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Spatio-Temporal Analysis of Landslide Distribution and Its Impacts in Nepal

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Abstract

Landslides pose a significant threat globally Nepal located in the Himalayas, exhibits diverse climatic zones and experiences a considerable amount of rainfall during the monsoon season. Landslide occurrences in Nepal are frequent, attributed to active seismotectonic activities, a fragile landscape, and land use practices. The spatial distribution of rainfall in Nepal varies by season due to the influence of different atmospheric phenomena. The study investigates the temporal and spatial patterns of rainfall-induced landslides in Nepal, over the past two decades with a specific focus on the impact of extreme precipitation events. Spearman rank correlation is employed to analyze monotonic relationship between the frequency of landslide incidents with the severity of impact. The results reveal an increasing trend in the number of landslide events and associated fatalities in Nepal, with a nonlinear relationship between events and deaths. Central Nepal experiences the highest concentration of deaths due to factors such as population growth, rural-urban migration, rapid urbanization, and haphazard road construction, particularly in rural areas.

Furthermore, compared to the Tarai region and the mountains, the number of fatalities is higher in the hills.

Introduction

Natural disasters particularly landslides present considerable threats to communities worldwide (Svalova et al., 2019). In recent years, the occurrence rate and severity of landslides have increased due to the combination of geological, climatic, and human-induced factors, transforming them into an ever-growing disaster threat (Petley et al., 2007 & Sati et al., 2011). Mass movements recognized as landslides emerge when soil, rock, and other debris slide down a slope due to gravity. Intense rains, earthquakes, or human activity bring the events (Walker et al., 2012). The impacts of landslides can be devastating, causing loss of life, infrastructure damage, and livelihood disruption. Assessing landslide risk is essential for informing disaster risk reduction strategies and building resilient communities (Dai et al., 2005). Vulnerability to landslides is not solely determined by natural hazards but is also shaped by intricate social, political, and economic factors (Blaikie et al., 1996). To effectively mitigate the impacts of these disasters and foster sustainable development, it is necessary to comprehensively understand potential hazards, the elements that contribute to vulnerability, and the probabilities and consequences of associated risks (Peters et al., 2019).

Landslides occurs in various geographic and environmental situations based on the features of the area's land formations, rock composition, soil type, water systems, weather patterns, how the land is utilized, and human influences (Tsangaratos & Ilia, 2016). Landslide is a frequent natural disaster in mountainous areas around the globe (Shirzadi et al., 2017). Landslides typically occur in regions with high elevations and steep surface slopes (Zhao et al., 2017). The Himalayan region, in particular, stands out as a hotspot for landslide occurrences, exacerbating the vulnerability of populations residing in the areas (Nadim et al., 2013; Petley 2012; Froude & Petley, 2018). Natural disasters cause severe damage to communities, affecting both people's lives and their livelihoods (Al Mamun et al., 2023). Landslides rank among the most serious natural hazards in Nepal, causing significant casualties and economic losses (K.c. et al., 2024). Numerous research has demonstrated the temporal and spatial distribution of landslides globally, shows landslides are a major hazard responsible for substantial human and economic losses annually. (Froude & Petley, 2018; Aristizábal & Sanchez, 2020).

There is high risk of landslides and debris flow hazards in Nepal due to seismic activity, monsoon rains, fragile terrain, and poor agricultural practices (Nyaupane, 2022). The distribution of large-scale landslides in Nepal is influenced by various factors, including geological formations, terrain and climatic conditions (Bhandary et al., 2013 & Timilsina et al., 2014). Rainfall is a critical factor in landslide events, the interplay of intensity, duration, and soil conditions determines the actual frequency of landslides (Kirschbaum et al., 2015). The seasonal clustering of landslides during peak monsoon months of July to September underscores climate change as a key driver of past and future landslide risk (Gariano & Guzzetti, 2016).

In Nepal, fatal landslides are increasing due to land-use changes, population growth, and infrastructure development. Understanding community vulnerability requires considering both physical hazards and socio-economic factors, as people may occupy landslide-prone areas due to economic benefits, despite awareness of the risks (Aksha et al., 2019). Anthropogenic activities, such as road construction and altering the slope of mountains, are directly linked to the loss of life and property (McAdoo et al., 2018). Landslides in Nepal cause significant loss of life and property, triggering downstream floods and carrying a heavy sediment load. These events impacted around 40% of Nepal's population from 1971 to 2019 and are the primary drivers of land degradation in the country (Ghimire, 2020). Losses and damages resulting from inadequate disaster risk reduction measures, insufficient coping and adaptation strategies, and unavoidable consequences (Van der Geest., 2018).

The frequency of these landslides is particularly high in areas near tectonic movements and in areas with an average slope angle of 27-36 degrees (Bhandary et al., 2013). The earthquake in Nepal in 2015 triggered a significant number of landslides and their distribution was influenced by factors such as ground acceleration, slope, stratification and surface deformation (Martha et al., 2017). Despite the lack of systematic spatial and temporal analysis of landslide distribution and its impacts in Nepal, this study aims to analyze the temporal distribution of landslides and their effects on the socio-economic conditions in the country.

Methods and Materials

Study Area

Nepal is situated in the southern part of the Himalayas bordering Tibet of China to the north, and India to the south, east, and west. Nepal lies in between the latitude of 26° 22' to 30° 27'N and in the longitudinal line between 80° 04' to 88° 12' E and its elevation ranges from 59m at Mukhiyapatti Musharniya (Dhanusha) 59 m (194 ft) to 8848.86m at Mount Everest from the mean average sea level where the distribution of population and economic activities varied significantly (Adhikari et al., 2021).

Geological Condition

The Nepal Himalaya is located in the middle of the Himalayan arc. The Indo-Gangetic Plain, Siwaliks, Lesser Himalaya, Higher Himalaya, and Tibetan-Tethys Himalaya are the five tectonic zones that make up its geological division. The main Himalayan thrust/faults divide these zones from one another. Sand, silt, and gravel make up the Indo-Gangetic Plain, which is located in the Himalayan foothills (Mugnier et al., 1999). Conglomerate, siltstone, and sandstone make up the Siwalik. The Lesser Himalaya is covered in meta-sedimentary rocks like quartzite, limestone, and slate as well as low-grade metamorphic rocks like schists, gneiss, and marble. In a similar vein, leucogranites and superior crystalline rocks make up the Higher Himalaya, which spans the whole Nepal Himalaya. The Tibetan-Tethys Zone, which is composed of sandstone, limestone, quartzite, and shale with a fossiliferous layer on top, covers this area (Godin, 2003).

Climatic Condition

Geology and climate exert an integral part in determining the type and magnitude of landslides in these areas. The Asian monsoon, which originates in the Bay of Bengal, brings a lot of rainfall to the Nepal Himalaya throughout the monsoon season. The average yearly rainfall is less than 100 mm in Mustang and more than 2000 mm in Kaski (DHM, 2017). The majority of the districts in the far-western and western regions exhibit a rising trend in precipitation from 1971 to 2014, while the central and eastern districts exhibit a declining trend (Hamal et al., 2020).

The average monthly rainfall is high during the period from June and high in July and tends to decrease it last till September. After that, the rainfall intensity gradually decreases and quite low till December it may last till February whereas from April it tends to increase. In Gandaki Province, the precipitation rate is high compared to the other provinces. Its value rises high during the monsoon period where it ranges up to 22 mm/day during July. The Bagmati province comes after that whose precipitation rate is quite similar to the other five provinces but in Sudurpaschim Province the precipitation rate is quite low.

Data and Analysis

This study is based on secondary data, including various publications from international organizations and government agencies. The secondary data sources were the Disaster Risk Reduction (DRR) Portal, the Ministry of Home Affairs (MoHA) Disaster Management Section, and reports from the World Bank. The landslide data were specifically gathered from two primary sources: the United Nations Office for Disaster Risk Reduction's (UNDRR) Desinventar database, which covered the years 2001–2011, and the MoHA data spanning from 2012 to July 30, 2022. The collected data were processed and analyzed using Microsoft Excel software. The results were presented in various forms, including graphs, charts, figures, and tables, to facilitate visual representation and interpretation of the landslide patterns and trends. Additionally, Geographic Information System (GIS) software tools, specifically ArcGIS, were employed to develop maps and conduct spatial analyses.

Spearman Rank Correlation

A non-parametric statistical test called Spearman's rank correlation ascertains the degree and direction of a monotonic relationship between two variables. (Saltelli & Marivoet, 1990). The Spearman's rank correlation coefficient (r_s) ranges from -1 to +1, with values closer to the extremes indicating a stronger monotonic relationship among the variables, positive values indicate a direct relationship, while negative values suggest an inverse relationship.

The correlation analysis is conducted to quantify the strength and direction of the relationships between landslide frequency and its human impacts, to identify the consequences closely associated with increased landslide occurrences. The following hypotheses were tested:

H_0: *There is no monotonic relationship between the frequency of landslide incidents and the severity of impact (fatalities, affected families, and injuries).*

H_1: *There is a monotonic relationship between the frequency of landslide incidents and the severity of impact (fatalities, affected families, and injuries).*

Results and Discussion

Seasonal Trend of Landslide

There are 3860 landside events during the monsoon season, 168 during post-monsoon 166 during pre-monsoon and lastly very low 53 during the winter season (Table 1). It is clear that due to high precipitation rate in monsoon shows a higher number of landslide events where winter having a low precipitation rate shows a smaller number of events. In the monsoon period number of affected family and deaths is higher than that of other seasons. Number of private houses damage partially and fully is too remarkably higher in monsoon. But in pre-monsoon, there is a slightly higher number than in the other two seasons but it is less than in the monsoon period.

Table 1: Season-wise Landslide Distribution

Seasons	Total no. of Landslide	Affected family	Injured	Death	Private house partially damaged	Private house fully damaged
Monsoon	3860	131458	1589	2674	8421	7647
Post Monsoon	168	3207	110	224	350	221
Pre-Monsoon	166	4106	85	98	20017	133
Winter	53	1701	50	27	15	7

Source: Government of Nepal, Ministry of Home Affairs, Disaster Management Section

Spatial and Temporal Analysis

A total of 4,247 landslides were recorded during this period. The spatial distribution revealed a significant concentration of these events in the Bagmati Province, which exhibited the highest frequency of landslides. Furthermore, this province also reported the highest number of fatalities and fully damaged private houses. Following Bagmati, Koshi, and Gandaki Province also demonstrated notably high landslide occurrences. In contrast, the remaining provinces experienced fewer incidents. The data suggests a major impact on the Bagmati Province, which accounts for 30% of total landslides, 30% of injuries, 24% of fully damaged private houses, 19% of affected families, and 31% of fatalities. Similarly, Gandaki Province bears a substantial burden, with 23% of landslides, 23% of injuries, 23% of fully damaged private houses, 13% of affected families, and 20% of fatalities. Madhesh Province stands out with minimal landslide impacts. The data indicates that this province experienced negligible effects, with no landslides, injuries, fully damaged private houses, or fatalities. However, it did report 5% of families being affected.

The spatial distribution of landslides in Nepal from 2001-2022 reveals a different pattern among the provinces (Figure 1). Location descriptions were correlated with spatial databases of district administrative boundaries in order to assess the spatial precision of each landslide incidence. The concentration of landslide incidents and their severe impacts in the Bagmati Province is particularly alarming. This region's vulnerability could be attributed to a combination of factors such as steep topography, geological instability, high population density, and possibly unsustainable land-use practices.

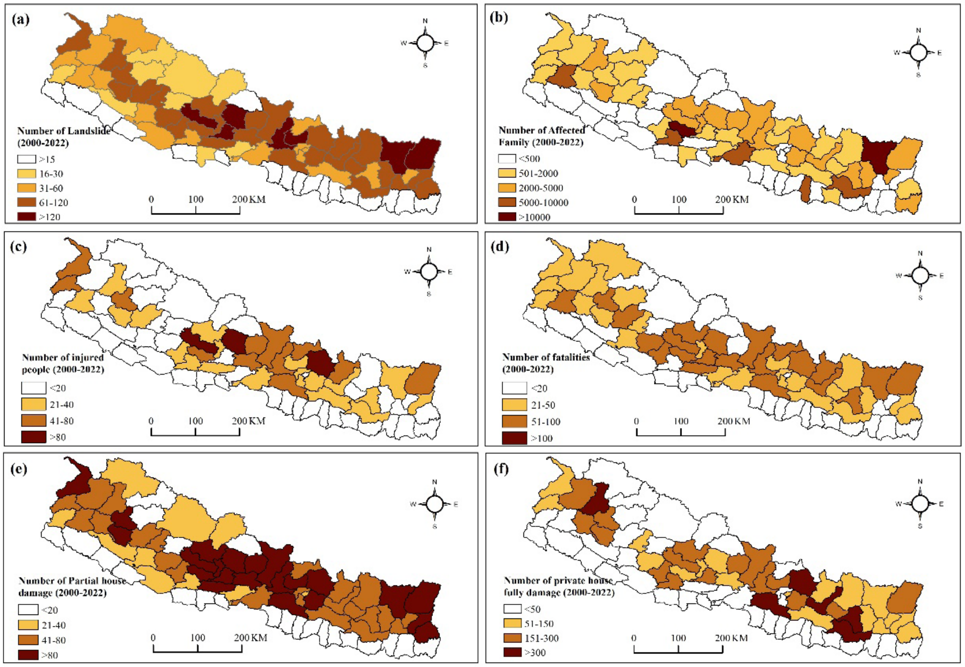

Figure 1: Spatial landslides distribution (2001-2022) :(a) Landslide, (b) Affected family, (c) Injured family, (d) Fatalities, (e) Private house partially damage, and (f) Private house fully damage

wThe high incidence of landslides in Bagmati, Koshi and Gandaki Province suggests that these regions share similar geo-environmental characteristics that predispose them to slope failures. These might include mountainous terrain, active tectonic zones, high rainfall, or human-induced changes like deforestation or poorly planned infrastructure development.

In contrast, the minimal impact observed in Madhesh Province is interesting. This stark difference could be due to its distinct geographical features, possibly a flat terrain that is less susceptible to landslides. However, 5% of families affected in this province, despite no reported landslides or direct physical impacts, suggest indirect effects. These families might have been impacted by landslides in neighboring regions, perhaps through disruptions in transportation, supply chains, or displacement of relatives.

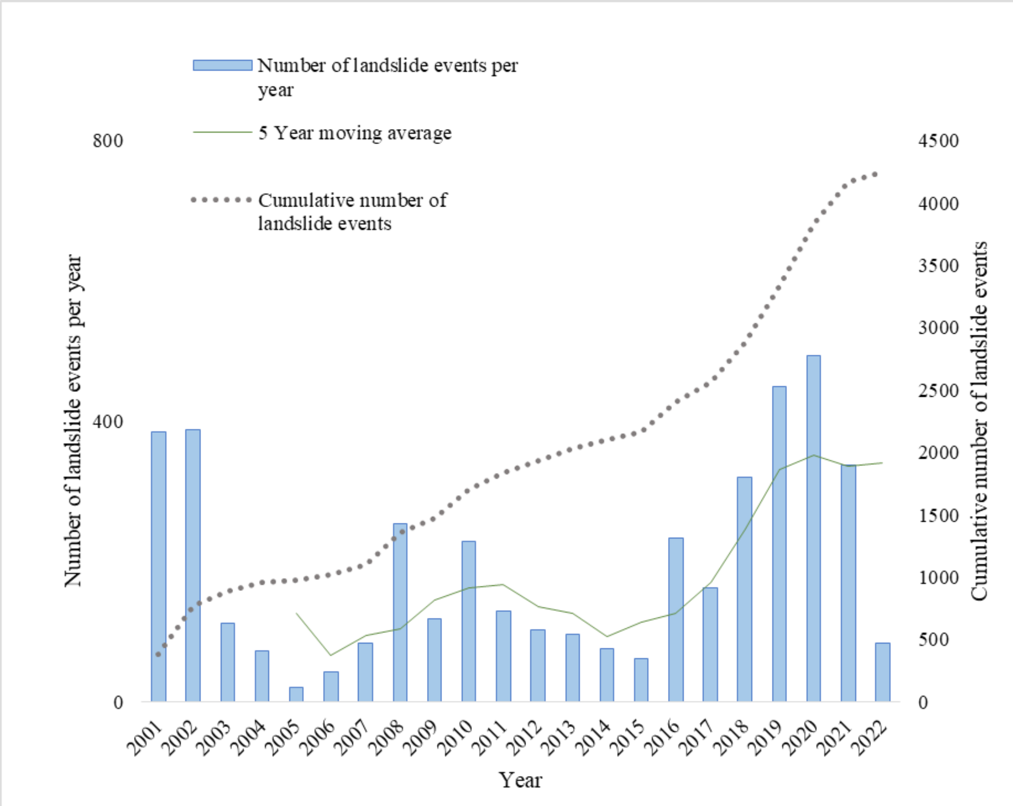

Figure 2: Landslide Events from 2001 to 2022

Further, the temporal analysis revealed a notable increase in occurrences over the study period. In the initial years, from 2001 to around 2007, the number of recorded landslide events remained relatively low, with fewer than 200 occurrences per year. This low frequency could potentially be attributed to factors such as less extensive monitoring and reporting systems or lower levels of triggering factors, such as rainfall or seismic activity, during that period (Tanyas et al., 2021). However, starting around 2008, a noticeable upward trend emerged in the annual number of landslide events. This trend became more pronounced from 2015 onwards, with several years experiencing over 600 recorded events.

Notably, the years 2019 and 2020 stand out as having the highest number of recorded landslide events, exceeding 800 occurrences, indicating an alarming increase in landslide activity during these years (Figure 2).

The 5-year moving average, represented by the solid line, shows a gradual upward trajectory, further suggesting that the frequency of landslide events has been increasing over time. Additionally, the cumulative number of landslide events, depicted by the dotted line, exhibits an exponential-like growth pattern, with the curve becoming steeper in later years, indicating an accelerating accumulation of landslide events. Though there are no definitive reasons stated for the rise in occurrences, it is probable that enhanced reporting procedures or the start of village road construction by local governments during that period contributed to the reported increase in landslide incidents.

Five years Interval Landslide Distribution

The fewest landslide events were recorded between 2006-2010 and from 2011 to 2015, despite the occurrence of the Gorkha earthquake in 2015 and 1986 in which 19, 29, and 86 people lost their lives (Lacroix, 2016). There was a lot of landslide events (≥ 100 events) between 2001–2005 and 2016–2022, the tendency of landslides varied across the span of time (Figure 3). There are no readily apparent causes the reason why there have been more incidents, despite it could be related to additional reporting or perhaps local governments began constructing village roads at that time (Heyns et al., 2021).

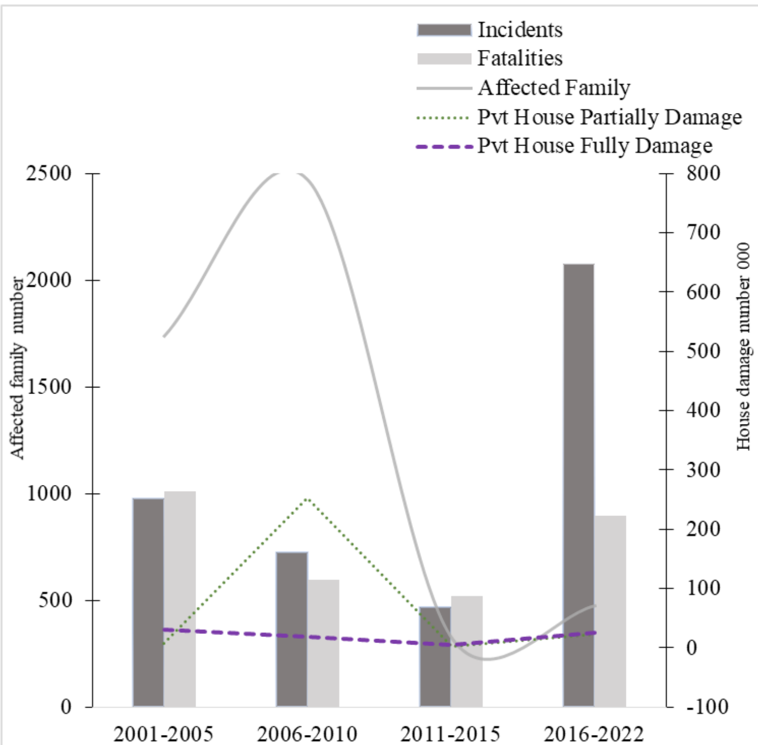

Figure 3: Five-year Interval of Incidents and Fatalities

With the intense rainfall observed in the Nepal Himalayas during 2006 and 2010, the number of impacted individuals was unprecedented (Dahal, 2012). The landslides caused significant damage to numerous properties, resulting in a loss of over nine million USD for the country during the assessed timeframe (Pandey, 2017). The significant rise in landslide incidents from 2015 onwards linked to the aftermath of the Gorkha earthquake, which not only triggered numerous landslides but also heightened awareness and documentation of such events (Valagussa et al., 2021). The rapid urbanization and population growth in hilly regions have led to more settlements in vulnerable areas, exacerbating the risk of landslides as more people and properties are exposed to these hazards (Uprety et al., 2023). The anthropogenic factors, such as deforestation and unregulated road construction, altered natural landscapes and drainage patterns, contributing to an increase in landslide occurrences (DRR Portal, 2020).

The p-values for the correlation among all variables were considerably lower than the significance level of 0.05 ($\alpha=0.05$), providing strong evidence to reject the null hypothesis. Consequently, the alternative hypothesis put forward that there is a non-zero correlation between landslide occurrences and their impacts (fatalities, affected families, and injuries), is supported by the data. Furthermore, Spearman's rank correlation coefficients (r_s) suggest a moderate positive monotonic relationship between these variables. This implies that as the number of landslide incidents increases, the number of fatalities, affected families, and injuries associated with these incidents also tends to increase.

Table 1: Test of Significance on Association between Landslide Incidents and Casualties, Affected Families, and Injured Individuals

Parameter	r_s	p-value
Incidents vs Fatalities	0.583	0.004367
Incidents vs Family Affected	0.443	0.03903
Incidents vs Injured	0.782	1.738e-9

The positive values of the correlation coefficients indicate a direct relationship, meaning Increased values of one variable are linked to higher values of the other variable. However, the moderate strength of the correlation coefficients suggests that while landslide incidents and their impacts are positively related, other factors may also contribute to the variability in the severity of impacts. These factors could include the magnitude and characteristics of the landslides, the preparedness and response efforts, the population density in affected areas, and the vulnerability of the affected communities.

The distribution of incident rates, affected families and injured counts exhibits a skewed pattern (Right Skewed). This suggests that while most time periods experienced relatively few landslide incidents, certain specific years were disproportionately affected by these events. The distribution of fatality rates resembles a normal curve, indicating most time periods experienced moderate levels of fatalities due to landslides, with fewer extreme cases at either end. The patterns observed in these pair plots suggest that while most time periods experienced relatively low levels of landslide incidents, fatalities, affected families, and injuries, there were specific time periods that were disproportionately impacted by these events (Figure 4). The positive correlation coefficient indicates that time periods with higher incident rates tended to have more affected families, fatalities, and injuries, suggesting that the severity of impacts was closely tied to the frequency of landslide occurrences in those times.

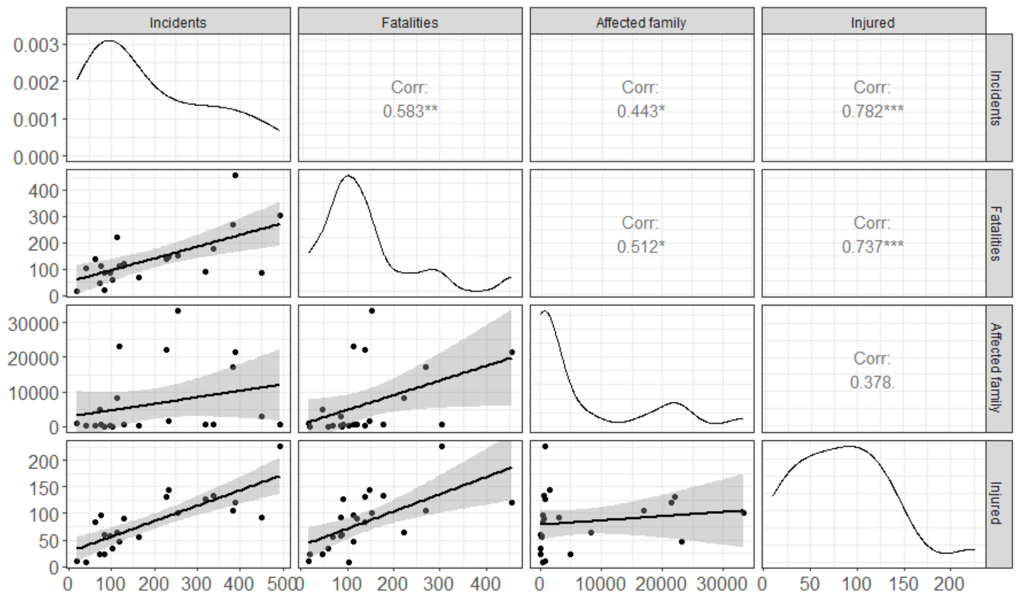

Figure 4: Relationships between the frequency of landslide incidents and the associated impacts (fatalities, affected families, and injuries), along with their corresponding Spearman's rank correlation coefficients (*p < 0.05, **p < 0.01, ***p < 0.001).

Conclusion

Landslide occurrences is frequent and attributed to active seismotectonic, influence of a strong monsoon, a fragile landscape, and landuse practices. The findings highlight the importance of tailoring landslide risk management strategies to regional contexts. High-risk provinces like Bagmati, Koshi, and Gandaki province require intensive interventions such as slope stabilization, improved drainage systems, stricter land-use regulations, and enhanced early warning systems. On the other hand, provinces with lower direct impacts should not be overlooked, as they may face indirect consequences that affect community well-being. The analysis of landslide event revealed a notable upward trend in occurrences over the study period. Further, Spearman's rank correlation analysis revealed the severity of impacts such as fatalities, affected families, and injuries was closely tied to the frequency of landslides from 2001 to 2022. While this relationship is evident, other factors beyond the frequency of incidents may also influence the severity of these impacts. Therefore, it is concluded that effective landslide risk management requires specific strategies for high-risk provinces while also addressing potential indirect impacts in lower-risk areas, as the increasing frequency of landslides correlates with severe impacts on communities.

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