Chapter 20
Spatiotemporal Distribution of Landslides in Nepal

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Abstract The occurrence of landslides in the Nepal Himalaya is a common phenomenon due to active seismotectonics coupled with the strong monsoon, fragile landscape, and inadequate agricultural practices. This research has analyzed the trends of landslide events, total fatalities, and economic losses from 1971 to 2016 and discussed the landslide early warning system initiatives in Nepal. Spatiotemporal variation of landslide events shows an increasing trend with nonlinear relationships between events and deaths. The highest number of events and fatalities is concentrated in central Nepal due to population growth, rural-urban migration, and haphazard road construction. Moreover, the number of deaths and economic loss is higher in the hills compared to the mountain and Terai. Only few early warning system initiatives were applied either in project or community basis in Nepal. Most of those initiatives vanished after the project completion. Nepal government should start to build a nationwide dynamic landslide inventory database system connected with weather stations for the monitoring and forecasting of the landslide.

Keywords Landslide · Trend · Nepal · Monsoon · Road · Landslide early warning systems · Spatiotemporal variation

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S. Eslamian, F. Eslamian (eds.), *Handbook of Disaster Risk Reduction for Resilience*, https://doi.org/10.1007/978-3-030-61278-8_20

1 Introduction

Landslide occurrence in the Himalaya is a natural process due to active seismotectonic activities, fragile landscape, and anthropogenic interventions. The continuous subduction of the Indian Plate beneath the Eurasian Plate creates earthquakes at different time scales and magnitude. Some large earthquakes that occurred in 1934, 1988, and 2015 had weakened the geology and created many coseismic landslides in the Nepal Himalaya. Moreover, strong Indian monsoon has been playing an important role for the generation of landslides and debris flow every year causing many deaths and loss of property. Some of the existing data estimated that the damage caused by landslide alone was more than one billion USD and 200 deaths every year. Moreover, 276 lives and 70 million USD economic losses occurred due to a landslide (MoHA 2017) in 2017.

Nepal Himalaya has experienced many large-scale landslides in different time that had changed the landscape completely (Table 20.1). Some large-scale landslides such as Darbang landslide and Jure landslide perished many lives and changed a spectrum of landslide research toward sustainable landslide risk reduction based on scientific research. Some previous researchers (Brunsden et al. 1975; Caine and Mool 1982; Dixit 1983; Fleming 1978; Kienholz et al. 1984; Laban 1979; Nepal 1992; Rimal and Tater 1968; Thouret 1981; Upreti and Dhital 1996; Wagner 1983; White et al. 1987) have presented a landslide mechanism using different models based on predisposing factors and geotechnical properties. These studies can be used for the spatiotemporal analysis to understand the trends of landslide and their impacts on the national economy (Adhikari and Adhikary 2019; Karmacharya 1989; Khanal 1991; Petley et al. 2007; Wagner et al. 1988). The losses of lives and properties are directly related to the anthropogenic activities, i.e., road construction and slope modification (Gerrard and Gardner 2000; McAdoo et al. 2018) in the mountains. These losses can be reduced with proper planning based on landslide susceptibility mapping because some studies (Acharya and Lee 2019; Devkota et al. 2013; Meena et al. 2019; Regmi et al. 2014) show that Nepal Himalaya has a high risk of landslides and debris flow hazard.

Landslide hazard mitigation is always a challenging task for developing countries due to the unavailability of sufficient resources and inaccessible geomorphological terrain. Different large- and small-scale interventions have already been applied for the slope protection; however, the country still lacks a holistic tool for landslide risk assessment, well-trained local professionals, comprehensive landslide databases, and sufficient programs to share good learning practices. Different approaches such as bioengineering, retaining walls and drainage management (Florineth et al. 2002; Howell 1999; Khanal and Watanabe 2005) with an awareness campaign, and enhancing preparedness and post-disaster management through early warning systems (Fathani et al. 2016; Michoud et al. 2013; Piciullo et al. 2018) have been applied in different parts of the country. Those engineering mitigation measures are sometimes not possible due to either inaccessibility or lack of sufficient resources. Therefore, landslide early warning systems (LEWSs) can be

Table 20.1 Large-scale landslides in modern history of Nepal

S.N.	Date	Name	Location	Description	Source
1	1934	Nepal	Nepal	1934 earthquakes have triggered many coseismic landslides	Auden (1935)
2	1962	Darbang	Myagdi	Buried the Darbang Bazzar and killed 500 people	YAGI et al. (1990)
3	1968	Lapu Besi	Gorkha	Blocked the Budhi Gandaki River and breaching of dam destroyed the settlement downstream	Sharma (1981)
4	1969	Bajhang	Bajhang	1969 earthquake triggered many landslides	Upreti and Dhital (1996)
5	1976	Jharlang	Dahding	Jharlang Village has shifted to another location	Yadav (1976)
6	1976	Bhagawati tar	Kaski	Landslide killed about 75 people	Upreti and Dhital (1996)
7	1978	Tinau	Palpa	Dry landslide destroyed a newly built bridge over the river at Butwal	Upreti and Dhital (1996)
8	1980	Bajhang	Bhajhang	Earthquake of 6.5 magnitude has triggered many landslides and 178 people died	Sharma (1981)
9	1988	Darbang	Myagdi	Killed 109 and dammed Myagdi Khola	Upreti and Dhital (1996)
10	1993	Phedi Gau	Makawanpur	Large-scale landslides and debris flow in Central Nepal and destroyed property. Phedigaon debris flow destroyed 52 houses and 52 deaths	Dhital et al. (1993)
11	1993	Jogimara	Dhading	The landslide blocked the Prithvi highway and carried two buses with passengers into the Trishuli River	Upreti and Dhital (1996)
12	2001	Krishna Bhir	Dhading	The debris and boulders blocked the Prithvi highway for 11 days	Maskey (1999)
13	2014	Jure landslide	Sindhupalchowk	Landslide has buried a village with 156 deaths and blocked the Sunkoshi River forming 55 m high dam	Van der Geest (2018)
14	2015	Central Nepal	Central Nepal	Gorkha earthquake 2015 has triggered more than 2000 landslides killing many people	Gnyawali and Adhikari (2017)

good option for continuous landslide monitoring to save lives. Different researchers applied LEWS in the past, but the history of LEWS is not so long in Nepal. Some regional LEWSs based on rainfall threshold (Dahal and Hasegawa 2008; Gabet et al. 2004; Kafle 2017; Malakar 2014; Phaiju et al. 2012) and local LEWS based on the displacement measurement of slope (MercyCorps 2014; Thapa and Adhikari 2019) were practiced. The establishment of LEWS is always a challenging task in difficult geomorphic terrain and diverse communities. In this context, this book chapter analyzes the trend of landslide distribution from 1971 to 2016 (Adhikari and Adhikary 2019; UNDRR 2019) and documents the previous LEWSs practiced in Nepal. This study only considered the data from 1971 to 2016 because the

Desinventar data set for Nepal has data till 2016. There are no segregated data that are collected from the published newspaper and has not exact spatial location with detailed description of types and dimensions of the landslides.

2 Material and Methods

The present study is a secondary data analysis of landslide events, deaths, and economic losses based on the data available from Desinventar (UNDRR 2019) and different published/unpublished papers/reports. Desinventar is a web-based platform managed by United Nations Disaster Risk Reduction (UNDRR) to store the data collected based on media reporting, i.e., daily national newspapers, periodicals, relevant reports, government records, journals, and researches in different countries. The data consists of deaths, affected population, and economic losses of all 75 districts of Nepal from 1971 to 2016. The downloaded data were analyzed using Statistical Package for Social Sciences (SPSS) and the ArcGIS platform. Similarly, information about LEWS was collected from published scientific research papers and unpublished reports.

3 Study Area

Nepal lies between China and India in South Asia and covers 147, 181km^2 surface area (Fig. 20.1). The altitude of Nepal ranges from 70 m (Terai) to the top of the world, Mount Everest (8848 m), within a north-south distance of 150 km. Nepal was divided of 75 districts and 5 developmental regions before 2015 where the distribution of population and economic activities differed significantly.

Nepal is divided into three ecological regions, namely, Terai, hills, and mountain which cover 15%, 68%, and 17% of the total area, respectively. These ecological divisions are based on altitude and climate. Terai lies in the southern part of Nepal that consists of Indo-Gangetic plain with a very gentle slope. The population density is very high (392) due to hill-Terai migration in different periods of time (CBS 2011). Terai districts consist of alluvial plain and the Siwaliks (Fig. 20.1).

Hill districts are distributed in the middle part of Nepal consisting of Chure and Mahabharat Lekh. This region has a steep slope, fragile geology, and deep river valleys. The population density is less than Terai, and most of the settlements are located either on old landslides or in midland valleys, i.e., Kathmandu, Pokhara, and Dang. This region has tropical to semi-temperate climate. Similarly, mountain region is located in the northern part of Nepal including Trans-Himalayan valleys, i.e., Mustang, Manang, and Dolpa. Settlements are very scattered with very low population density. The world's highest peaks such as Mt. Everest, Annapurna, Makalu, and Dhaulagiri lie in this region.

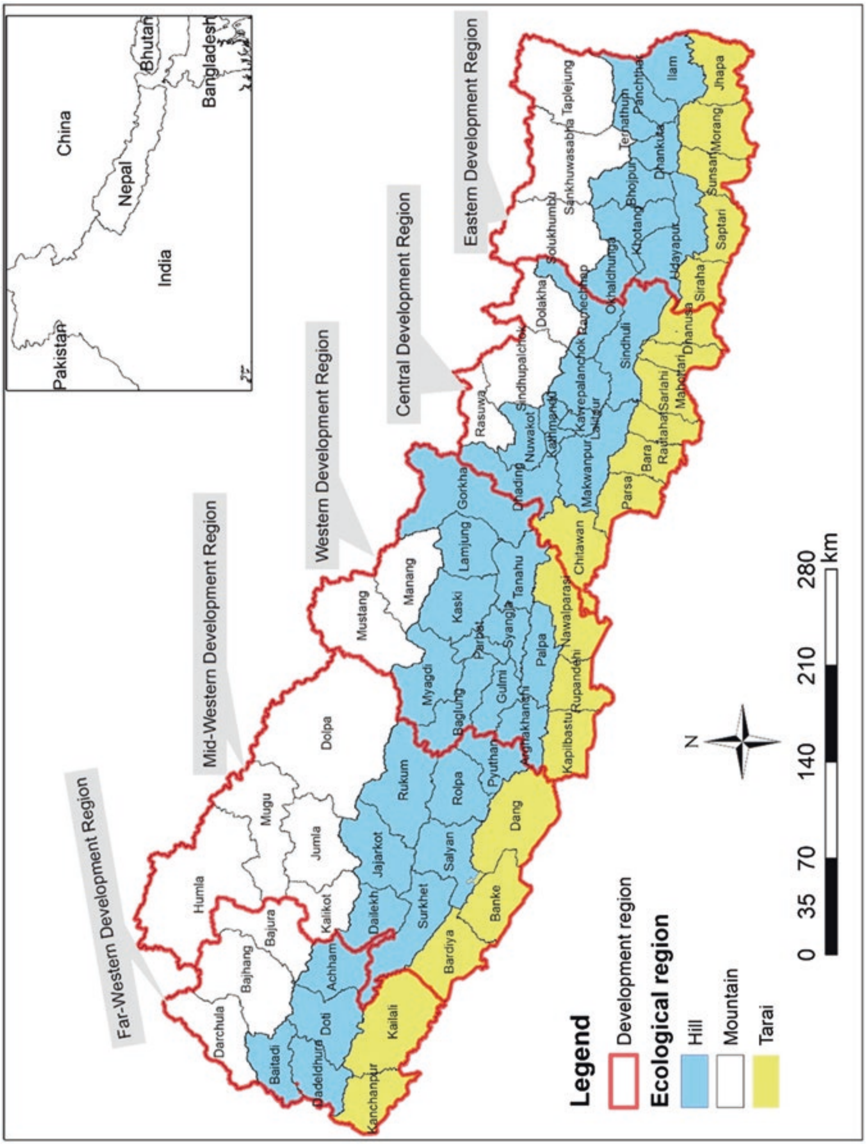

Fig. 20.1 Map of Nepal showing ecological boundaries. The inset shows the location of Nepal in South Asia

Nepal Himalaya lies in the central part of the Himalayan arc. Geologically, it is divided into five tectonic zones, namely, Indo-Gangetic Plain, Siwaliks, Lesser Himalaya, Higher Himalaya, and Tibetan-Tethys Himalaya. These zones are separated from each other by the principal Himalayan thrust/faults. Indo-Gangetic Plain lies in the foothills of the Himalaya and consists of sand, silt, and gravel (Mugnier et al. 1999). The Siwalik consists of sandstone, siltstone, and conglomerate (Dhital 1995; Dhital 2015; Nakayama and Ulak 1999). Low-grade metamorphic rocks, i.e., schists, gneiss, marble, and meta-sedimentary rocks like quartzite, limestone, and slate, are spread over the Lesser Himalaya (DeCelles et al. 2001; Frank and Fuchs 1970). Similarly, Higher Himalaya consists of leucogranites and high-grade crystalline rocks along the entire length of the Nepal Himalaya (Le Fort 1975; Upreti 1999). This region is overlaid by Tibetan-Tethys Zone that consists of sandstone, limestone, quartzite, and shale with a fossiliferous layer (Bordet 1971; Colchen 1999; Godin 2003). The nature and extent of the landslide in these zones are mostly controlled by geology and climate.

Nepal Himalaya has diverse climatic zones and receives a high amount of rainfall in the monsoon season due to the Asian monsoon originated from the Bay of Bengal. The maximum and minimum average annual rainfall are >2000 mm (Kaski) and < 100 mm (Mustang), respectively (DHM 2017). Districts of central and eastern development regions show a decreasing annual precipitation trend, whereas most of the districts of far-western and western development regions show an increasing trend from 1971 to 2014. Nepal Himalaya is drained by three river basins, namely, Koshi, Gandaki, and Karnali to the Ganga River. This region has about 6000 various types of rivers (including rivulets and tributaries) with drainage density of about 0.3 km/km^2, and the overall cumulative length of the rivers is about 45,000 km (WECS/DHMN 1996). Similarly, the temperature trend shows that the normal annual minimum temperature is low (<0^0 C) in the mountain districts (Humla, Mugu, Dolpa, Mustang, and Manang), while the districts of hills and Terai (Surkhet, Tanahun, Makwanpur, Sindhuli, and Udaypur) have a highest temperature (15^0 C–20^0 C) (DHM 2017).

4 Results

4.1 Landslide Trend

Spatiotemporal distribution of landslides in the Nepal Himalaya shows irregular trends. There were altogether 3419 events, which took 5190 lives, and 207,979 people were affected (Fig. 20.2). The distribution of landslide events and deaths differs in different years. The highest number (388) of landslides occurred in 2002 where 445 people lost their lives. The analysis shows that the relationship between events and deaths is not linear. The number of deaths not only depends on the number but also depends on size and extent of the landslides. The lowest number of landslide

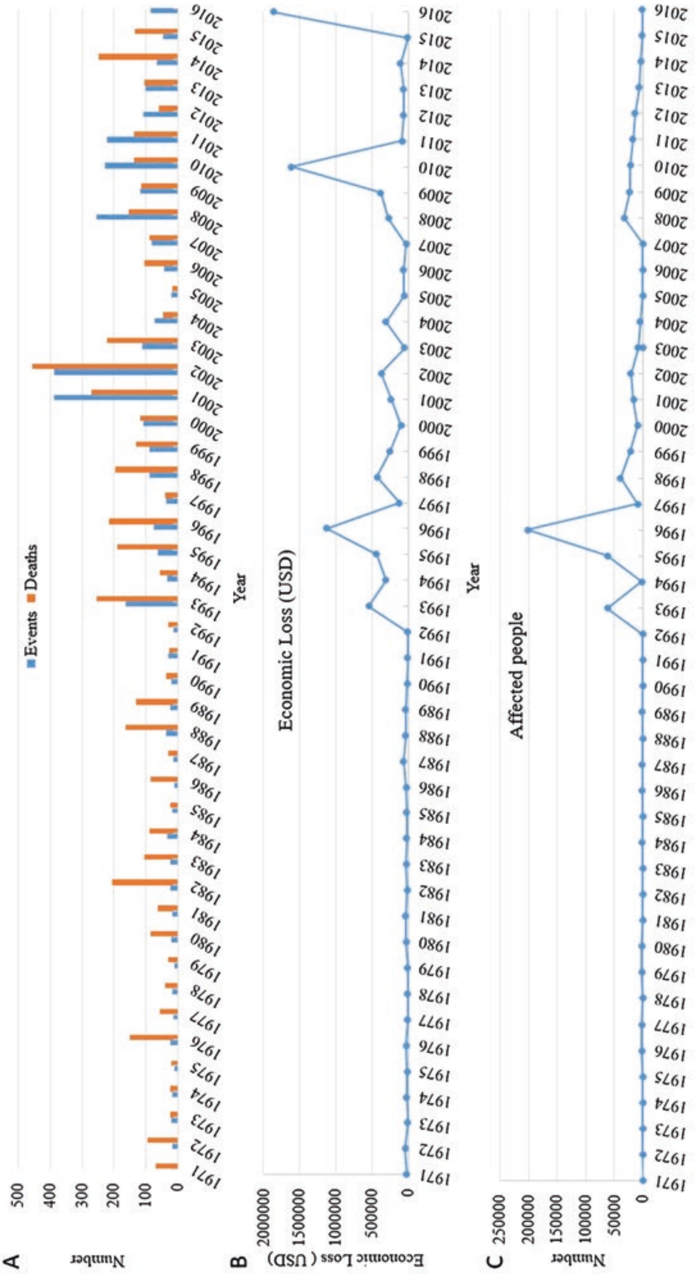

Fig. 20.2 Yearly record of landslide in Nepal from 1971 to 2016. **(a)** Number of landslide events vs. total deaths, **(b)** economic loss in USD, and **(c)** affected people

events (11) occurred in 1975, 1979, and 1986 in which 19, 29, and 86 people lost their lives, respectively (Fig. 20.2a). The number of landslide events was high (≥ 100 events) in 1993–1996, 2000–2003, and 2007–2013; however, the trend of the landslide was fluctuating over the period of time (Fig. 20.2a). There are no clear explanations for increased events; however, it might be a result of increased reporting or local governments started to construct village road during that time. Adhikari and Adhikary (2019) and Petley et al. (2007) reported a similar trend of landslide events and correlated with climatic factors. Similarly, the number of affected people was exceptionally high in 1996 due to heavy rainfall in the Nepal Himalaya (Fig. 20.2c). These landslides destroyed many properties, and country lost more than nine million USD during the analyzed period (Fig. 20.2b).

Geographically, almost all districts of Nepal have landslides (Fig. 20.3), but the density is mostly concentrated around the districts located in the Mahabharat Lekh, Chure range, and central Nepal (Dhading, Sindhupalchowk, and Syangja districts). The landslide distributions in the hills are mainly controlled by the fragile geology, rugged topography, and concentrated rainfall (Petley et al. 2007). There is a positive association between the number of landslides and fatalities; however, this is not true in all districts. For example, Makawanpur, Syangja, Kaski, Bhaktapur, Taplejung, and Doti districts have an inverse association between landslide and fatalities (Fig. 20.3a). The economic loss also shows irregular trends, i.e., Bajura, Kalikot, Gulmi, Taplejung, and Okhaldhunga districts have a high economic loss despite having a low number of landslide events (Fig. 20.3b).

The landslide fatalities were highest in the central development region (1762) followed by the western development region (1404) (Fig. 20.4). These fatalities are mostly related to the population density (CBS 2011) and scattered settlements on vulnerable mountain slopes.

The physiography and climate change significantly varies from Terai to Higher Himalaya due to the high elevation differences. Therefore, the distribution of landslides is also different in three different ecological regions. Hills and mountain regions consist of the highest number of the landslide events and deaths. The trend of landslide events was similar until 1992 in all ecological regions (Fig. 20.5); however, the trend increased after 1992 reaching highest in 2003 (Fig. 20.5a). A trend of deaths shows that the number of deaths is high in the hills followed by mountain and Terai regions (Fig. 20.5b).

4.2 Landslide Early Warning System

The history of LEWS is very short in the Nepal Himalaya. Based on the available literature, the Government of Nepal installed a landslide monitoring system in 1993 for the first time to monitor the Kathmandu-Trishuli road. Then, both government and development organizations started to install regional as well as local LEWSs in different places with different capacities. Regional LEWSs based on rainfall threshold are popular in Nepal because of the cost-effectiveness, easy applicability for

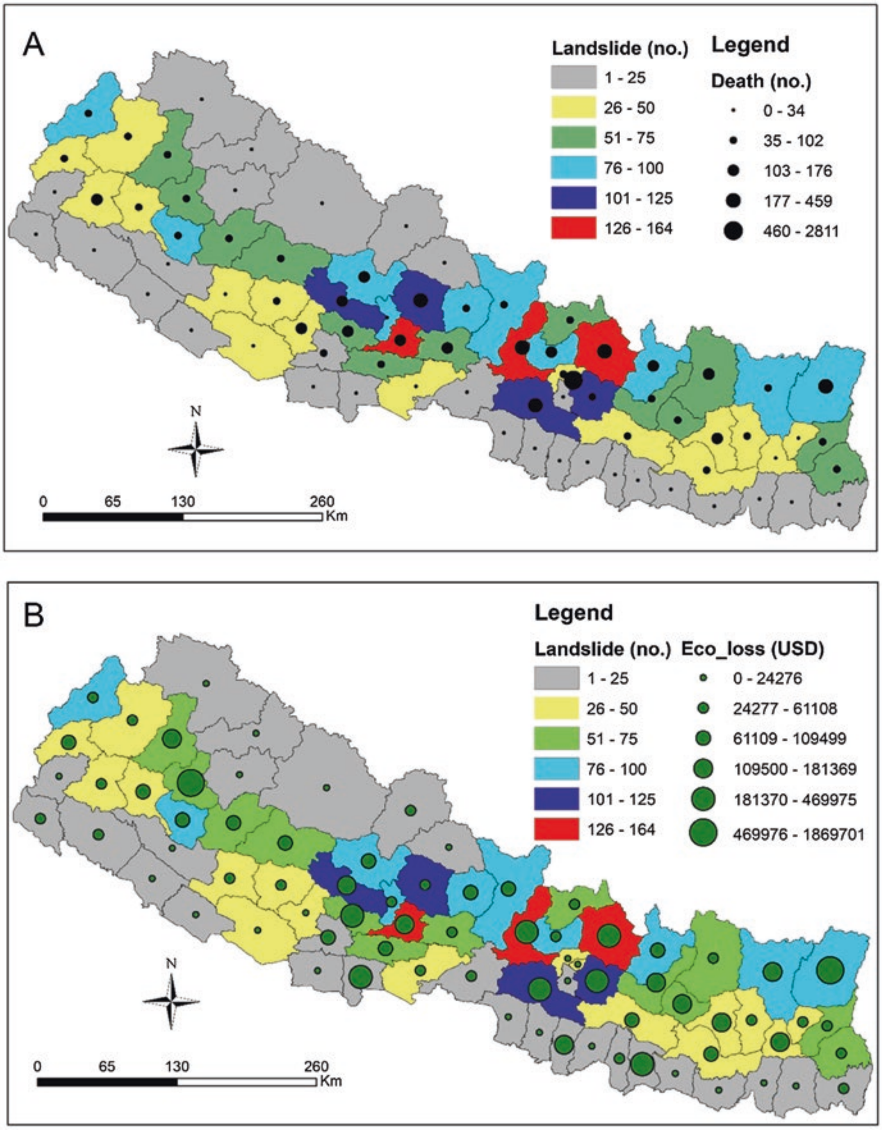

Fig. 20.3 Distribution of landslides from 1971 to 2016. (**a**) Number of landslides vs total death; (**b**) Number of landslides vs economic loss

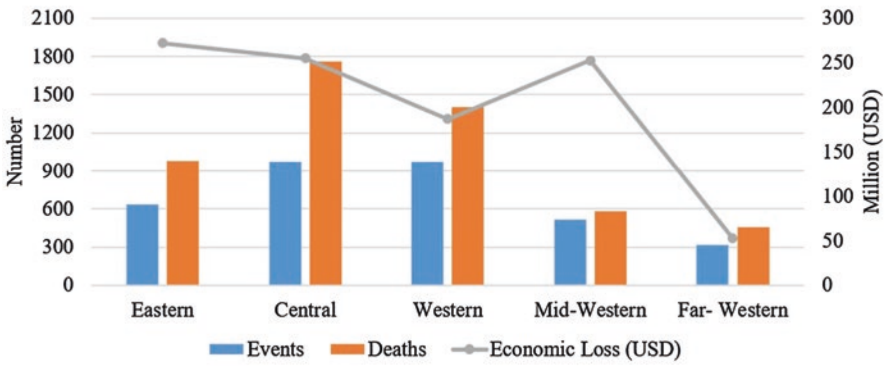

Fig. 20.4 Distribution of lightning events, death, and economic loss in different development regions

large and densely populated areas, and easy to upgrade with new technologies (Calvello 2017). Different previous LEWSs are discussed below.

4.2.1 Kathmandu-Trishuli Road, Central Nepal

Water Induced Disaster Prevention Technical Centre (DPTC), Government of Nepal, installed rain gauge, piezometer, moving pegs, tiltmeter, and extensometers in the Km-19 landslide along the Kathmandu-Trishuli road, central Nepal, in 1993 (Poudel et al. 2001). The landslide damaged more than a 100 m long section of the road and affected 0.015 km^2 of land uphill side of the road. Many tension cracks and inclined trees were monitored with the help of simple and automatic extensometers. The displacement data recorded using simple and automatic extensometers showed a direct relationship with rainfall. This is the first recorded landslide monitoring system to understand the mechanism of a particular landslide in the Nepal Himalaya.

4.2.2 Bhanu VDC, Tanahun

Practical Action, UK, with co-funding from the European Commission Humanitarian Aid and Civil Protection (ECHO) in coordination with the Government of Nepal installed community-based LEWS in 2012 in the Bhanu Village Development Committee (VDC), Tanahun, Nepal, to monitor small-scale landslides (Malakar 2014). More than eight landslides occurred in 2008 in the red to light brown colluvial soil along with residual soil on the top. These landslides destroyed more than 0.057 km^2 arable land, partially damaged houses, and lost livestocks. The project installed both automatic rain gauge (tipping bucket) and manual rain gauge for rainfall measurement. The automatic system was connected to an electronic display board via mobile SIM cards. The alert system was

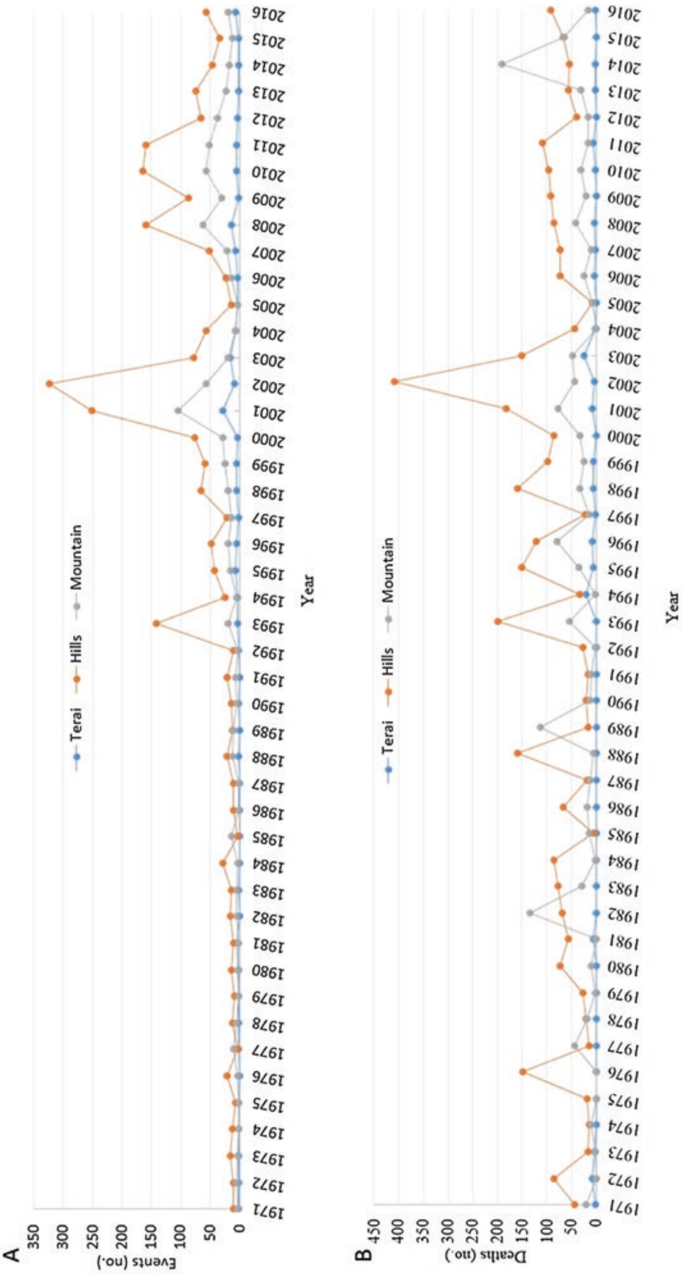

Fig. 20.5 Distribution of events and deaths in three ecological regions of Nepal. **(a)** Number of landslide events vs Year; **(b)** Number of death vs year

placed with hand-operated sirens and megaphones to communicate with the local community. This alert system was based on rainfall durations in 1 and 24 h. The system recorded rainfall from 2012 to 2013. The maximum recorded rainfall was 44.2 mm (1 h and 128 mm (24 h) in July 2013. However, the system did not alert the message because the rainfall was below the threshold (200 mm/24 h) during the project period.

4.2.3 Massey Village, Kailali

Landslide monitoring system (moving peg method) was established in 2014 in the Massey village, Kailali, by Mercy Corps with technical assistance from the Institute of Engineering, Tribhuvan University, Nepal, in coordination with the Government of Nepal (Adhikari and Sitoula 2017). The landslide was 120 m long and 50 m in width making eight houses vulnerable. This system consists of wooden posts longitudinally installed in two series at the interval of 10 meters from the crown to the toe of the Massey landslide (Fig. 20.6a). This landslide monitoring project trained LEWS task force for the regular measurements of the distance between two pegs, which were geo-referenced to the stable points. The maximum rainfall (144.8 mm/24 h) was measured in a nearby station (Sandepani, Kailali) on 14th of August 2014; however, there was no landslide movement during the project period (August 2014–July 2015). Therefore, this rainfall amount can be the rainfall threshold of that area, yet the landslide does not only depend on rainfall but also on local geological and geomorphological conditions.

4.2.4 Nigali VDC, Kailali

Community-led rainfall monitoring was established by Mercy Corps and Practical Action in coordination with the Government of Nepal in Sahajpur and Nigali VDCs of Kailali district in 2012 (Phaiju et al. 2012). This system was installed after the occurrences of large numbers of landslides due to heavy rainfall in September 2008. The system considered both manual rain gauges (200 mm diameter) and automatic rain gauge stations (tipping bucket). The system was able to record data with the help of a data logger, and those data were displaced in the digital board (Fig. 20.6c and d). Rainfall accumulated in 1 h, 12 h, and 36 h were shown by the display board and used for both short- and long-term rainfall monitoring. The community focal person was able to send the warning message after receiving the alert message from that system. Hand-operated sirens and megaphones were used to send the warning to the community.

Fig. 20.6 Some examples of landslide early warning systems in Nepal. (**a**) Measuring landslide displacement by moving peg method; (**b**) LEWS installation in Bijulikot, Ramechhap (Source: Shreelal Poudel); (**c** and **d**) automatic rain gauge and rainfall display board in Kailali; (**e**) LEWS in Sundrawati village, Dolakha; (**f**) LEWS installation in the Khani Gau, Gorkha. (Source: Lalu Sinjali)

4.2.5 Upper Bhote Koshi Valley, Nepal

The National Society of Earthquake Technology (NSET) established a landslide monitoring system with the help of Durham University, UK, in the upper Bhote Koshi valley of central Nepal in 2017 (Durham University 2017). This area is the worst-hit area due to the Gorkha earthquake 2015 and triggered many landslides (Gnyawali and Adhikari 2017). This project installed ten automatic extensometers, with rain gauge equipped with mobile SIM cards and data directly transferred to the Durham University server. The details status of the web-based monitoring system can be accessed from http://community.dur.ac.uk/nepal.2015eq/. This system was developed mostly for scientific research, and there was no warning mechanism and community involvement in the ground.

4.2.6 Ramechhap, Nepal

Mission East Nepal has installed an automatic rain gauge and display board in the Bijulikot, Ramechhap, Nepal, with help from Durham University, UK, to monitor the landslide for the LEWS establishment in 2017 (Oven and Rosser 2017). The Bijulikot landslide, 300 m wide and 400 m long, was located on a dip slope of the laminated schist providing the smooth surface for material move downward. The sliding material consists of saturated silt and clay. This project has installed a strain-based monitoring system using a low-cost moving peg method, and communities were trained for the effective implementation of the LEWS (Fig. 20.6b).

4.2.7 Sundrawati, Dolakha

The Department of Forests and Soil Conservation, Government of Nepal, with the help of Food and Agricultural Organization (FAO) installed automatic rain gauge, soil moisture sensor, and extensometer for LEWS in the Mehele landslide, Dolakha, in 2018 (Thapa and Adhikari 2019) (Fig. 20.6e). The landslide is about 160 m in length and 40 m wide and covered with grassland. Many cracks are present in the upper and middle parts of the slide. Geologically, this area is mostly dominated by mica-schist, augen gneiss, gray phyllites, and quartzite (DMG 2011). The system was connected to a mobile SIM card to provide an alert message and siren. The threshold value was assigned for 24-h accumulated rainfall, which was equal or more than 50 mm and crack opening equal to or more than 30 cm. The LEWS orientation program was conducted in rural municipality/ward office, Local Disaster Management Committee (LDMC), and district soil conservation officers for effective communication of the warning and response. The LEWS worked perfectly during the landslide occurrence on 23rd of August 2018, and more than 400 people were saved.

4.2.8 Khani Gau, Gorkha

The National Academy of Science and Technology (NAST) has installed LEWS in Khani Gau, Gorkha, in 2019. The system installed the Global Positioning System (GPS) to record the movement of the landslide and the mobile SIM card to transfer the data to the control station (Fig. 20.6f). The landslide occurred in colluvial deposits and mostly composed of silt, gravel, and boulders. Communities were involved during the installation and got training for operation and rescue during the landslides.

5 Discussions

The landslide trend analysis from 1971 to 2016 shows the positive relationship between landslide and geographical distribution. The landslide occurs on the slopes of the mountains which destroys many lives and property as most of the settlement are residing in the paleo-landslides. The number of deaths is higher in hills compared to mountains and Terai, which might be due to high population density (186) in hills compared to mountains and Terai (CBS 2011). For example, the 1993 cloud burst event in central Nepal killed 52 people and destroyed many houses in Phedi Gau, Makawanpur district (Dhital et al. 1993). Besides this, the number of landslides increased significantly after the Nepalese government prioritized road construction after 1992. Therefore, almost all Village Development Committees (VDCs) and municipalities spent most of their annual budget for road construction. Unfortunately, most of those road constructions were not fully engineered. So, many landslides were triggered in the following monsoon. This change in fatalities coincides with the Maoist civil war (1996–2006) because the conflict had increased the vulnerability due to the constant migration from Maoist-controlled rural areas to government-controlled urban areas (Petley et al. 2007). McAdoo et al. (2018) have reported that the new road construction in the Nepalese mountains has severely hindered the socioeconomic developments and contributes to loss of life. Even these days, roads in rural areas are being constructed without considering engineering norms and values. If the road construction continues in a similar approach, then there will be more landslide in the future. People migrated toward the road corridor from the rural areas for economic opportunities and started to build houses along the road. Such migration increases the vulnerability in the mountain slopes. The increasing number of landslide events in the database in recent years might be related to a global increase in mobile technology and the Internet. Gorkha earthquake 2015 has triggered many coseismic landslides (Gnyawali and Adhikari 2017; Roback et al. 2018) in central Nepal. These landslides were reactivated by the monsoon in the next years. Anthropogenic activities such as slope modification, improper agricultural practice, and deforestation are also playing an important role in landslide generation (Froude and Petley 2018).

The rapid and informal house construction in the landslide hazardous zone after the earthquake is mostly due to low income or lack of awareness. Therefore, the Government of Nepal should emphasize proper planning on construction, safe area identification, and awareness raising about landslide hazards. Currently, the government mostly focuses on mitigation of landslide using high-tech engineering construction, i.e., retaining walls and bioengineering to control major landslide in the mountains. However, it is important to install LEWS where mitigation options are not feasible and very expensive. Some installed LEWSs are project basis and do not work for a longer period after the project termination. Therefore, the preparation of a nationwide landslide hazard map and web-based landslide recording system for future prediction should be implemented urgently. It is also recommended that the proposed system should be connected with existing weather stations of the Nepal Himalaya.

6 Summary and Conclusions

The landslide trend analysis identified the landslide hotspot districts in Nepal. The analysis shows that the number of deaths not only depends on number of landslides but also depends on size and extent of landslides and location of settlements from the landslides. Hilly districts of central and western Nepal are the most affected areas due to fragile geology and concentration of population. The trend shows that the number of landslides is increasing almost every year since 1992 due to nonengineered road construction, rural-urban migration, increased population, and heavy rainfall. There are some existing landslide early warning system (LEWS) practices in the Nepal Himalaya, but most of them vanished after the completion of the project. Low-cost community-based LEWSs are the most effective methods in the rural parts due to its easiness to handle and operate, and therefore they should be replicated in other parts of Nepal. Nepal government should start to build a nationwide dynamic landslide inventory database system connected with weather stations for the monitoring and forecasting of the landslide.

References

Acharya, T. D., & Lee, D. H. (2019). Landslide susceptibility mapping using relative frequency and predictor rate along Araniko highway. *KSCE Journal of Civil Engineering, 23*(2), 763–776.

Adhikari, S., & Adhikary, D. (2019). *An account of Nepal disasters and economic fallout*. Lyon, France: Project Research and Management Associates.

Adhikari, B. R., & Sitoula, N. R. (2017). Analyzing the effectiveness of moving peg method for landslide monitoring and its potentiality for replication in the Nepal Himalaya. In R. Shaw, E. Chan, F. Lian, L. Lu, P. Shi, S. Yang, G. Chan, & J. Wong (Eds.), *Co-designing disaster risk reduction solution: Toward participatory action and communication in science, technology and academia*. Hong Kong: ASTAAG, IRDR and CCOUC.

Auden, J. (1935). Traverses in the Himalaya. *Records of Geological survey of India, 69*, 123–167.

Bordet, P. (1971). *Recherches géologiques dans l'Himalaya du Népal, région de la Thakkhola*. Éd. du Centre Nat. de la Recherche Scientif. Paris.

Brunsden, D., Doornkamp, J. C., Fookes, P. G., Jones, D. K. C., & Kelly, J. M. H. (1975). Large scale geomorphological mapping and highway engineering design. *Quarterly Journal of Engineering Geology, 8*(4), 227–253.

Caine, N., & Mool, P. K. (1982). Landslide in the Kolpu Khola drainage, Middle Mountain, Nepal. *Mountain Research and Development, 2*(2), 157–173.

Calvello, M. (2017). Early warning strategies to cope with landslide risk. *Rivista Italiana di Geotecnica, 2*, 63–91.

CBS. (2011). *Nepal population and housing census* (264 pp). Center Bureau of Statistics, Government of Nepal.

Colchen, M. (1999). The Thakkhola–Mustang graben in Nepal and the late Cenozoic extension in the higher Himalayas. *Journal of Asian Earth Sciences, 17*(5–6), 683–702.

Dahal, R. K., & Hasegawa, S. (2008). Representative rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology, 100*(3–4), 429–443.

DeCelles, P. G., Robinson, D. M., Quade, J., Ojha, T., Garzione, C. N., Copeland, P., & Upreti, B. N. (2001). Stratigraphy, structure, and tectonic evolution of the Himalayan fold-thrust belt in western Nepal. *Tectonics, 20*(4), 487–509.

Devkota, K. C., Regmi, A. D., Pourghasemi, H. R., Yoshida, K., Pradhan, B., Ryu, I. C., Dhital, M. R., & Althuwaynee, O. F. (2013). Landslide susceptibility mapping using certainty factor, index of entropy and logistic regression models in GIS and their comparison at Mugling–Narayanghat road section in Nepal Himalaya. *Natural Hazards, 65*(1), 135–165.

Dhital, M. (1995). *Geology and structure of the Siwaliks and lesser Himalaya in the Surai Khola-Bardanda area, mid Western Nepal* (Vol.. 4, pp. 1–70). Bulletin of Department of Geology, Tribhuvan University, Nepal.

Dhital, M. R. (2015). *Geology of the Nepal Himalaya: Regional perspective of the classic collided orogen*. Cham: Springer.

Dhital, M. R., Khanal, N., & Thapa, K. B. (1993). *The role of extreme weather events, mass movements, and land use changes in increasing natural hazards* (p. 123). Workshop on causes of recent damage incurred in south-central Nepal. ICIMOD, Kathmandu, Nepal.

DHM. (2017). *Observed climate trend analysis in the districts and physiographic regions of Nepal (1971–2014)*. Department of Hydrology and Meteorology, Government of Nepal.

Dixit, A. M. (1983). *Report on preliminary engineering ecological investigation of landslide and subsidence in Kerabari and Charchare area, Siddhartha highway.* Palpa District, Nepal: Department of Mines and Geology, HMG, Nepal.

DMG. (2011). *Geological map of Eastern Nepal.* Department of Mines and Geology, Government of Nepal.

Durham University. (2017). *Earthquake landslide in Nepal*. http://community.dur.ac.uk/nepal.2015eq/. Accessed 2 July 2020.

Fathani, T. F., Karnawati, D., & Wilopo, W. (2016). An integrated methodology to develop a standard for landslide warning systems. *Natural Hazards and Earth System Sciences, 16*(9), 2133–2135.

Fleming, W. M. (1978). *Classification of catchments in the western development region of Nepal, Erosion Hazard and land management problems*. Kathmandu, Nepal: Department of Soil and Water Conservation, HMG.

Florineth, F., Rauch, H. P., & Staffler, H. P. (2002). Stabilization of landslides with bio-engineering measures in South Tyrol/Italy and Thankot/Nepal. In *International congress INTERPRAEVENT 2002 in the Pacific rim-Matsumoto* (pp. 827–837). Japan Congress Publication.

Frank, W., & Fuchs, G. R. (1970). Geological investigations in West Nepal and their significance for the geology of the Himalayas. *Geologische Rundschau, 59*(2), 552–580.

Froude, M. J., & Petley, D. (2018). Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences, 18*, 2161–2181.

Gabet, E. J., Burbank, D. W., Putkonen, J. K., Pratt-Sitaula, B. A., & Ojha, T. (2004). Rainfall thresholds for landsliding in the Himalayas of Nepal. *Geomorphology, 63*(3–4), 131–143.

Gerrard, A., & Gardner, R. (2000). The nature and management implications of landsliding on irrigated terraces in the Middle Hills of Nepal. *The International Journal of Sustainable Development & World Ecology, 7*(3), 229–235.

Gnyawali, K. R., & Adhikari, B. R. (2017). Spatial relations of earthquake induced landslides triggered by 2015 Gorkha earthquake Mw = 7.8. In *Workshop on world landslide forum* (pp. 85–93). Cham: Springer.

Godin, L. (2003). Structural evolution of the Tethyan sedimentary sequence in the Annapurna area, Central Nepal Himalaya. *Journal of Asian Earth Sciences, 22*(4), 307–328.

Howell, J. (1999). *Roadside bio-engineering*. His Majesty's Government of Nepal, Department of Roads.

Kafle, S. K. (2017). Disaster early warning Systems in Nepal: Institutional and operational frameworks. *Journal of Geography and Natural Disasters, 7*(2), 1–11.

Karmacharya, R. (1989). *Report of the Bungamati landslide* (p. 7). Lalitpur, District, Central Nepal. Department of Mines and Geology.

Khanal, R. K. (1991). *Historic landslides of Nepal during 1970–1980 A.D* (94 pp). Kathmandu: Tribhuvan University.

Khanal, N., & Watanabe, T. (2005). Landslide and debris flow hazards induced by heavy precipitation in Nepal. In *Proceedings of Himalaya international symposium on landslide Hazard in orogenic zone from the Himalaya to island arc in Asia* (pp. 111–118). Nepal Landslide Society, Kathmandu.

Kienholz, J., Hafner, H., & Schneider, G. (1984). Mountain hazards mapping in Nepal's middle mountains, maps of land use and geomorphic damage (Kathmandu-Kakani area). *Mountain Research and Development, 3*(3), 195–220.

Laban, P., 1979. *Landslide occurrence in Nepal* (p. 27). HMG/FAO and UNDP, Ministry of Forest, Department of Soil Conservation, Integrated Watershed Management, Nepal.

Le Fort, P. (1975). Himalayas: The collided range. Present knowledge of the continental arc. *American Journal of Science, 275*(1), 1–44.

Malakar, Y. (2014). *Community-based rainfall observation for landslide monitoring in western Nepal, landslide science for a safer geoenvironment* (pp. 757–763). Cham: Springer.

Maskey, S. (1999). A case study of the Krishna Bhir slope failure disaster: Past and present scenario at a glance. *International Journal of Rock Engineering and Mechanics, 2*(1–11).

McAdoo, B. G., Quak, M., Gnyawali, K. R., Adhikari, B. R., Devkota, S., Rajbhandari, P. L., & Sudmeier-Rieux, K. (2018). Roads and landslides in Nepal: How development affects environmental risk. *Natural Hazards and Earth System Sciences, 18*(12), 3203–3210.

Meena, S. R., Ghorbanzadeh, O., & Blaschke, T. (2019). A comparative study of statistics-based landslide susceptibility models: A case study of the region affected by the Gorkha earthquake in Nepal. *ISPRS International Journal of Geo-Information, 8*(2), 94.

MercyCorps. (2014). *Piloting monitoring system for Early Warning System (EWS) of landslides in far-West Nepal* (p. 54). Kathmandu: MercyCorps.

Michoud, C., Bazin, S., Blikra, L. H., Derron, M.-H., & Jaboyedoff, M. (2013). Experiences from site-specific landslide early warning systems. *Natural Hazards, Earth Systems Science, 13*, 2659–2673.

MoHA. (2017). *Nepal disaster report: The road to Sendai* (92 pp). Ministry of Home Affairs, Government of Nepal, Kathmandu, Nepal.

Mugnier, J., Leturmy, P., Huyghe, P., & Chalaron, E. (1999). The Siwaliks of Western Nepal: II. Mechanics of the thrust wedge. *Journal of Asian Earth Sciences, 17*(5–6), 643–657.

Nakayama, K., & Ulak, P. D. (1999). Evolution of fluvial style in the Siwalik group in the foothills of the Nepal Himalaya. *Sedimentary Geology, 125*(3–4), 205–224.

Nepal, K. M. (1992). *Landslide hazard zonation of Kulekhani catchment area Central Nepal* (101 pp). Indian School of Mines, Dhanbad, India.

Oven, K., & Rosser, N. (2017). *Landslide Hazard assessment, report for Mission east, community development society, the local disaster management committee and the affected in ward 6 of Bijulikot DVC* (p. 14). Ramechhap District, Central Nepal. Durham University.

Petley, D. N., Hearn, G. J., Hart, A., Rosser, N. J., Dunning, S. A., Oven, K., & Mitchell, W. A. (2007). Trends in landslide occurrence in Nepal. *Natural Hazards, 43*(1), 23–44.

Phaiju, A., Malakar, Y., Ghimire, A., Pokharel, A. K., & Shrestha, R. (2012). *Estimating landslide probability, A community based approach for rainfall monitoring*. European Commission, MercyCorps, Practical Action.

Piciullo, L., Calvello, M., & Cepeda, J. (2018). Territorial early warning systems for rainfall-induced landslides. *Earth-Science Reviews, 179*, 228–247.

Poudel, M., Bhattarai, D., & Tiwari, B. (2001). Landslide monitoring: A case study of the km 19 landslide along the Kathmandu-Trishuli road, Central Nepal. In L. Tianchi, S. R. Chalise, &

B. N. Upreti (Eds.), *Landslide Hazard mitigation in the Hindu Kush-Himalayas*. Kathmandu: International Centre for Integrated Mountain Development.

Regmi, A. D., Yoshida, K., Pourghasemi, H. R., Dhita, L., & M.R. and Pradhan, B. (2014). Landslide susceptibility mapping along Bhalubang – Shiwapur area of mid-Western Nepal using frequency ratio and conditional probability models. *Journal of Mountain Science, 11*(5), 1266–1285.

Rimal, D. N., & Tater, J. M. (1968). *Taplejung landslide (a report on aerial survey)*. Kathmandu: Nepal Geological Survey, Ministry of Industry and Commerce.

Roback, K., Clark, M. K., West, A. J., Zekkos, D., Li, G., Gallen, S. F., Chamlagain, D., & Godt, J. W. (2018). The size, distribution, and mobility of landslides caused by the 2015 Mw7. 8 Gorkha earthquake, Nepal. *Geomorphology, 301*, 121–138.

Sharma, C. K. (1981). *Landslide and soil erosion in Nepal*. Kathmandu: Sangeeta Sharma.

Thapa, P. S., & Adhikari, B. R. (2019). *Application of low-cost community based landslide early warning systems in the Nepal Himalaya* (p. 14). Thailand: International Symposium on Disaster Resilience and Sustainability Development, AIT.

Thouret, J. C. (1981). *Geodynamique des Grands Versants de L'Ankhu Khola, Nepal Central* (p. 281). Paris, France: Centre NAtional de la Recherche Scientifique (CNRS).

UNDRR. (2019). *Disaster loss data for sustainable development goals and Sendai framework monitoring system*. United Nations disaster risk reduction, https://www.desinventar.net/. Access 2 July 2020.

Upreti, B. (1999). An overview of the stratigraphy and tectonics of the Nepal Himalaya. *Journal of Asian Earth Sciences, 17*(5–6), 577–606.

Upreti, B. N., & Dhital, M. (1996). *Landslide studies and management in Nepal*. Kathmandu: ICIMOD.

Van der Geest, K. (2018). Landslide loss and damage in Sindhupalchok District, Nepal: Comparing income groups with implications for compensation and relief. *International Journal of Disaster Risk Science, 9*(2), 157–166.

Wagner, A. (1983). *The principal geological factors leading to landslides in the foothills of Nepal. A statistical study of 100 landslides: Steps for mapping the risks of landslides*, Department of Roads, SATA, ITECO, Nepal.

Wagner, A., Leite, E., & Oliver, R. (1988). Rock and debris slide risk mapping in Nepal, a user friendly PC system for risk mapping. In *Fifth international symposium on landslides lausanne* (pp. 1251–1258). Switzerland.

WECS/DHMN. (1996). *Methodologies for estimating hydrologic characteristics of ungauged locations of Nepal* (Vol. 2-Annexes). Water and energy commission secretariat and Department of Hydrology and Meteorology of Nsepal.

White, P. G., Fort, M., & Shrestha, B. L. (1987). Prototype 50000 scale mountain hazard mapping in Nepal. *Journal of the Nepal Geological Society, 4*(1 & 2), 43–53.

Yadav, R. N. (1976). *Preliminary geological report on Jharlang Area* (p.32). Central Nepal, Department of Mines and Geology, HMG, Nepal.

Yagi, H., Maruo, Y., Saijo, K., & Nakamura, S. (1990). The Sept. 1988 large landslide in the vicinity of MCT, Darbang, Nepal. *Journal of the Japan Geological Society, 26*(4), 45–49.