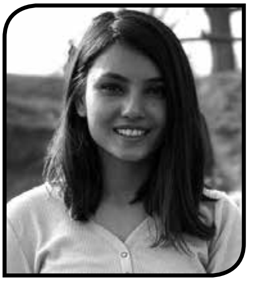
Glacial Hazards and Avalanches in High Mountains of Nepal Himalaya

Sudeep Thakuri, PhD*
Associate Professor, Central Department of Environmental Science, Tribhuvan University
**Corresponding author's e-mail: sthakuri@cdes.edu.np*
Raju Chauhan
Visiting Faculty, Central Department of Environmental Science, Tribhuvan University
Preshika Baskota
Research Asst., Central Department of Environmental Science, Tribhuvan University

Abstract





This paper provides a comprehensive overview of the glacial hazards (GHs) and reflects the situations in the Nepal Himalaya. We discuss on the different GHs with focus on the avalanches (snow, ice, and rock), presenting a nation-wide database on avalanches compiled from literature. We also share the relevant policies in the GHs and lays groundwork for future research on the high-altitude hazards. GHs are prone to high mountains of Nepal, yet it is startling that the area has received the least priority. Almost every year, human casualties and property losses reported due to various disastrous events in the country. We documented 60 avalanche events since the 1920s across the country, ensuing the loss of more than 370 human lives. Almost all high-altitude regions of Nepal are prone to avalanches. Number of avalanche events and casualties were the highest in the Khumbu region of Nepal. In recent years, the avalanche records and casualties are also expanding in other parts of the country, most likely due to increased human activities at high altitude regions and documentation. It is inevitable to analyze the hazards prevalent in the mountains to ensure safe and secure livelihood, trekking, and mountaineering activities. We also underline the urgent research priorities to provide a more systematic understanding of GHs in Nepal.

Keywords: *Mountain Hazards, Avalanche, Snowstorm, GLOFs, Rock fall*

Introduction

Mountains across the globe have been the most interesting places for the trekking and mountaineering adventure tourism (Thakuri & Koirala, 2019; Mu & Nepal, 2016). Further, most mountains serve as the important sources of water as they store water in the form of snow and ice and supply water downstream during the dry periods, but the traveler and mountain dwellers are usually unsafe and insecure due to various mountain hazards. Mountains present varieties of hazards (Table 1), including glacial hazards. Unlike low lying plain areas, various mountain hazards can be observed in the Nepal Himalaya. The possible mountain hazards are (a) swollen river/increased discharge/river flow – high water levels, (b) avalanches, (c) serac collapse, (d) landslides – downslope movement, (e) debris flow, (f) rock falls, (g) crevasses, (h) extreme weather/storm, (i) high altitude sickness (Acute mountain sickness, High-altitude pulmonary Oedema, High-altitude cerebral oedema); and (j) snow cornices (Corona & Stoffel, 2016; Gruber & Haeberli, 2007; Zingari & Fiebiger, 2002; Richardson & Reynolds, 2000).

The GHs are the processes related to mountain glaciers, ice caps, or ice sheets that threaten lives and properties. High mountains are particularly prone to GHs related to snow, ice and permafrost as these elements exert key controls on mountain slope stability. Two main types of GHs can be observed in high mountains: (1) direct action of ice and/ or snow; this includes events such as avalanches of ice, and snow, glacier outburst floods and glacier advances, and permafrost hazards, and (2) indirect GHs that arise as a secondary consequence of a glacial feature or process and may include catastrophic breaching of moraine dammed lakes, rock avalanche etc. (Hewitt, 2002 & 2009; Richardson & Reynolds, 2000; Bell et al., 1990). The GHs have a direct connection and consequences for human society as they can impact on infrastructure, hydropower, agriculture, and tourism through the loss of lives and properties. Further, these hazards are the potential threats for the mountaineering activities that can destroy the infrastructures, trekking trails, and result in the demise of mountain climbers (Thakuri & Koirala, 2019; McClung, 2016; Mu & Nepal, 2016).

Table 1: Loss of lives in the country by disasters in the last decade (2011-2019) (MoHA, 2020)

Types of Hazards	2011	2012	2013	2014	2015	2016	2017	2018	2019
Avalanche		9	8	16	23		1		8
Cold Wave	41	25	2				1	47	
Earthquake	6	1	0		8962				
Epidemic	9	33	4	12	3	19	10	5	
Fire	25	77	59	67	75	63	63	87	77
Flood	126	52	131	129	0	101	166	17	73
Landslide	110	60	87	113	138	148	70	91	86
Storm (Snow, Wind, Hailstorm)	6	18	3	43	12	2	5	24	42
Thunderbolt	76	118	147	97	103	118	85	75	94
Total	**399**	**393**	**441**	**477**	**9316**	**451**	**401**	**346**	**380**

In this paper, we present different glacial hazards with focus on the avalanches (snow, ice, and rock), We also share the relevant policies in the GHs and lays groundwork for future research on the high-altitude hazards. The paper is based on the analysis of the existing data and published literatures. Data on avalanche hazards were collected from different sources, graphically presented, and documented. Literatures were searched by using some key words, like "glacial hazards", "avalanche", "disaster", "glaciers", and high-altitude. In this study, literatures published (journal articles, conference proceedings, abstracts, thesis, project reports) up to the end of February 2020 are incorporated.

Glacial hazards

Avalanche hazards

As the peaks of northern part of the country are covered with ice/snow, avalanches are very common in Nepal and claim the life of human and loss of properties (McClung, 2016). An avalanche is a massive slide of snow, ice, rock or debris down a mountainside, caused by the released build-up of snow (Park & Reisinger, 2010) and thus, can appear as a) snow, b) rock, c) ice avalanches, or d) mix of any of these. It is typically caused when material on a slope breaks loose from its surroundings which then quickly collects and carries additional material down the slope. Various kinds of avalanches exist in the mountains, including rock avalanches (which consist of large segments of shattered rock; Deline et al., 2015; Hewitt, 2002 & 2009), ice avalanches (which typically occur in the vicinity of a glacier), and debris avalanches (which contain a variety of unconsolidated materials, such as loose stones and soil) (Birkeland, 2018). Avalanche usually occurs when stress from the pull of gravity and/or applied load exceeds the strength of the snow cover. Although avalanches can occur on any slope given the right conditions, certain times of the year and certain locations are naturally more dangerous than others. Wintertime, particularly from December to April, is when most avalanches tend to happen (NSIDC, 2019). About 90% of all avalanches begin on slopes of 30-45°, and about 98% occur on slopes of 25-50°. Avalanches strike most often on slopes above timberline that face away from prevailing winds (leeward slopes tend to collect snow blowing from the windward sides of ridges).

Landslides and snow avalanches cause major disasters on a global scale every year, and the frequency of their occurrence seems to be on the rise (Nadim et al., 2006). The main reasons for the observed increase in landslide disasters are a greater susceptibility of surface soil to instability and greater vulnerability of the exposed population. Furthermore, traditionally uninhabited areas such as mountains are increasingly used for recreational and transportation purposes, pushing the borders further into hazardous terrain (Nadim et al., 2006). Snow avalanches represent a significant natural hazard to infrastructure and residents in high mountain regions of the world (Brundl et al., 2004; cited in Laxton & Smith, 2009). Tourism destinations are easily impacted by a variety of natural disasters which cause serious damage to the visited regions (Murphy & Bayley, 1989; cited in Park & Reisinger, 2010). The occurrence of natural disasters leads to a decrease in the tourists' arrivals (Park & Reisinger, 2010).

GLOF hazards

ICIMOD (2011) reported 24 glacial lake outburst flood (GLOFs) in Nepal. Further, some other GLOFs events (e.g., Figure 1) have been reported until 2018 from different parts of Nepal (Thakuri & Koirala, 2019). About 28 GLOF events have already been experienced in the Nepal Himalaya causing the loss of lives and properties, originating from the outburst of lakes located in Nepal and the Tibetan part of China.

Many glacial lakes are emerging as potentially dangerous once due to enlargement from the combination of small lakes and melting of the glacier ice (Khadka et al., 2018; Salerno et al., 2016). Even the Tsho Rolpa Glacial Lake located in the eastern Nepal (Figure 2), which was lowered by 3 m water level in 2000 for preventing from the outburst (Rana et al., 2000), is recently emerging as the most dangerous lake threatening downstream population. The lake was 149 hectares in 2000 just after the lake lowering activity, while in 2018; the lake surface area has increased to 160 hectares (increased by about +7%). This lake is prone to frontal

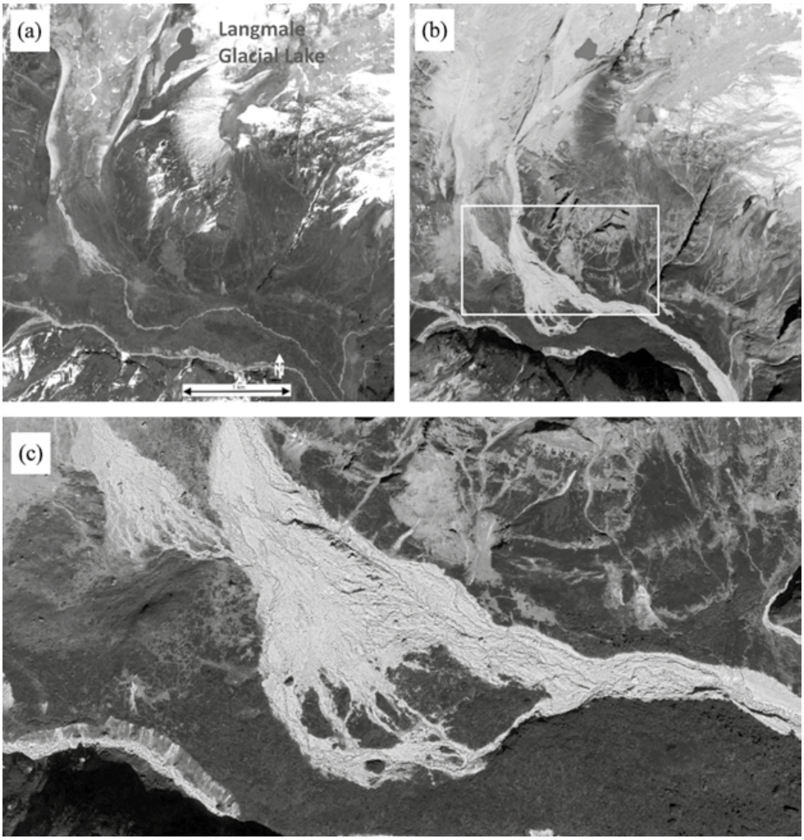


Figure 1: *Comparison of satellite imagery before (a) and after (b) the glacial lake outburst flood of the Langmale Glacial Lake in the Barun valley of the eastern Nepal. A focused outwash plain with sediment deposits from the April 20, 2017 GLOFs (Byer et al., 2018) is shown in (c) (Source: GoogleEarth, 2020).*

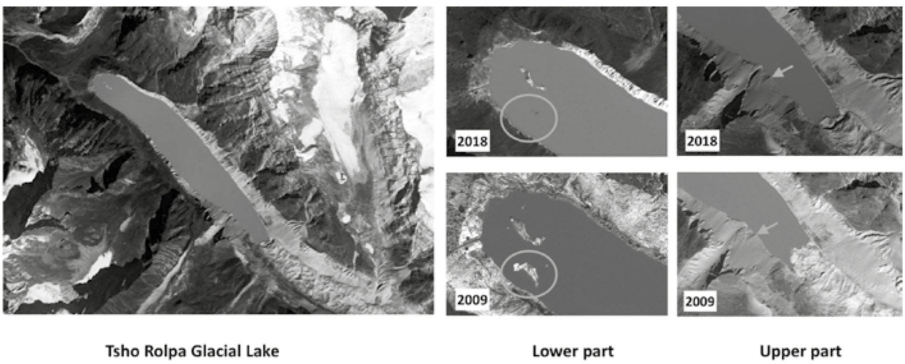


Figure 2: *(a) Tsho Rolpa Glacial Lake, b) Comparison of lower part of the lake, showing that the lake elevation has increased in recent year. Small permanent islands in the middle of the lake are submerged under the water, and c) The lake is expanding toward the northeast by melting the glacier ice (Source: GoogleEarth, 2020).*

moraine dam break. This glacial lake is connected to the glacier ice on one side (eastward). The lake can increase in the size (towards – southeast) further more by melting the glacier ice.

Permafrost hazards

The permafrost is a ground (soil or rock, and included ice and organic material) that remains at or below 0 °C for at least two consecutive years (Van Everdingen, 1998). It is, therefore, called as a permanently frozen ground and is defined exclusively on the basis of temperature irrespective of texture, degree of induration, water content or lithological characteristics. Since permafrost is a thermal state, the determination of the energy balance to the ground is very important for its modelling and prediction of future changes (Chauhan & Thakuri, 2017; Arenson, 2002). Several factors and effects have a major influence on the thermal regime in the ground. Perennially frozen ground is very sensitive to climate change. Due to the retarded response of permafrost to cycles of air temperature, permafrost temperatures have been used to examine past climate changes. Climate change may result in new different ground freezing conditions, thereby influencing the surface velocity and the maximum depth of solifluction processes (Gruber & Haeberli, 2007).

Permafrost hazards relate to infrastructure that is partly or entirely placed in the vicinity or on top of the permafrost- and glacier-affected frozen rock masses or debris. Changes in permafrost and glacier dynamics may derive from atmospheric warming, but as well from human-environment interaction (Gruber & Haeberli, 2007). Mountain infrastructure can be negatively affected by ground-ice degradation induced by the combined effects of construction activity, the structure itself and climate change (Bommer et al., 2010). A widespread loss of permafrost will trigger erosion or subsidence of ice-rich landscapes and in addition, the thawing will have a severe impact on infrastructure due to excessive settlements and exploration, and will result in rapid coastal erosion (Arenson, 2002).

Snow, ice and rock avalanche: Splendid mountains turn into dangerous places

More than 60 avalanches tolling 372 persons death since 1922 has been reported from the

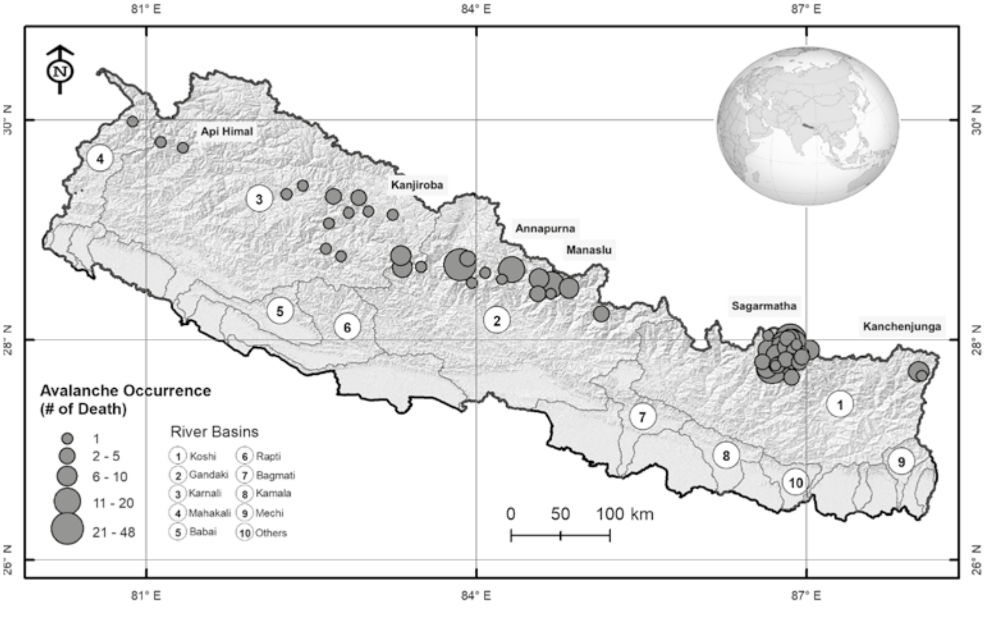


Figure 3: *Avalanches recorded in Nepal Himalaya from 1922 to 2020: Showing avalanche prone areas based on the previous avalanche records (Table 2). The Everest region is the most disastrous place for avalanches.*

Nepal Himalaya (Figure 3 & Table 2). Almost all the high-altitude regions of Nepal are prone to avalanches (Figure 3). The avalanche records since 1922 show that the number of casualties and the avalanche events are the highest in the Khumbu region compared to other parts of Nepal (Figure 3 & 4). In recent years, the records and the casualties are expanding in other parts of the country which might be due to increased human (tourism) activities and the recording system.

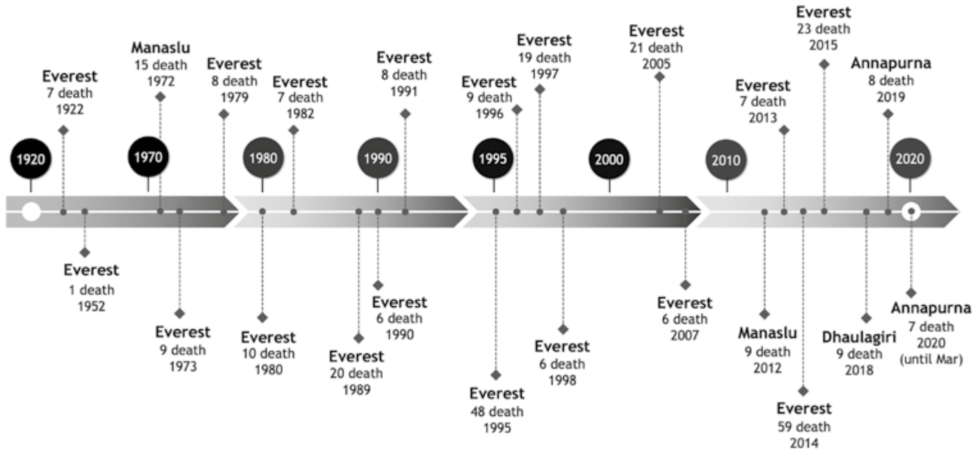


Figure 4: *A historic timeline of the major avalanche events in Nepal Himalaya from 1920 to 2020, developed based on different data sources (For further details, referred to Table 2)*

Avalanche in Mt. Everest (2014 and 2015) and Langtang valley (2015)

The 18 April 2014 avalanche was the second deadliest disaster in the history of Mt. Everest (8848 m) in Nepal, after the avalanches that struck the southern side of the mountain following year on 25 April, 2015, which were triggered by an earthquake of magnitude 7.8 in Nepal Figure 5; McClung, 2016). An avalanche occurred in the early morning towards the southern side of Mt. Everest at an elevation of approximately 5800 m, near Everest Base Camp (ABC). Within the Khumbu Icefall, on the route between camp I and camp II, this was the disastrous avalanche that killed 16 men, mostly the Sherpa guides.

Figure 5: *Tragedy in the Himalaya: An ice-snow avalanche originating from the steep slope of Mt Everest hit the Khumbu ice fall and Everest base camp in 2014 (Source: B.B Rai/AFP/Getty Images).*

On 25 April 2015, a series of avalanches triggered by the earthquake of magnitude 7.8 in Nepal. Climbers at the base camp of the Mt Everest and others on the higher elevations were trapped during the disaster (McClung, 2016). At least 23 people were killed and 61 injured. The avalanche began in the late morning on Mount Pumori (7,161 m), a mountain just a few kilometers west of the Everest, gathering strength as it headed toward the base camp, where climbing expeditions were preparing to make their way to the summit. Furthermore, the earthquake triggered avalanches, landslide, and rock falls in the Langtang valley which caused the loss of more than 350 people's lives and destroyed the village of Langtang (Fujita et al., 2017; Kargel et al., 2016). These casualties are categorized under the Earthquake hazards since it was difficult to discern the direct cause of the avalanches (Table 1) and excluded in Figure 3 and 4.

Avalanche in Annapurna circuit 2014

On 14 October 2014 a snowstorm and series of avalanches occurred on and around Annapurna and Dhaulagiri in the Manang and Mustang Districts of Nepal. Injuries and fatalities resulted in the deaths of at least 43 people of various nationalities, including at least 21 trekkers. The storm arose from the Cyclone Hudhud (NDMA, 2015) and was the worst in a decade with almost 1.8 m of snowfall within 12 hours.

Figure 6: *Steep mountain slopes are the potential source of the rock/ice avalanche. (Source: S. Thakuri, 2014)*

Table 2: Avalanches occurred in the Nepal Himalaya and human casualties due to avalanche and snowstorm for the year 1922 to February 2020. The years 1995, 2014, and 2015 are the top three years with more deaths due to avalanche and snowstorms. The data is compiled from different literatures.

Year	Incident	Incident description	Total death
1922	Avalanche	British Mount Everest Expedition	7
1952	Avalanche	Swiss expedition, Lhotse Face	1
1970	Avalanche	Ice-fall avalanche in the Khumbu Icefall, during production of "The Man Who Skied Down Everest" between Base Camp and Camp I	6
1972	Avalanche/Snowstorm	South Korean Mountaineering Expedition, Nepalease Sherpa, Koreans and Japanese killed at the 26,658 feet of Mt. Manaslu	15
1973	Avalanche/Snowstorm	S.W. Face	9
1974	Avalanche	French expedition from the West Ridge to Mt. Everest	6
1977	Avalanche	Sisne Himal	1
1978	Avalanche/Snowstorm	Khumbu Icefall	7
1979	Avalanche/Snowstorm	Below North Col, Japanese Alpine Club reconnaissance expedition	8
1980	Avalanche/Snowstorm	7900 m North Face	10
1981	Avalanche/Snowstorm	6900 m W. Cwm	4
1982	Avalanche/Snowstorm	Khumbu Icefall	7
1984	Avalanche	Ice-fall avalanche in the Khumbu Icefall	3
1987	Avalanche/Snowstorm	Everest basecamp	2
1988	Avalanche	Climbers' camp at 23,625 feet towards Mt. Everest	2
1989	Avalanche/Snowstorm	Polish Climbers on Mt. Everest on a 7200 m W. ridge; and Spanish climbers in Mt. Pumori while traversing Mt Pumori's exposed slopes	20
1990	Avalanche/Snowstorm	Everest region	6
1991	Avalanche/Snowstorm	Everest region	8
1992	Avalanche/Snowstorm	Khumbu region	2
1994	Avalanche/Snowstorm	Everest region	2
1995	Avalanche/Snowstorm	Intense snowfall generated numerous avalanches throughout the Khumbu region Near Mt. Kanchenjunga base camp	48
1996	Avalanche/Snowstorm	Mount Everest during attempts to descend from the summit, at Lhotse face	9
1997	Avalanche/Snowstorm	Everest region, Everest	19

1998	Avalanche/Snowstorm	Everest region, Everest	6
1999	Avalanche/Snowstorm	Everest region, Everest; Chunchet, Gorkha	6
2005	Avalanche/Snowstorm	Powder-snow avalanche, induced by several hours of heavy snowfall, plowed into a French expedition’s base camp	21
2006	Avalanche	Due to a massive serac (ice fall) collapsing at the Khumbu icefall on Mt Everest	3
2007	Avalanche/Snowstorm	Everest region, Everest	6
2009	Avalanche	Khumbu Icefall	2
2010	Avalanche	Big avalanche swept away a leading Sherpa along with his guide, in windy conditions fixing ropes near the summit of Mount Baruntse	2
2012	Avalanche	Avalanche hit camp three of the Manaslu peak, resulting in a flood of snow	9
2013	Avalanche	Everest region, Everest	8
2014	Avalanche/Snowstorm	Snowstorm and series of avalanches occurred on and around Annapurna and Dhaulagiri in the Manang and Mustang districts; Seracs on the western spur of Mount Everest failed, resulting in an ice avalanche	59
2015	Avalanche/Snowstorm	Shaking from the 25 April 2015 earthquake triggered an avalanche from Pumori into Base Camp on Mount Everest	23
2017	Avalanche	11-year-old boy went missing in an avalanche at Chorkhola area in Kaike village council, Dolpa while they were going to their animal sheds in Chormara Lek	1
2018	Avalanche/Snowstorm	Heavy snowstorm followed by landslide buried the base camp of Mt. Gurja at 3,500 m on the lap of the south face of Mt Dhaulagiri	9
2019	Avalanche	Avalanche at Annapurna trekking route in Nesyang Rural Municipality of Manang district; Dolpa; Dhading	8
2020 until Mar	Avalanche	Avalanche struck the famous Mount Annapurna circuit climbing route (3230 m) after heavy rains and snow	7

Storms and avalanches of Khumbu and Kanchenjunga Himal (1995)

On November 9 and 10, 1995, a severe storm hit the Nepal Himalaya, triggering several snow and ice avalanches in different parts of the country. As a result, 24 people were killed in a lodge near the village of Pangkha in the Gokyo Valley (Yamada et al., 1996) and 7 other deaths resulted from an avalanche in the Kanchenjunga area of far eastern Nepal (Kattelmann & Yamada, 1995). This storm was the most intense event to occur during the autumn in the recorded past at least 50 years. The autumn season in the Himalaya tends to be quite dry, so this storm seemed extraordinary. Precipitation gauges at lower elevations caught 50 to 200 mm of rain during the storm. Cold temperatures led to snowfall above 3,500 m in the Khumbu region, and snow depths increased rapidly with elevation. About 30-50 cm of snow fell at 3,800 m; 50-100 cm of snow was found at about 4,000 m; and 100-200 cm of snow was deposited above 5,000 m. The intense snowfall generated numerous avalanches throughout the region.

The aforementioned three events are the largest reported storms and avalanches events in Nepal. The events not only hampered the tourism industry of Nepal, but also directly affected the life of the people who were employed only because of tourism.

Triggers and avalanche risks in high mountains

Triggering factors

Avalanches are triggered by either natural forces (e.g., precipitation, wind drifting snow, rapid temperature changes) or human activities. Overloading of snow on the slope, shearing and bonding of snow molecules, vibrations resulting from sound, skiing, earthquake, construction, and explosive blasts etc. trigger the avalanches. According to Schweizer (2003), the triggering of an avalanche can occur as a result of (i) localized rapid near-surface loading by, for example, people or explosives (the latter being called artificial triggering), (ii) gradual uniform loading due to precipitation or other factors, or (iii) a no-loading situation that changes snowpack properties, for example, surface warming (called natural triggering or spontaneous release).

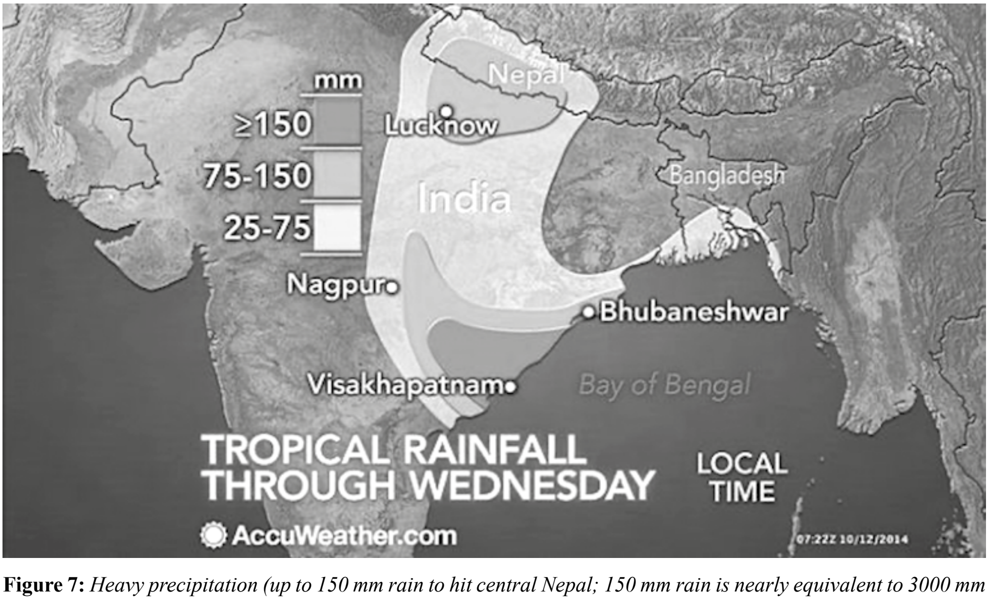


Figure 7: *Heavy precipitation (up to 150 mm rain to hit central Nepal; 150 mm rain is nearly equivalent to 3000 mm snow) was predicted in Nepal during the tropical Cyclone Hudhud, begun to form on 6 October 2014 and dissipated on 14 October 2014 (NDMA, 2015) triggered heavy snowstorm in the Annapurna region, killing at least 43 persons (Source: AccuWeather.com).*

Complex interactions between the terrain, snowpack, and meteorological conditions lead to avalanche process. The only constant factors for the snow avalanche are the terrain characteristics and slope with an inclination greater than 30° (Corona & Stoffel, 2016). Terrain roughness also influences avalanche formation by hindering the formation of continuous, weak snowpack layers (Schweizer, 2003). The day to day stability of snowpack is also influenced by the orientation of the slopes with respect to the sun and dominant winds. Most of the factors contributing to snow avalanching are related either to the strength or to the load of snow and its variation over time. In addition to terrain, four essential factors leading to the release of snow avalanches are precipitation (snowfall), wind, temperature, and snowpack stratigraphy (Corona & Stoffel, 2016; Schweizer, 2003). Being the phenomena controlled by climate, snow and ice avalanches are not only expected to be affected by changes in atmospheric conditions, but also by climatic change.

A rock avalanche, sometimes referred to as sturzstrom, is a type of large and fast-moving landslide (Deline et al., 2015). Occurrences of rock avalanches are affected by several factors such as (i) inherent factors (e.g., rock structure, slope form), (ii) preparatory factors (e.g., weathering, climate change), (iii) triggering factors (e.g., earthquake, rainstorm) (Weidinger et al., 2002), and (iv) factors that may affect mobility (e.g., glacier surface) (Pacione, 1999). Permafrost thaw could also trigger the rock avalanche as the freeze-thaw action is condition by the temperature fluctuations and volumetric expansion of ice on the slope generally widens existing fractures and prepares for rock failure (Gruber & Haeberli, 2007). Climate change and more extreme weather conditions may also be contributing factors. Earthquakes often trigger avalanches, rock falls and tsunamis (Fujita et al., 2016; Park & Reisinger, 2010). Observations indicate that most natural avalanches are triggered by heavy snowfall (Conway & Wilbour, 1999; Hirashima et al., 2008), a sharp rise in temperature or rainfall (Baggi & Schweizer, 2009; Gauthier et al., 2017) as well as earthquakes (Podolskiy et al., 2010; Pérez-Guillén, et al., 2014; cited in Hao et al., 2018). The 2015 earthquake triggered avalanches in the Mount Everest region and in the Langtang Valley flattened the villages and people were made homeless within less than a minute (Kunwar & Limbu, 2015).

Avalanche risks

Snow, ice, and rock avalanches have frequently been responsible for large disasters in high mountains. Different evidences of avalanche can be observed based on the altitudinal gradient (Zimmermann et al., 1986). Above the snowline, the avalanches occur throughout the year, but especially during and after the summer monsoon. At this region, avalanche can be observed directly. Below the snowline, avalanche occurrences are very rare. Rock avalanche can be observed occasionally at these elevations (Deline et al., 2015).

Nepal is considered as one of the most susceptible countries for the climate risk, according to the Global Climate Risk Index (GCRI), which assesses the impacts of meteorological events in relation to economic losses and human fatalities (Eckstein et al., 2019). The country is in top 20 of all the multi-hazard countries in the world. More than 80% of the population is exposed to the risk of natural hazards (MoHA, 2017), which include water-induced disasters and hydro-meteorological extreme events such as droughts, storms, floods and inundation, landslides, debris flow, soil erosion, avalanches, extreme temperature, and glacier lake outburst floods (GLOFs). The existing mechanisms for developing risk assessments in Nepal are presented in Table 3.

The frequency of avalanches may increase due to the global warming. Nepal Himalaya is experiencing a continuous elevation-dependent warming in the last four decades, i.e., high mountains areas are more rapidly warming compared to the southern lowlands. Maximum air temperature has increased by 0.045 °C/yr and the minimum temperature by 0.009 °C/yr from 1976 to 2015 (Thakuri et al., 2019). Glacial lakes are considered a sensitive indicator of climate change and glacier dynamics (Salerno et al., 2016). In the situation of outburst, glacial lakes can threaten the downstream communities and have significant socio-ecological consequences. The glacial lakes, mostly located above 4000 m elevation, show heterogeneous rates of expansion in different river basins and by elevation zones, with apparent decadal emergences and disappearances in the Nepal Himalaya. In general, both the number and surface areas of the glacial lakes has increased continuously in the last four decades. Overall, the glacial lakes exhibited ~25% expansion of the surface areas in the last three decades (Khadka et al., 2018). A continued expansion of the glacial lakes is posing the risk of GLOFs threatening the downstream population and infrastructure.

Table 3: Existing mechanisms for developing risk assessments in Nepal (Adopted from UNDRR, 2019)

Assessment Mechanism	Method
Nepal Hazard Risk Assessment (NHRA) 2010	Multi-hazard risk map for Nepal, based on description of the available data, hazard assessment and mapping for earthquakes, floods, droughts, landslides and epidemics at the national level.
Urban Risk Atlas (URA) 2013	The URA was developed based on RADIUS tool for risk analysis. The data input includes base maps, major infrastructure, buildings, critical infrastructure, building typologies and number of people at home when the earthquake occurs as basic for casualty estimations (based on day/night cycle).
Vulnerability and Risk Assessment Framework (VRAF) 2017	VRAF describes a conceptual framework for vulnerability and risk assessment, methodological process for conducting VRAF and provides a set of vulnerable and risk indicators to be accounted for in different sectors, i.e. urban settlement & infrastructure, water resources & energy. This supports the measurement of climate risk to determine climate adaptation priorities and devising climate adaptation strategies.

Policies and legal provisions

The Constitution of Nepal (2015) has identified disaster management as one of the key priorities of all tiers of the government (federal, provincial and local) in the list of the concurrent powers of the federal, provincial and local levels. To meet the vision of the Constitution, a comprehensive Disaster Risk Reduction and Management (DRRM) Act (2017) was endorsed by the Nepal government. Later in 2018, the National Policy on Disaster Risk Reduction 2018 and the National Disaster Risk Reduction Strategic Action Plan (2018-2030) were endorsed, to further strengthen the government's initiatives on DRM (MoHA, 2019; Table 4).

The DRRM Act (2017) focuses on the disaster risk reduction as well as management. The act was developed in the federal context of Nepal and makes provision for the formation of National Disaster Management Council, National Disaster Risk Management Authority, Disaster Management Committees at all three tiers of the government and executive committees at federal and provincial levels. Although this act and its regulations have not focused on the hazard specific disaster, it includes both natural and non-natural disaster. It defines 'natural disaster' as the disaster that is caused due to snowfall, hailstorm, avalanche, GLOF, heavy rainfall, drought, flood, landslide and soil erosion, inundation, storm, cold waves, heat waves, lightening, earthquake, volcano, wild fires and other types of hazards.

Therefore, the act is inclusive of the GHs. Similarly, the act makes provision for declaring any area that has been hit by serious natural disaster as the 'Disaster Crisis Zone'. This provision is particularly relevant in the context of high mountain areas which are often hit by large, but unprecedented disasters such as landslides, avalanches and GLOFs.

The National Disaster Risk Reduction Policy (2018) mainly aims at reducing significantly the loss and damage of life and property, human health, livelihood and productive resources, physical and social infrastructures, cultural and environmental heritage from natural and human-caused hazards. The policy is aligned with the priority areas of the Sendai Framework for Disaster Risk Reduction (SFDRR). Among 59 SFDRR polices adopted, some of them are directly related in managing high mountain disaster while others are linked indirectly. The policy has put emphasis on providing disaster management information to the general public and stakeholders by developing disaster management information based on Remote Sensing System, Geographic Information System and Open source Technology. It encourages research on disaster risk, mitigation, preparedness, and capacity building on search and rescue, reconstruction and recovery and therefore envisions establishing National Disaster Risk Reduction Research and Training Academy. Although the word 'avalanche' has not been mentioned anywhere in the policy document, it aims to continuously monitor glacial lakes and other mountain hazards, and develop and implement forecast-based preparedness and response plan. Much emphasis has been given to the development and implementation of well-functioning early warning system, which is the necessity of high mountain hazards such as heavy snowfall, storms, glacial lake outbursts, and avalanches. The policy encourages the development and use of Web-based systems, Mobile Apps, Short Message Service, Interactive Voice Response, Emergency Telecommunication for the communication of early warning information for effective and timely preparedness and response.

Table 4: Nepal's legislative frameworks for disaster risk reduction (Adopted from UNDRR, 2019)

Legislation	Purpose	Scope	Responsible Institution
Natural Calamity Relief) Act, 1982 (Amended in 1989; 1992)	First structured disaster policy of Nepal; Legal instrument focusing on disaster response. The Act gave MoHA the responsibility to oversee overall disaster management activities.	National, districts and municipalities	Ministry of Home Affair
Local Self Governance Act 1999	Delegated administrative power to local authorities on overall local development processes including disaster risk reduction.	Municipalities	Local governance
National Action Plan for Disaster Risk Management 1996	Action plans for pre-disaster and post-disaster phase.	National, districts and municipalities	Ministry of Home Affairs
National Strategy for Disaster Risk Management (NSDRM) 2009	Formulated to set up 29 strategies to transform Nepal's response- focused disaster management approach to a more comprehensive and proactive risk reduction approach.	National	Ministry of Home Affairs

Nepal's New Constitution 2015	Mentions DRM for the first time under Article 51 and has clearly assigned DRM as a concurrent responsibility for all tiers of government.	National, districts and municipalities	Government of Nepal
Disaster Risk Reduction and Management Act (2017)	Replaces the Natural Calamity (Relief) Act 1982. Sees disaster risk management as a process focusing on different stages of the disaster management cycle.	National	Ministry of Home Affairs
Local Government Operation Act, 2017	Outlines the roles and responsibilities of Urban and Rural Municipalities.	Districts and municipalities	Ministry of Home Affairs
National Disaster Risk Reduction Policy 2018 (Nation DRR Policy	Serves as the national framework for disaster risk reduction, aligned with the SFDRR, with the vision: Sustainable Development through DRR actions and climate change adaptation.	National	Ministry of Home Affairs
National Disaster Risk Reduction Strategic Action Plan, 2018 - 2030 (NDRRSAP)	Guides priorities of actions towards the concluding years of SFDRR.	National	Ministry of Home Affairs

The National Disaster Risk Reduction Strategic Action Plan (2018-2030) (NDRRSAP) was formulated based on the learnings and challenges of implementing a National Strategy for Disaster Risk Management (2009) to fulfill the commitments made by Nepal as part of the Sendai Framework for Disaster Risk Reduction (2015-2030). The NDRRSAP has identified 4 priority areas and 18 priority actions to be carried out in the short term (by 2020), medium term (by 2025) and long-term (by 2030) basis for disaster risk reduction and management in Nepal. The four priority areas are (i) understanding the disaster risk, (ii) improving disaster risk governance at federal, provincial and local level, (iii) promoting private and public investment for enhancing disaster risk reduction and resilience based on multi-hazard risk knowledge and (iv) improving preparedness for effective response and recovery and build back better. Under the first priority area, NDRRSAP adopts following strategic activities to understand the underlying risk of high mountain hazards such as avalanche and glacial lake outburst flood:

- Establish a real time snow, glacier, and glacial lake observation system;
- Prediction, mapping and scoping of major glacier, avalanche, GLOF affected areas and making that information publicly available;
- Map out the infrastructures, settlement and population (disaggregated) at risk of glacier, avalanche, GLOF in terms of exposure and vulnerability and disseminate the information for public use;
- Prepare glacier, avalanche, GLOF risk sensitive land use plan and make it publicly accessible;

Under other priority areas, the NDRRSAP has emphasized on promoting preparedness, multi hazard early warning system, community-based disaster risk reduction, risk transfer, and capacity building in search and rescue.

The Local Government Operation Act (2017) has also mandated local governments to take initiatives on DRRM to mainstream in the development, risk reduction and natural resource management. Similarly, the Climate Change Policy of Nepal (2019) aims to reduce the loss of climate-induced disasters to lives and property, health, livelihoods, physical infrastructures and cultural and environmental resources. It aims to enhance and make preparedness and response effective by developing, monitoring, forecasting, and early warning system for disasters including flood, landslide, land erosion, avalanche, drought, lightning, windstorm, heat wave, cold wave, wildfire, fire etc.

The Sendai Framework for Disaster Risk Reduction (2015-2030) is the major international commitments on disaster risk reduction that Nepal has made for managing disaster risk. This was adopted by UN Member States on 18 March 2015 at the Third UN World Conference on Disaster Risk Reduction in Sendai City, Miyagi Prefecture, Japan. The Sendai Framework is the first major agreement of the post-2015 development agenda, with seven targets and four priorities for action. The Framework aims to achieve the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries over the next 15 years.

Concluding remark

GHs are issues of glacier, snow and ice-covered areas (referred as "cryosphere") in the northern part of Nepal. The avalanches are triggered by the human activities, earthquake, heavy precipitation and wind and aggravated by the climate change. Climate change can increase the intensity of the hazards, including the increased number of avalanches, rock falls and landslides in the mountain slopes. Due to resource limitations and difficult working environment, limited information is available on the avalanches in the high mountains of Nepal. Yet the risks from these events are growing in many of mountain areas, due to increased populations, infrastructural developments, utility facilities, and even increasing human activities. There are many policies and legislation that are developed for disaster risk reduction and management. Most of them are focused on multi-hazard risk rather than focusing on a single hazard. The existing provisions regarding the high mountain disaster management are focused on understanding the underlying risk of the mountain hazards, developing effective early warning system, and effective warning communication mechanism, capacity building for search and rescue and enhancing the role of local governments for disaster management.

No legislative provision exists for addressing the hazard specific disasters, e.g., avalanche and the high-altitude GHs in the country, but instead exists overarching act and its regulations for both natural and non-natural disaster in the country. A separate policy for addressing the mountain hazards such as avalanche, flashflood and GLOF is required. At the same time, emergency response plan and operating procedure for search and rescue is of immediate need for the large mountain disaster such as the Khumbu avalanche. The visitors and mountaineers visiting in the high mountains need reliable information about the mountain geo-hazards and their associated risks. Satellite-based hazard assessment is an effective technique for certain hazards, e.g., GLOFs, rock fall etc., however field-based in-situ measurements are necessary in most cases. Hazard maps, monitoring of the rock fall events, permafrost conditions, and early information to the mountaineers can aid to make accurate and timely decision.

Acknowledgements

The disaster database of the Nepal Disaster Risk Reduction Portal of the Government of Nepal was used for the study.

References

Arenson, L. (2002). Unstable alpine permafrost: A potentially important natural hazard. PhD dissertation, Institute for Geotechnical Engineering Technische Wissenschaften ETH, Zurich.vd/f Hochschulverlag, Zurich, Switzerland.

Baggi, S., & Schweizer, J. (2009). Characteristics of wet-snow avalanche activity: 20 years of observations from a high alpine valley (Dischma, Switzerland). *Natural hazards*, 50, 97-108.

Bell, I., Gardner, J., & Scally, F. D. (1990). An estimate of snow avalanche debris transport, Kaghan Valley, Himalaya, Pakistan. *Arctic and Alpine Research*, *22*(3), 317-321.

Birkeland, K. W. (2018, February 14). Retrieved from Encyclopaedia Britannica: https://www.britannica.com/science/avalanche.

Bommer, C., Phillips, M., & Arenson, L. U. (2010). Practical recommendations for planning, constructing and maintaining infrastructure in mountain permafrost. *Permafrost and Periglacial Processes*, *21*(1), 97-104.

Brundl, M., Etter, H. J., Steiniger, M., Klingler, C., Rhyner, J., & Ammann, W. J. (2004). IFKIS - a basis for managing avalanche risk in settlements and on roads in Switzerland. *Natural Hazards and Earth System Science*, 257-262.

Byers, A. C. & 5 others .(2018). A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal. *Landslides*, *16*(3), 533-549.

Chauhan, R. & Thakuri, S. (2017). Periglacial environment in Nepal Himalaya: Present contexts and future prospects. *Nepal Journal of Environmental Science*, 5, 35-40.

Conway, H. & Wilbour, C. (1999). Evolution of snow slope stability during storms. *Cold Regions Science and Technology*, 67-77.

Corona, C. & Stoffel, M. (2016). Snow and Ice Avalanches. *International Encyclopedia of Geography: People, the Earth, Environment and Technology: People, the Earth, Environment and Technology*, 1-7.

Deline, P., Hewitt, K., Reznichenko, N., & Shugar, D. (2015). Rock avalanches onto glaciers. In: *Landslide hazards, risks and disasters* (263-319). Academic Press.

Eckstein, D., Hutfils, M. L. & Winges, M. (2019). Global Climate Risk Index 2019; Berlin: Germanwatch.

Fujita, K., Inoue, H., Izumi, T., Yamaguchi, S., Sadakane, A., Sunako, S., Nishimura, K., Immerzeel, W. W., Shea, J. M., Kayastha, R. B., & Sawagaki, T. (2016). Anomalous winter-snow-amplified earthquake-induced disaster of the 2015 Langtang avalanche in Nepal. *Natural Hazards and Earth System Sciences*, *17*(5), 749-764.

Gauthier, F., Germain, D., & Hetu, B. (2017). Logistic models as a forecasting tool for snow avalanches in a cold maritime climate: northern Gaspesie Quebec, Canada. *Natural hazards* 89, 201-232.

Gruber, S. & Haeberli, W. (2007). Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *Journal of Geophysical Research*, 112, F02S18, doi: 10.1029/2006JF000547.

Hao, J.S., Huang, F. R., Liu, Y., Amobichukwu, A. C., & Li, L. H. (2018). Avalanche activity and characteristics of its triggering factors in the western Tianshan Mountains, China.

Journal of Mountain Science, 1397-1411.

Hewitt, K. (2002). Styles of rock-avalanche depositional complexes conditioned by very rugged terrain, Karakoram Himalaya, Pakistan. *Reviews in Engineering Geology*, 15, 345-377.

Hewitt, K. (2009). Rock avalanches that travel onto glaciers and related developments, Karakoram Himalaya, Inner Asia. *Geomorphology*, 1*03*(1), 66-79.

Hirashima, H., Nishimura, K., Yamaguchi, S., Sato, A., & Lehning, M. (2008). Avalanche forecasting in a heavy snowfall area using the snowpack model. *Cold Regions Science and Technology*, 191-203.

ICIMOD (2011). *Glacial lakes and glacial lake outburst floods in Nepal*. ICIMOD.

Kargel, J. S., Leonard, G. J., Shugar, D. H., Haritashya, U. K., Bevington, A., Fielding, E. J., ... & Anderson, E. (2016). Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. *Science*, *351*(6269), aac8353.

Kattelmann, R. & Yamada, T. (1995). *Storms and Avalanches of November 1995, Khumbu Himal, Nepal.*

Khadka, N., Zhang, G., & Thakuri, S. (2018). Glacial Lakes in the Nepal Himalaya: Inventory and Decadal Dynamics (1977–2017). *Remote Sensing*, 10, 1913, doi:10.3390/rs10121913.

Kunwar, R. R. & Limbu, B. (2015). Tourism and earthquake: A case study of Nepal and Turkey. *In Building Better Tourism with Renewed Strength, XXth NATTA Convention* (16-31).

Laxton, S. C. & Smith, D. J. (2009). Dendrochronological reconstruction of snow avalanche activity in the Lahul Himalaya, Northern India. *Natural hazards*, 459-467.

McClung, D. M. (2016). Avalanche character and fatalities in the high mountains of Asia. *Annals of Glaciology*, *57*(71), 114-118.

MoHA (2015). *Nepal Disaster Report 2015*. Government of Nepal, Ministry of Home Affairs (MoHA) and Disaster Preparedness Network-Nepal (DPNet-Nepal).

MoHA (2019). *Nepal Disaster Report 2019*. Government of Nepal, Ministry of Home Affairs (MoHA).

MoHA (2020). Nepal Disaster Risk Reduction Portal. Retrieved from www.drrportal.gov.np. on 15 March 2020.

Mu, Y. & Nepal, S. (2016). High mountain adventure tourism: Trekkers' perceptions of risk and death in Mt. Everest Region, Nepal. *Asia Pacific Journal of Tourism Research*, 21(5), 500-511.

Murphy, P. & Bayley, R. (1989). Tourism and disaster planning. *Geographical Review*, 36-46.

Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C., & Jaedicke, C. (2006). Global landslide and avalanche hotspots. *Landslides 3*, 159–173.

NDMA (2015). Strategies and Lessons for Preparing Better & Strengthening Risk Resilience in Coastal Region of India. National Disaster Management Authority (NDMA), 58 pp.

NSIDC (2019). Snow Avalanches. Retrieved from National Snow and Ice Data Center (NSIDC) https://nsidc.org/cryosphere/snow/science/avalanches.html on 15 February 2016.

Pacione, M. (1999). *Applied Geography: Principles and Practice*. Routledge, London, 664 pp.

Park, K. & Reisinger, Y. (2010). Differences in the Perceived Influence of Natural Disasters and Travel Risk on International Travel. *Tourism Geographies*, 1-24.

Pérez-Guillén, C., Tapia, M., Furdada, G., Suriñach, E., McElwaine, J. N., Steinkogler, W., & Hiller, M. (2014). Evaluation of a snow avalanche possibly triggered by a local earthquake at Vallée de la Sionne, Switzerland. *Cold Regions Science and Technology*, 149-162.

Podolskiy, E. A., Nishimura, K., Abe, O., & Chernous, P. A. (2010). Earthquake induced snow avalanches: Experimental study II. *Journal of Glaciology,* 56(197), 447-458.

Rana, B., Shrestha, A. B., Reynolds, J. M., Aryal, R., Pokhrel, A. P., & Budhathoki, K. P. (2000). Hazard assessment of the Tsho Rolpa Glacier Lake and ongoing remediation measures. *Journal of Nepal Geological Society*, 22, 563-570.

Richardson, S. D. & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary Internationals*, 65/66, 31-47.

Salerno, F., Thakuri, S., Guyennon, N., Viviano, G., & Tartari, G. (2016). Glacier melting and precipitation trends detected by surface area changes in Himalayan ponds. *The Cryosphere*, *10*(4), 1433-1448.

Schweizer, J., Bruce Jamieson, J., & Schneebeli, M. (2003). Snow avalanche formation. *Reviews of Geophysics*, *41*(4), 1016, doi: 10.1029/2002RG000123.

Thakuri, S. & Koirala, S. (2019) Climate change and mountaineering in Nepal: Issues and Challenges. *Journal of Nepal Mountain Academy*, *1*(1), 137-152.

Thakuri, S., Dahal, S., Shrestha, D., Guyennon, N., Romano, E., Colombo, N., & Salerno, F. (2019). Elevation-dependent warming of maximum air temperature in Nepal during 1976–2015. *Atmospheric Research*, 228, 261-269.

UNDRR (2019). Disaster Risk Reduction in Nepal: Status Report 2019. Bangkok, Thailand, United Nations Office for Disaster Risk Reduction (UNDRR), Regional Office for Asia and the Pacific.

Van Everdingen, R. O. (Ed.). (1998). *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms*. International Permafrost Association, Terminology Working Group.

Weidinger, J. T., Wang, J., & Ma, N. (2002). The earthquake-triggered rock avalanche of Cui Hua, Qin Ling Mountains, PR of China—the benefits of a lake-damming prehistoric natural disaster. *Quaternary International*, 93, 207-214.

Yamada, T., Fushimi, H., Aryal, R., Kadota, T., Fujita, K., Seko, K., & Yasunari, T. (1996). Report of avalanche accident at Pangka in 1995, Khumbu region, Nepal. *Journal of the Japanese Society of Snow and Ice*, *58*(2), 145-155.

Zimmermann, M., Bichsel, M., & Kienholz, H. (1986). Mountain hazards mapping in the Khumbu Himal, Nepal. *Mountain Research and Development*, 29-40.

Zingari, P. C. & Fiebiger, G. (2002). Mountain risks and hazards. *Unasylva*, *53*(208), 71-77.