	Dig Tsho	1985	Nepal	–	Life loss and infrastructure damage	Gurang et al. (2017a, b)
	Chubung lake	1991	Nepal	–	Property loss and transport system collapsed	Westoby et al. (2014)
	Khumbu Himal	1998	Sabai Tsho, Nepal	–	Infrastructure damage	Nie et al. (2018)
	Kara, Hussain, Yigeong	2000	Glacial lake, China and India	–	Property loss	
	Parechu Zhu	2005	China and India	–	Infrastructure damage, property loss, and transport system collapsed	
	Chorabari lake	2013	India	1600	Infrastructure damage and transport system collapsed	Allen et al. (2016)
	Lhotse glacier	2015	Supraglacial lake, Nepal	–	Infrastructure damage and transport system collapsed	Rounce et al. (2017)
	Lhotse glacier	2016	Supraglacial lake	10	Infrastructure damage	
	Gongbatongsha Tsho	2016	Tibet	5	Infrastructure damage and property loss	

Western Himalayan region		2021	Chamoli, Uttarakhand	61	Infrastructure damage and property loss	Vishwanath and Sharma (2021)
Eastern Himalayan region	Lunana glacier	1960	Northern Bhutan	–	Property loss and transport system collapsed	Nie et al. (2018)
	Zharico lake	1981	Tibet	–	Life loss and infrastructure damage	Yao et al. (2018)
	Luggye Tsho lake	1994	Tibet	20	Infrastructure damage	Gurang et al. (2017a, b)
	Gangri Tsho	1998	Tibet	–	Property loss	Nie et al. (2018)
	Lemthang Tsho	2015	Tibet	–	Infrastructure damage	Gurung et al. (2017a, b)

Table 16.5 Occurrence of snow avalanche in Himalayan mountain regions

Region	Factors	Year	Location	Casualties	Impact	References
East central Himalayan region	Manaslu Nepal avalanche	April, 1972	Nepal	15	Transport system collapsed and property loss	Thakuri et al. (2020)
	Gokyo avalanche	November, 1995	Nepal	42 people died	Transport system collapsed and property loss	
	Mount Everest	May, 1996	Nepal	3 people died	Transport system collapsed	
	Manaslu	September, 2012	Nepal	11 people died	Life loss and transport system collapsed	
	Mount Everest avalanche	April, 2014	Nepal	16 people died	Life loss and transport system collapsed	
	Mount Everest avalanches	April, 2015	Nepal	22 people died	Life loss, property loss, and transport system collapsed	
Northeastern Himalayan region	Mokokchung debris avalanche	May, 2005	Nagaland	14 people died	Life loss and transport system collapsed	Singh (2018)
	Kohistan avalanche	February, 2010	Pakistan	102 people died	Life loss and transport system collapsed	Khan and Qureshi (2019)
	Gayari sector avalanche	April, 2012	Pakistan	138 people died	Life loss and transport system collapsed	
Western Himalayan region	Gurez sector avalanche	January, 2017	Jammu and Kashmir	28 people died	Life loss and transport system collapsed	Khan and Qureshi (2019)
	Massive rock and ice avalanche	February, 2021	Uttarakhand	200 people died	Life loss, property loss, and transport system collapsed	Shugar et al. (2021)

mass would reflect in ground subsidence over the regions of Umli-Bhandarigaon, Talla Dhumar, and Bagi (Rautela, 2005). The Indian continent's northward movement have been seen at the surface as a southward migrating wave of subsidence and uplift, which has been observed from the Himalaya to the Ganges basin (Webb et al., 2017). The Kailas basin is a one kind of perched basin that was created by dynamic deflection inside a mountain belt (Shen et al., 2020).

3.7 Climate Extreme Events: Temperature, Droughts, and Wildfires

Extreme temperature events were more prevalent in Himalayan mountain compared to the other regions of the world (Singh et al., 2011). Warm spells are becoming more common in the Himalayan highlands. The cold spell is decreasing primarily in valley areas, such as Kathmandu and Karnali, as well as the Himalayan Chisapani region. On an annual basis, the maximum temperature is increasing (0.05 °C/year) than the minimum temperature (0.003 °C/year) (Awasthi & Owen, 2020).

Extreme drought occurrences in the Himalayas have become common and intense over the last three to four decades, during both winter and summer seasons (Dahal et al., 2016). Trans-Himalaya exhibited the highest temperature variation during summer (7 °C) and a low during winter (−13 °C). The mountain plains (the Terai in Nepal and the Indo-Gangetic Plain in India) had the highest temperature varying from 16 to 30 °C, whereas the middle mountains (north of the Terai up to the Himalayan peaks in Nepal) had a range of 7–20 °C. More than 75% of the area in the mountains had a soil moisture deficit index (SMDI) below −1, while drought (SMDI < -3) prevailed over the Koshi River basin area for >40% during 2005–2006 (Nepal et al., 2021). The extreme heat and wildfire events that occurred over Himalayan mountain regions are detailed in Table 16.6.

4 Observation and Monitoring Systems

The cascading disasters occurring in Himalayas increase every day and trigger one another, creating a cumulative hazard. The Himalayan mountains are geologically fragile, vulnerable to various climate change impacts, including erosion, landslides, glacial floods, avalanches, etc. There is a pressing requisite for dramatic step in the monitoring processes for growing environmental concerns. Such highly bio-diverse and multi-hazard zones demand focused risk reduction strategies, considering bio-physical and sociocultural certainties of the mountains.

For the wide range analysis of earth surface processes, Himalayan topography assessment is a prime requisite to assess where disaster events cause threat to population and infrastructure. Various techniques are available to observe and monitor the pre- and post-disaster, which are detailed under each climate risks and

Table 16.6 Recent occurrence of heat extremes and wildfire events in Himalayan mountain regions

Types of disaster	Factors	Year	Location	Casualties	Environmental loss	References
Asian heatwave	Heatwave	2007	India, Pakistan, Bangladesh, and Nepal	More than 200 people died	Life loss, property loss, and transport system collapsed	Naveena et al. (2021)
Uttarakhand wildfire	Heatwave	2016	Uttarakhand	7 people died	Infrastructure damage	Biswas et al. (2018)
Northern Indian cold wave	Cold wave	2017	Jammu and Kashmir, Himachal Pradesh	7 people died	Infrastructure damage and transport system collapsed	Das et al. (2020)
Shimla forest fire	Crown fire	April,1999	Himachal Pradesh	–	Biodiversity loss and reduced forest area	Kanga et al. (2017)
Uttarakhand forest fire	Crown fire	April, 2020	Uttarakhand	2 people died	Biodiversity loss and infrastructure damage	Latestly (2021)
Uttarakhand forest fire	Crown fire	April, 2021	Uttarakhand	–	Biodiversity loss and infrastructure damage	Latestly (2021)

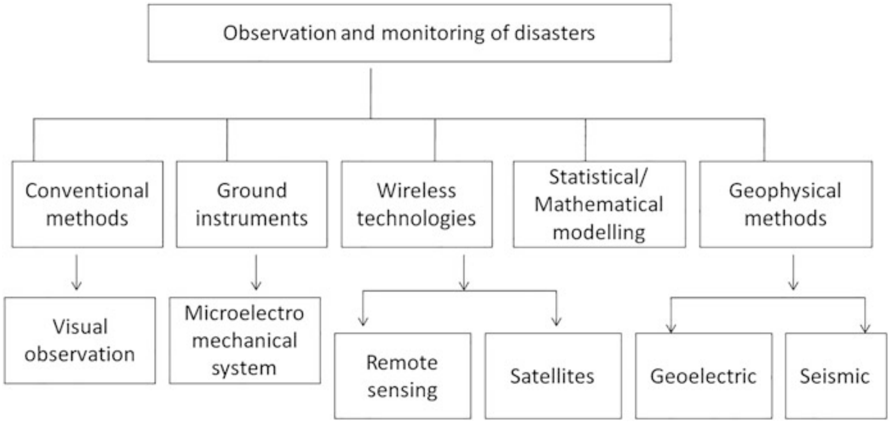

Fig. 16.2 Disaster observation and monitoring techniques over Himalayan mountain regions

briefed in Fig. 16.2. The processes find ease after the advent of remote sensing technologies.

4.1 Earthquakes

Understanding the earthquake mechanism, structural complexities of fault zones, and its recurrence interval has greatly enhanced the need and interest on earthquake prediction techniques. Sudden disturbance on the earth manifests the surface causing interruption on seismic waves and ground shaking. Prediction of expected magnitude, geographical location, and time of occurrence with accurate precision would be indispensable. Macro-level zonation mapping based on peak ground acceleration (PGA) was implied to be imprecise compared with micro-level zonation. The major drawback associated with such map is that it was designed depending only on past events. Hence, a scientific seismic hazard analysis and reliable zoning are essential for effective monitoring. Various models have been devised to forecast the seismic activity rates. A well-acknowledged "regional time and magnitude predictable model" was proposed by Papazachos (1989) to assess the probability of occurrence of forth-coming main shock at specified time and magnitude in seismogenic source zone. Radon, being sensitive to tectonic disturbances, is used as seismotectonic indicators (Ramola et al., 2008; Barkat et al., 2017). Ramkrishnan et al. (2021) have developed ground motion prediction equation based on moment magnitude and hypocentral distances, which could accurately predict PGA than previous reports.

Freeman (1975) has evaluated the capacity spectrum technology for damage and loss assessment of earthquake and attained transition from employing intensity parameters to physical parameters like spectral accelerations and spectral displacements. Bradley et al. (2015) have attempted the comparisons of ground motion equation and simulation-based technique. The result of the study recommends that rupture kinematics allows better-constrained damage and loss estimates. However, the difficulty and uncertainties associated with it reveal stochastic methods as better compromise in observing variability of interest.

4.2 Landslides

Earthquakes or rainfall-triggered landslides cause devastation in highlands, either causing severe threat to human lives or damaging roads, forests, and agricultural land. The prediction of landslides is unattainable as it involves continuous monitoring of minor likely regions within large area and relies on complex parameters, such as topography, geology, environment, and anthropogenic activities. Various techniques have been adapted for landslide susceptibility assessments, including expert knowledge and statistical methods (linear, logistic, multiple and geographically weighted regression, frequency ratio, and function of past evidences). In general, landslide hazards are initially assessed by landslide susceptibility mapping (hazard zonation mapping). Such maps and photo interpretation provide widespread knowledge on location and type of past landslide occurrences, frequency of occurrence, casual factors, volume, and damages that have been associated with previous reports (Raetzo & Loup, 2016; Ambrosi & Scapozza, 2015). It is then performed based on the state of activity of mapped phenomena acquired from synthetic aperture radar (SAR) (Calvello et al., 2017). The severity is determined by measuring the volume and velocity and debris thickness from field survey. Several GIS-based soft-computing models being used for envisaging landslide susceptibility include super vector machines (Nhu et al., 2020), artificial neural networks (Tien Bui et al., 2019), adaptive network-based fuzzy interference system (Polykretis et al., 2019), and decision tress (Hong et al., 2015). Digital elevation model (DEM) generated using GIS delivers topographic attributes for hazard assessment (Sarkar et al., 2015).

4.3 Floods

The extreme precipitation events have resulted in flash floods. The acceleration of climate change in Himalayas has resulted in glacial lakes, and recent decades have witnessed glacier melt (Maurer et al., 2019). Management of Himalayan flood is critical as it results from the combination of land and atmospheric processes. The prime step involved is hazard mapping, risk zonation, and enhancing early warning systems and forecasting. Flood forecasting serves as a more efficient and cost-effective technique than flood control measures. The ground details of watershed morphometrics conjoined with land and slope aid in assessing the hazard vulnerability. Various stochastic methods have been used widely for simulating and forecasting rainfall, temperature, water level, and hydrological time series, such as

Box-Jenkins or ARIMA (autoregressive integrated moving average) (Parvaze et al., 2021), ARMA (autoregressive moving average), and SARIMA (seasonal autoregressive integrated moving average) (Valipour and Eslamian, 2014). These models require key features, such as mechanism of precipitation formation, snowmelt modelling, catchment runoff, and flood routing. The occurrence of glacial lake outburst floods has been recognized by satellite imagery and first-hand observations. The frontal topographical analysis could be the first-order approximation of future disasters. Devrani et al. (2015) have determined spatial pattern of Mandakini river basin with the topographical analysis as first-order prediction measuring normalized channel steepness with chi analysis. The integrated use of linear imaging self-scanner satellite data and advanced space-borne thermal emission and reflection radiometer digital elevation model (DEM) by Meeraj et al. (2015) have assessed the influence of morphometry, landcover, and slope on flood vulnerability, which strongly governs hydrological functionality and response. In the absence of finer-resolution data, global DEM are often used (Watson et al., 2015).

4.4 Avalanches

The observations on activity of avalanche are significant, since they are strong and trustworthy indicator of snow instability and its detection is presently carried out by aerial reconnaissance by experts. Traditional field-based method to monitor the snow cover holds hurdles as it is time-consuming and labour-intensive and becomes impossible when harsh climate exists. Several physical and statistical models are used in avalanche forecasting, which encompasses its own limitations with the mathematical formulations. Snowmelt runoff model developed by Martinec (1975) has been used in over 100 basins, which simulate daily runoff ensuing from snowmelt and rainfall using daily temperature, precipitation, and daily snow area as input parameters. An attempt by Larsen et al. (2013) have evaluated the deposits of avalanche using object-oriented approach and validated with manually generated debris maps. The fresh avalanches in the image could be detected by conducting texture classification of image and removing the false detection. Besides, manual monitoring ground-based radar or laser scanning is also being used in monitoring the avalanche occurrence. The high spatial variability endowed causes difficulty in representing the actual snow cover (Rathore et al., 2018).

The automatic detection and mapping of snow avalanche debris in regions of Western Himalayas was conducted by Singh et al. (2020a, b) using satellite data and to formulate an index. The spectral signature of avalanche and non-avalanche snow detected using near-infrared wavelength and object-based image analysis was suggested to be accurate than pixel-based methods. Kaur et al. (2021) have used a multi-model decision support system for predicting avalanche in north-west Himalaya, which integrates four avalanche forecasting models. Singh et al. (2021a, b, c) have assessed the snow cover change using MODIS in basins of

Western Himalayas, whose results revealed ~95% mean overall accuracy of cloud removal.

4.5 Subsidence

The monitoring techniques of subsidence are point-based including leveling, GPS, and ground-based observation field data, which are now substituted by space-based observations. Interferometric synthetic aperture radar (InSAR) was the first method to monitor ground subsidence, which covers hundreds to thousand square kilometers per interferogram (Prati et al., 2010). Generation of high spatial resolution deformation maps covering centimeters to millimeters (Xu et al., 2016) was monitored using differential interferometric synthetic aperture radar (DInSAR) and greatly used to assess the temporal evolution of land subsidence and compaction of subsurface layers. Bali et al. (2021) have studied mining-induced subsidence assisted by ground-penetrating radar in structural and engineering aspects of sinkhole kinematics of subsidence phenomena, geometrical pattern of deformation structures, sags, paleo collapses, groundwater table, etc., Such prospects using high-resolution antenna configuration would successfully map a network of structures responsible for creep process.

4.6 Drought and Wildfires

Several indices are available for assessing, monitoring, and quantifying drought that evaluates its intensity and duration like modified Palmer drought index, surface water supply index, soil moisture anomaly index, drought severity index, etc. Khatiwada and Pandey (2019) have studied the drought dynamics evaluating various indices for characterizing hydrometeorological drought. Standardized precipitation index serves as a powerful tool, which requires only data on precipitation for evaluating the intensity, duration, magnitude, severity, and frequency of drought predicting the drought risk (Khan et al., 2020).

Understanding of anthropogenic, ecological, and environmental drivers of wildfires is the chief component in assessing the occurrence of wildfires. The active fire detection and monitoring capabilities were assessed using moderate resolution imaging spectroradiometer (MODIS) satellite sensors (Cochrane, 2003). A specific biomarker for fire emission is levoglucosan (You & Xu, 2018), and its detection has been reported in regions surrounding Himalayas (You et al., 2016). The fine-scale analysis of fire incidences at Himalayan foothills was demonstrated by Murthy et al. (2019).

5 Risk Reduction and Management in Himalayan Region

People in the region have evolved to cope with the unpredictability of climate change, variability, and extremes by modifying their livelihoods, agricultural techniques, and cultural traditions; they have even endured great loss. Despite the fact that cultural norms influence people's adaptation options, new vocations and livelihood practices that are socially and culturally undesirable have emerged in response to climate-related changes and stress in some circumstances. Enhancing adaptive capacities for collective water management, equitable distribution of irrigation facilities, livestock management, communal grazing, and development of infrastructure for flood management and water security requires social networks and local institutional support with good governance and planning (Hua, 2009). The following are a few steps that can be initiated to reduce the risk and damage caused due to climate-induced and geological disasters.

5.1 Understanding Risk

The impact of climate change induced and geological disaster at the Himalaya region is not well understood to predict the full-scale downstream impact. Hence, in-depth studies of snow, glaciers, landslides, earthquakes, floods, snow avalanches, and drought need to be carried out in the vulnerable region. There lacks a baseline study for most of the areas especially in regions greater than 4000 meters above mean sea level (masl), and very few long-term monitoring studies of climate variables have been conducted (Liu & Chen, 2000; Rees & Collins, 2006). Furthermore, the complexity due to its topography is one common feature for all mountain areas, and hence, the precipitation and temperature vary for every short distance eventually making the projection studies difficult. Hence, understanding the risk through forecasting and modeling studies is vital to reduce the risk and managing them in Himalayan region. In addition, the link between climate change, geological disasters, and built environment is multifaceted and hence has to be understood through an interdisciplinary perspective (Nibanupudi & Shaw, 2015).

In order to build adaptation and mitigation strategies, up to date scientific data on climatic parameters and their implications should be collected in a systematic way in partnership with government agencies, academia, and local-level partners. By exchanging data across partner nations in the area, data banks may be maintained up to date. In this method, regional climatic models may be built to better understand the climate process. The initial step in developing successful adaptation strategies should be to create a list of acceptable factors and analyze them. For fast risk evaluations of development projects, a mechanism for screening climate threats should be developed. The program should be able to determine if expected climatic changes will increase or decrease hazards, allowing planners to make informed decisions. This is especially true in case of hydropower projects, which have a lot of potential in mountainous nations and may help with national development. Choosing the right type of hydropower project (run-of-river or storage) is an important step toward ensuring the long-term viability of hydropower projects. Other water storage solutions (ponds, lakes, and aquifer recharges) should be selected based on geographical regions and implemented based on hydrological, geological, and climatic criteria (Tse-ring et al., 2010).

Furthermore, knowledge regarding the risk's potential and its communication, which includes a solution and direction to risk discourse, may help to successfully mitigate catastrophic adversity. Mountain is riskier due to its unique characteristics and proclivity to several risks. As a result, landscape-level complexity evaluation is valuable for a range of practical applications and policy planners (Papadimitriou, 2012). The risk assessment would educate on the potentiality of catastrophe risk based on the system under consideration (Das et al., 2018) as well as develop future dialogue to mitigate the potential danger. The risk assessment takes into account the system's adaptive capacity and sensitivity and may thus be used to improve the inherent and external features that are causing the system to deteriorate (Sekhri et al., 2020; IPCC, 2021).

Due to their nature and methodology, risk assessment and discourse frameworks for multi-hazards are unique (Gill & Malamud, 2016). In the mountains, particularly in the Himalaya, a lack of a consistent strategy to risk management limits the integration of risk assessments (Wester et al., 2019). The existing gap was widened by the lack of uniform and varied risk assessments, which hampered the vulnerable region's comprehensive mountain-specific development. Danger discourse would be guided by two simultaneous techniques based on actual evidence of possible risk analyzed from risk information and assessment. These two action-based solutions would make it easier to cope with risk and give options for mitigation if the risk is greater than the coping capacity. The study includes a coping capacity component in the risk assessment formulation, making it possible to give metrics to comprehend various aspects of risk. As a result, the coping capacity may be changed to offset the weaknesses of the system's exposed units based on the probable risk during a crisis. Furthermore, the mitigation plan must be integrated with the coping strategy, which includes preventative and inbuilt remedial action based on local resources and tactics, as well as lessons learnt from previous catastrophes.

5.2 *Mountain Specific Risk Management Framework (MSMRMF)*

The Mountain Specific Risk Management Framework (MSMRMF) is a tool for analyzing risk reduction methods by altering the system's internal strength and risk mitigation capability, as well as recommending feasible adaptation techniques based on multi-hazard risk. The MSMRMF is divided into two parts and is based on a multidisciplinary approach. The first component, termed as "risk information," is to qualify and create information on the system's risk. The second component of risk is known as "risk discourse," and it deals with addressing and mitigating the risk. Risk information includes components of hazard, climate exposure, and susceptibility, and it aids risk assessment of the mountain region's multi-hazards. The methods section has further information on each component. Risk information is used to manage and mitigate system risk, as well as to steer risk discourse, which leads to an explanation of how to address the risk (Sekhri et al., 2020). Hence it is imperative to identify risk drivers (Cardona & Dario, 2009) in the context of spatially explicit hazards, developing proactive measures (UNISDR, 2017), managing risk measures (Azadi et al., 2020) through various individual, community, and institutional supports (UNISDR, 2017), and finally confronting multi-hazard risks with all physiological, psychological, natural, and social hazards (Twigg, 2004; UNISDR, 2017).

5.3 *Reducing Risk and Increasing Resilience to Disasters*

Resilience demonstrates the ability to adapt, alter, and recognize the existence of change (Folke, 2006). Furthermore, the capacity of a system to resist change, preserve structure, demonstrate consistency, and facilitate strength to persevere through adversity without affecting the system's overall welfare is referred to as resilience (Pachauri et al., 2014). Due to the availability of space and expansion potential, mountains containing smaller towns have a higher capability to adapt and enhance resilience than many major metropolitan centers (Sakai et al., 2019). Communities with well-planned infrastructure, well-formulated emergency responses, a healthy population, hereditary and taught skill sets, and greater literacy rates are more resilient (Hatai & Sen, 2008). Moreover, communities from the Himalayan region's traditional wisdom aid in improving community resilience (Wester et al., 2019). Local community members' participation in developmental initiatives may put forth concepts and ideas based on a community's livelihood, observations, viewpoints, and wants (Ahmed et al., 2019), as well as provide locals more authority to interact with development. Additionally, the method would help to improve resilience and would be in line with disaster risk reduction (DRR) (Ahmed et al., 2019) and community-driven development (Ahmed et al., 2019). (CDD).

The basic goal of adaptation techniques for wildlife and habitat protection is to maintain ecosystem resilience (IPCC, 2021). Ecosystems will be better able to withstand anthropogenic environmental pressures, such as climate change, if they retain biological variety, decrease habitat fragmentation and degradation, and promote functional connectedness across habitat fragments. Reducing or eliminating current pressures is an excellent technique for doing this. Ecosystem adaptation alternatives, on the other hand, are limited, and their efficacy is unknown. Climate change-specific measures are unlikely to be extensively implemented sufficiently to safeguard the variety of ecological services on which civilizations rely. Fortunately, minimizing the negative effects of non-climate pressures on ecosystem would also protect ecosystem against climate change's negative consequences.

5.4 Adaptation Strategies

Adaptation to climate-induced and geological disasters is related to both vulnerability and potential impacts in the near future. Effective adaptation includes the formation of adaptive capacity (knowledge, awareness, and governance) and adaptation (changing the lifestyle, practices, and behavior according to the new conditions) (Mirza, 2007). Various factors like scale (local, regional, or national), context (management of water demand and new farming practices), and approach (poverty alleviation, better transparency in decision-making, women empowerment) strongly influence the adaptation strategies. One of the prime factors that makes adaptation strategy difficult for poor people is the structural inequality. Hence, measures have to be taken in moving all the people out of poverty and must enhance the capacity to adopt. Other adaptation measures include good governance to transform the climate change into institutional, general political, and developmental reforms, health education programs, and advancement in early warning systems.

5.5 Decision-Making

The vision of national and global institution guides the bulk of the catastrophe response strategy. The Sendai Disaster Framework 2015–2030 of the UNDP, the Resilient Development Framework of USAID, and Nepal's NAPA, for example, continue to be an important driver of local activities. While each framework emphasizes stakeholder interaction, the process begins with the frameworks' pre-defined corporate objectives. As a result, external institutions remain in charge of the planning process that forms the entire risk reduction arena. Hence, although local institutions frequently determine priority, external institutional rules determine the knowledge acquired and the methods for execution. Furthermore, the NGOs may cause problems when it comes to developing long-term, sustainable decision-making procedures for disaster risk reduction. Rounce et al. (2017) observed multiple situations in which government engagement in program management was reduced as a result of the existence of NGO programs (Thompson et al., 2020).

5.6 Sustainable Development Goal

The increased intensity and frequency of disasters in Himalayan regions is in one way due to high population density and increasing developmental activities. Several unsustainable constructions due to increased tourism have replaced the farmlands and forests, thereby violating the laws. Though tourism is one of the prime revenues in these regions, the importance of agriculture and agro-based industries should not be overlooked. In this regard, there is an urge in integrating the DRR with sustainable development goals. Models, land zonation maps demarcating the regions prone to geological disasters, and hazard scenarios have to be developed. Human habitation must be confined to safe zones; the mitigation plan should have a balance between the acceptable and development level of risk (Singh et al., 2021a, b, c). The key principles in the Himalayan regions for sustainable development are as follows:

- Building of a sustainable and viable forest-based economy.
- The approaches for water development must balance the threat to living being and the choice for energy.
- Enhanced early warning system and immediate response of local communities to disasters.
- Enhanced access to emergency evacuation, shelter, and protection against disasters.
- Strengthening the disaster risk management (DRM).
- The energy requirement for the remote villages must be secured.

5.7 Risk Reduction by Technological Advancement

Deeper human causes and impacts of catastrophes, such as inequality and poverty, which define the exposed and impacted entities owing to risks, are not usually addressed by technological answers. This implies the need to enhance effective links between research, technology, and decision-makers in order to develop long-term technological catastrophe risk reduction solutions (Busayo et al., 2020). People-centered technology may aid in effectively combating several risks in the society (Huang et al., 2017). The use of technology to collect data directly from the impacted population gives clear proof for damage estimates and makes catastrophe risk mitigation easier (Sakurai & Murayama, 2019). To reduce the effect of dangers, pre-disaster monitoring systems, such as early warning systems, can be built (Gupta, 2018). For example, the application of sensors and artificial intelligence for the detection of water levels in a river to assess rising water levels demarcates the pre-disaster technological advancements and can be used to generate timely warnings (Gupta, 2018). In a multi-hazard environment like the Himalayan region, effective technology for early warning systems for multi-hazard hazards, like cloud burst, strong rains, and landslides, might be created and used for disaster response planning (Wester et al., 2019). Overall, need-based disaster technology, including indigenous and traditional techniques in terms of early warnings, catastrophe facilitation through communication, and other necessary resources, would be highly effective in combating the damage caused due to these climate-induced and geological disasters. The various risk reduction techniques that can be adopted for Himalayan region are given in Fig. 16.3.

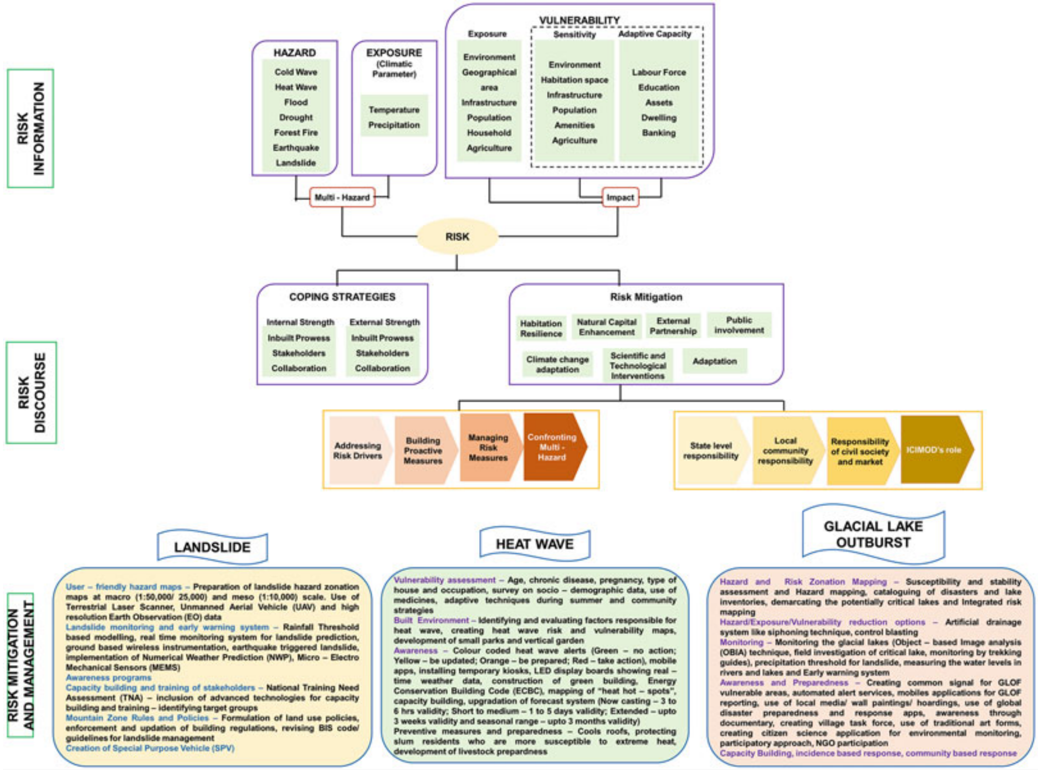

Fig. 16.3 Risk reduction strategies for Himalayan regions

5.8 Policies to Reduce Risk

Since certain disasters have worldwide implications, mitigating the risks associated with such extreme hazards necessitates intergovernmental collaboration. Human health, water supply and sanitation, energy, transportation, industry, mining, construction, commerce and tourism, agriculture, forestry, fisheries, environmental protection, and disaster management are the primary development sectors that are directly impacted by climate change (World Bank, 2006). Government and non-government organizations should work together to safeguard the ecosystem in the mountains and uplands as well as assist local inhabitants in adapting to changing ecological, economic, and health-related consequences. Policies should also seek to persuade important global players, such as the World Trade Organization (WTO), to include mountain concerns in future trade agreements and commercial practices. Governments in the nations have chosen the approach of recognizing the negative effects of climate change and severe events on future development and incorporating this understanding into policy and strategy papers. Adaptation actions should be woven into current development plans (Alam & Regmi, 2004). Different stakeholders, such as government policymakers, implementing agencies, development partners, the commercial sector, and communities, must participate and cooperate. Policies should incorporate adaptation actions into sectoral activities: policies, initiatives, and strategies used to deal with the effects of hazards should be changed to reflect the combined effects of climate change.

6 Conclusion

The Intergovernmental Panel on Climate Change (IPCC) referred to the Himalayan area as a "white spot" in the context of climate change, stressing the paucity of data. However, in the last 5 years or so, data gaps have begun to close. According to recent statistics, the Himalayas are expected to warm faster than the world average, with extreme temperature rise forecast in some areas. Glaciers are expected to continue to lose mass, and exceptional events are anticipated to grow more violent, if not more often. Drought during the premonsoon season may worsen, affecting key processes, such as spring flow, seed germination of important tree species, forest fires, and tourism. Some initiatives that directly benefit local people may result in favorable changes in forest carbon sequestration and biodiversity. Unless they occur in a densely populated region and result in the loss of life and property, all dangers are not catastrophes. Hazards, on the other hand, are only declared catastrophes when they devastate the landscape, kill people, and cause damage to residential areas, industry, and agricultural land. The Uttarakhand catastrophe was exacerbated by the building of villages along streams and large rivers, which were discovered to be the sites of the majority of victims. Many towns and villages are built on debris deposition of floodplains. The pilgrimage to Kedarnath and Srinagar town are two classic examples. The most susceptible regions are the growing number of hotels, guest houses, and towns along the routes leading to the pilgrimage centers. The quality of the landscape and the construction of dwellings may have a significant impact on settlement safety. The building of communities near the riverbank should be discouraged. The necessity of the hour is for a holistic strategy to reduce the number of people killed or injured as a result of natural disasters. People in the community and the government should come out and collaborate. In the context of climate change and mountain specificities, solid science based on credible, salient, and authentic knowledge may frequently lead to appropriate policy, and vice versa. For poverty reduction and long-term development, reducing the hazards of catastrophic calamities is critical. Hydrometeorological data must be shared in a regional trans-boundary, upstream-downstream context in order to build effective early warning systems and catastrophe preparedness.

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