Calamity
Calamity: A Journal of Disaster Technology and Engineering
Calamity 2(2): 100–115
ISSN 3025-4140

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Landslide characteristics triggering evacuations: A comparative study of community responses and disaster management approaches

Satria Indratmoko[1], Raldi Hendro Koestoer[1,*]
[1] *Environmental Science, School of Environmental Science, Universitas Indonesia, Central Jakarta, Jakarta, 10430, Indonesia.*
*Correspondence: satria@ui.ac.id

Received Date: December 3, 2024 Revised Date: January 31, 2025 Accepted Date: January 31, 2025

ABSTRACT

Landslides are one of the most dangerous geological disasters in the world due to the movement of earth material caused by gravity. Landslides also threaten the environment, property, and human life risks in high-risk areas. This study compares how landslide characteristics impact evacuation planning in Indonesia and various other countries. Utilizing a Systematic Literature Review (SLR) of studies published between 2019 and 2024, this research examines landslide characteristics that prompt community evacuation responses, such as landslide triggers, physical conditions, and the number of people affected. Findings reveal that while Indonesia and other high-risk countries face substantial landslide risks, challenges remain in enhancing disaster preparedness, including evacuation planning to minimize casualties. Physical characteristics and the preparedness of early warning systems are crucial in shaping community responses to landslides. This case study illustrates how a combination of steep slopes over 40 degrees, heavy rainfall intensity of more than 200 mm in one week, weak soil textures, and dense vegetation can trigger devastating landslides. However, landslides triggered by seismic activity result in significantly higher fatalities, and special attention is needed in areas prone to landslides and earthquakes, as happened in Nepal (highland and mountainous climate). In China (subtropic region), landslides are primarily triggered by moisture-saturated soils, which are vulnerable to ground motion, particularly during prolonged rainfall. In Indonesia as tropical region, landslides triggering evacuation predominantly occur in areas with highly erodible and unstable soils, exacerbated by high rainfall. Evacuation planning must be more adaptive and supported by GIS technology to identify high-risk areas. Globally, evacuation success relies on infrastructure, community awareness, and disaster preparedness. This study highlights the importance of crisis management strategies tailored to the specific landslide characteristics of each region, as well as the crucial role of community involvement and technology in ensuring effective evacuations.

KEYWORDS: community response; evacuation planning; GIS; landslide; landslide characteristics; systematic literature review.

1. Introduction

Landslides, floods, tsunamis, cyclones, and earthquakes are among the most frequent natural disasters, and their impacts can be catastrophic, particularly when multiple events occur simultaneously (Cutter et al., 2008, Pradhan et al., 2019). While tsunamis have the highest potential for widespread devastation due to their immense force and coastal impact, landslides occur more frequently and are responsible for the highest number of fatalities

Cite This Article:
Indratmoko, S., & Koestoer, R. H. (2025). Landslide characteristics triggering evacuations: A comparative study of community responses and disaster management approaches. *Calamity: A Journal of Disaster Technology and Engineering, 2*(2), 100-115. https://doi.org/10.61511/calamity.v2i2.2025.1437

compared to other natural disasters (Petley, 2012; Sugiarto et al., 2019). Landslides, often triggered by heavy rainfall, seismic activity, or human-induced factors like deforestation, have become a significant natural risk in many countries, including Indonesia (Glade, 2003). In fact, landslides pose a considerable threat not only in Indonesia but also in other parts of the world, particularly in mountainous regions (Highland & Bobrowsky, 2008).

According to Hadmoko et al., (2010), landslides are a common occurrence in countries with steep terrain and significant rainfall. Indonesia, with its mountainous topography and seasonal monsoons, is particularly vulnerable to landslides (van Westen et al., 2006). Fig. 1 presents global landslide event data from 2008 to 2018, illustrating the regions most affected by this type of disaster. The Pacific Northwest, High Mountain Asia, the Philippines, and Indonesia are highlighted as the major landslide hotspots, marked in red, indicating their elevated risk and frequent occurrences of landslides, which contribute to substantial loss of life and property damage (Froude & Petley, 2018).

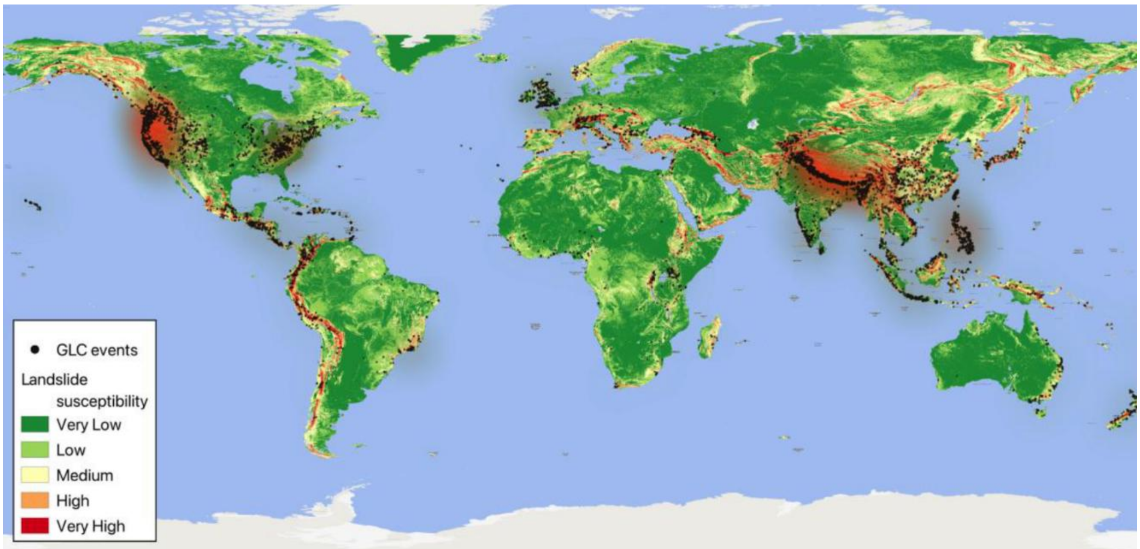

Fig. 1. Global landslide susceptibility map and landslide events (Dandridge et al., 2023)

The lack of preparedness management is a significant factor contributing to high fatalities during natural disasters (Wisner et al., 2004; Zayn et al., 2020). In the absence of effective disaster preparedness, communities become more vulnerable to the destructive impacts of natural hazards. This vulnerability often results in greater loss of life and more extensive damage to infrastructure when disasters occur (Tierney, 2007; Eslamian et al., 2021). One crucial aspect of disaster preparedness is evacuation planning, which has proven to be an effective measure in reducing fatalities and injuries (Lindell & Perry, 2003). The concept of "road to zero victims" emphasizes the importance of proactive measures such as evacuation to minimize the loss of life during disasters (Alexander, 2005; Mei et al., 2013).

Evacuation decisions often depend on the type of hazard and the level of threat it poses to the community (Cutter et al., 2008 Harris et al., 2021). Understanding the specific characteristics of hazards, such as their frequency, intensity, and potential impact, helps determine the appropriate response, including whether evacuation is necessary (Mileti, 1999). This highlights the importance of hazard mapping, which involves identifying the types of hazards prevalent in a given area. By mapping these hazards, authorities can develop tailored evacuation plans, ensuring that the community is prepared and responsive when disaster strikes. Effective mapping and preparedness can significantly reduce disaster-related risks and enhance community resilience (Berke & Campanella, 2006).

Geographic Information Systems (GIS) are crucial for assessing landslide hazards and identifying areas highly prone to landslides (van Westen et al., 2006; Ermanto, 2024). By analyzing physical characteristics, historical landslide data, and factors such as population exposure, GIS helps develop a framework for assessing landslide characteristics. This framework is vital for identifying types of landslides that necessitate evacuation (Corominas et al., 2014). This study aims to review and compare landslide characteristics that trigger evacuations, focusing on Indonesia and case studies from several countries worldwide. The goal is to enhance understanding of evacuation triggers, which can improve disaster management strategies and response efforts (UNISDR, 2015).

2. Methods

This study utilizes a Systematic Literature Review (SLR) approach to gather relevant literature on landslides and evacuation. The literature was sourced from the Scopus database, focusing on publications from 2019 to 2024. A comprehensive search query was utilized, incorporating keywords such as "landslide," "hazard," and "evacuation." In addition to these core keywords, strict selection criteria were applied to filter for articles that were marked as "final" publications and specifically from "journal" sources. This ensures the inclusion of peer-reviewed and authoritative articles in the analysis.

The search process resulted a total of 66 documents, which were saved in CSV format for further processing. These documents were then imported into VOSviewer software, which is designed to facilitate bibliometric analysis and visualization. The use of VOSviewer allows for the creation of network maps that help identify key trends, research clusters, and connections within the literature on landslides and evacuation. Fig. 2 shows the network visualization produced from this analysis, providing a clear overview of the major research themes and the relationships between various articles.

In addition to the general search process, the researchers applied strict criteria during the country analysis to ensure that only studies relevant to the specific geographical regions under consideration were included. This rigorous approach enables a focused exploration of the intersection between landslide hazards, evacuation strategies, and country-specific factors, providing valuable insights into how different regions address and manage the risks associated with landslides. The SLR methodology and the use of VOSviewer facilitate an in-depth understanding of the current landscape of landslide research, which is crucial for informing future disaster management strategies.

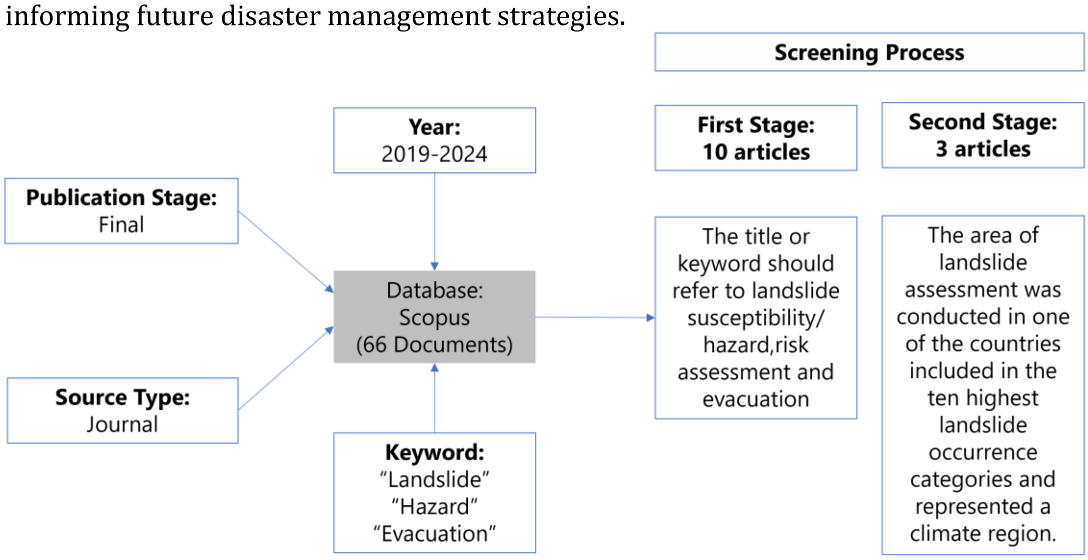

Fig. 2. The systematic review of the search criteria and screening process.

The sample area studied in this research focuses on mountainous regions, as these areas are where the majority of landslides occur due to the steep terrain and vulnerability to hydrometeorological events. The research specifically selects three countries as case studies, drawn from the ten nations with the highest frequency of landslide events and fatalities between 2004 and 2016 (Table 1). These countries Indonesia, China, and Nepal were selected not only because of their high incidence of landslides but also based on their distinct climatic regions, which are highly relevant for understanding the impact of weather patterns on landslide occurrences (Fig. 3). Landslides are classified as hydrometeorological disasters, primarily triggered by rainfall, seismic activity, and other climatic factors. As such, the selection of these countries is grounded in their unique climatic zones: China, representing the subtropical region; and Nepal, which exemplifies the highland and mountainous climate.

The tropical climate of Indonesia, characterized by high rainfall and monsoon seasons, contributes to the frequency and severity of landslides, particularly in areas with steep slopes and deforested land. Similarly, the subtropical climate in China, which experiences seasonal rains and varied topography, plays a significant role in the occurrence of landslides, especially in the mountainous regions along fault lines. Nepal, with its highland and mountainous climate, faces unique challenges in landslide risk management due to its extreme altitudes, steep slopes, and vulnerability to heavy monsoonal rainfall. These three countries, each representing different climatic conditions, provide a broad perspective on the impact of hydrometeorological factors on landslide occurrences and the associated risks.

Table 1. Comparison Top 10 the number of landslide events and the number of fatalities in the world year 2004–2016

Country	Number of Events	Number of Fatalities	Standard Deviation of Events
India	923	11.203	18.3
China	647	11.031	13.3
Philippines	479	7.749	20.2
Nepal	478	2.277	13.9
Indonesia	352	3.486	9.0
Pakistan	257	2.690	7.4
Bangladesh	153	747	12.1
Vietnam	144	803	4.0
Brazil	136	2.754	9.0
Colombia	129	1.566	6.4

Global Fatal Landslide Data
(Froude & Petley, 2018)

Table 1. provides a comparison of the top 10 countries with the most significant landslide events and fatalities between 2004 and 2016. India leads the list with the highest number of landslide incidents, recording 923 events and 11.203 fatalities. China follows closely with 647 landslide events and 11.031 fatalities. The Philippines, Nepal, and Indonesia round out the top five, with Indonesia experiencing 352 landslides and 3.486 fatalities during the same period. This data underscores the increasing frequency and severity of landslides in these countries, highlighting the urgent need for more effective disaster preparedness and risk reduction measures.

The trend reflected in Table 1 reveals a concerning rise in disaster-related fatalities in countries with high landslide occurrences. From 2004 to 2016, these nations experienced a steady increase in the number of fatalities due to landslides, with India and China consistently ranking as the countries with the highest death tolls. The increasing number of landslide events and fatalities calls for a deeper examination of the factors contributing to this trend. It also highlights the need for improved disaster management strategies, including early warning systems, evacuation plans, and community-based preparedness programs, to address the escalating landslide risk in these regions.

This growing trend of landslide fatalities emphasizes the critical need for research into disaster preparedness, specifically tailored to the unique characteristics of each country's climate and geography. As these nations continue to face the dual challenges of rapid urbanization and climate change, it becomes increasingly important to understand how different environmental and socio-economic factors intersect to exacerbate landslide risk.

The findings of this research aim to provide valuable insights that can help improve disaster response strategies, mitigate fatalities, and enhance the overall resilience of communities in landslide-prone areas.

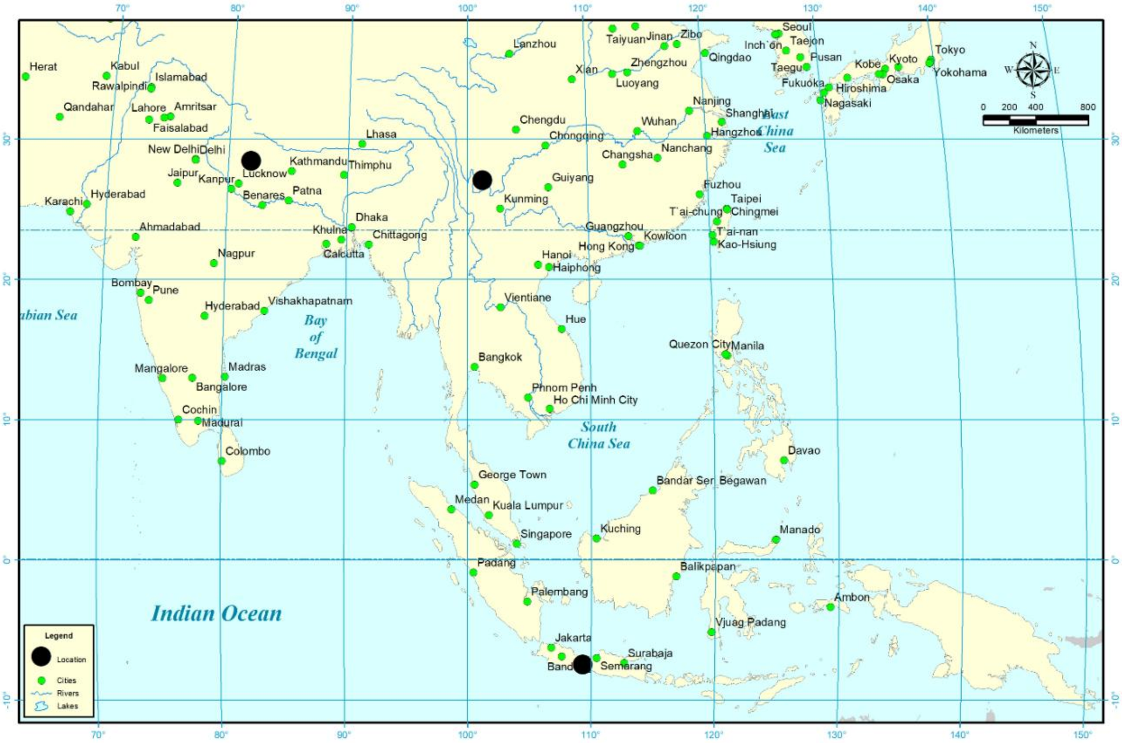

Fig. 3. The location of study

Reviewing landslide characteristics that prompt community evacuations involves comparing several key aspects, including the physical characteristics of landslide-prone areas, historical landslide data, landslide triggers, and the number of affected populations. The physical characteristics in this context include the extent of the landslide, slope conditions, rainfall levels, land use patterns, and soil types.

3. Results and Discussion

3.1 Global trends in landslide and evacuation

The VOS Viewer network visualization reveals several main thematic clusters related to "Landslide & Evacuation" (Fig. 3). Four dominant color clusters each represent distinct research focus areas. The red cluster includes themes like early warning systems, risk assessment, and emergency response, emphasizing preparedness and mitigation efforts for landslides and disaster response. The blue cluster, which shows landslide evacuation, focuses on evacuation modeling and landslide hazard assessment for supporting disaster preparedness. This is in accordance with the study by Harris et al. (2021), which stated that an essential part of evacuation planning is knowing the locations and understanding of landslide hazards, vulnerable areas, and potentially exposed communities. The green cluster covers earthquake events, geological hazard, and volcanic islands, highlighting natural phenomena, particularly earthquakes and geological processes affecting land stability. This is in accordance with the research findings of Pradhan et al. (2019); at the local and regional levels, slope failure is frequently associated with the triggering variables that aid mass movement, which include significant precipitation, seismic activity, volcanic activity, and flooding. The yellow cluster centers on flooding, humans, and disasters, addressing the impact of disasters on communities, including flood events often linked to landslides.

At the center of this visualization, landslide appears as the core topic, underscoring its central role in this research network. Landslide connects strongly to various concepts such as risk assessment, hazard assessment, and evacuation, all essential in mitigating and managing landslide disasters. Hazard and risk assessments are particularly prominent around the landslide theme, emphasizing the importance of evaluating risk and hazards to anticipate impacts and prepare effective early warning systems.

The connection between the early warning system and evacuation suggests that early warning is crucial to providing adequate time for community evacuation. Additionally, the links between disasters, humans, and risk perception underscore the importance of community understanding of disaster risks and the need for education to enhance preparedness. The use of GIS (Geographic Information Systems) across several topics further highlights the vital role of GIS technology in mapping landslides and other disaster risks.

Social and environmental aspects are also reflected in connections between risk perception and humans, indicating the need to understand public risk perception and the impacts of disasters on communities. Furthermore, terms like landscape evolution and slope instability emphasize the role of geological factors in landscape changes and land stability, which directly influence landslide risk, especially in hilly and slope-prone areas.

The emphasis on themes such as mitigation measures and monitoring in this visualization suggests that this research area may offer concrete policy recommendations for landslide mitigation, such as improving early warning systems and rapid disaster response. Integrating geological analysis and GIS technology in this network can support better decision-making, including developing accurate data-based evacuation simulations.

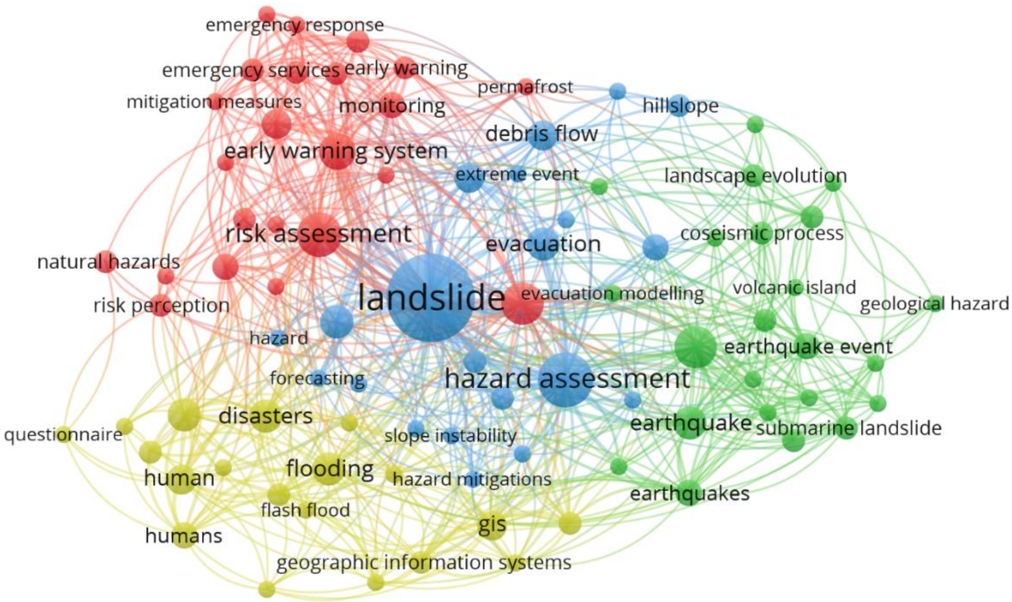

Fig. 4. Keywords associated with landslide, hazard assessment, and evacuation

The VOS Viewer network visualization reveals temporal and thematic trends in landslide and evacuation research from 2020 to 2023 (Fig. 4). Central terms like "landslide," "risk assessment," "hazard assessment," and "evacuation" form the core of this research area, indicating a foundational focus on understanding and managing landslide-related hazards. The visualization shows an evolution in research priorities over time. Studies from earlier years (represented in blue, around 2020-2021) emphasize "risk perception," "natural hazards," and "questionnaire," suggesting a focus on assessing public awareness and attitudes toward landslide risks. These studies likely aimed to gather baseline information on community perceptions, which can inform evacuation strategies and public engagement efforts.

In recent years (2022-2023), there has been a notable shift towards practical and technical topics. Terms like "evacuation," "hazard assessment," and "geological hazard" are highlighted in yellow, reflecting a growing interest in real-time hazard assessment and the application of geological data in evacuation planning. The prominence of the "early warning system" in recent research also indicates advancements in technology for monitoring landslide-prone areas, which are critical for timely evacuations and disaster response.

Spatial analysis using GIS has become a significant element in this field, as indicated by terms like "GIS" and "geographic information systems." This trend demonstrates an increasing reliability of GIS in evaluating landslide risks, optimizing evacuation routes, and supporting hazard mitigation planning. Furthermore, the presence of terms such as "earthquake event," "submarine landslide," and "coseismic process" points to a deeper exploration of geological factors that may trigger landslides, particularly in seismically active regions.

Additionally, terms like "flooding," "flash flood," and "human" underscore an ongoing interest in the interaction between various natural hazards and their impact on communities. These studies highlight the compounded risks of flooding and landslides in vulnerable regions. Overall, the visualization illustrates a trend from understanding risk perception and general hazard awareness to developing advanced, technology-driven approaches for hazard assessment and evacuation planning. This progression underscores the shift toward data-driven strategies, supported by GIS and early warning systems, to enhance community resilience against landslide hazards.

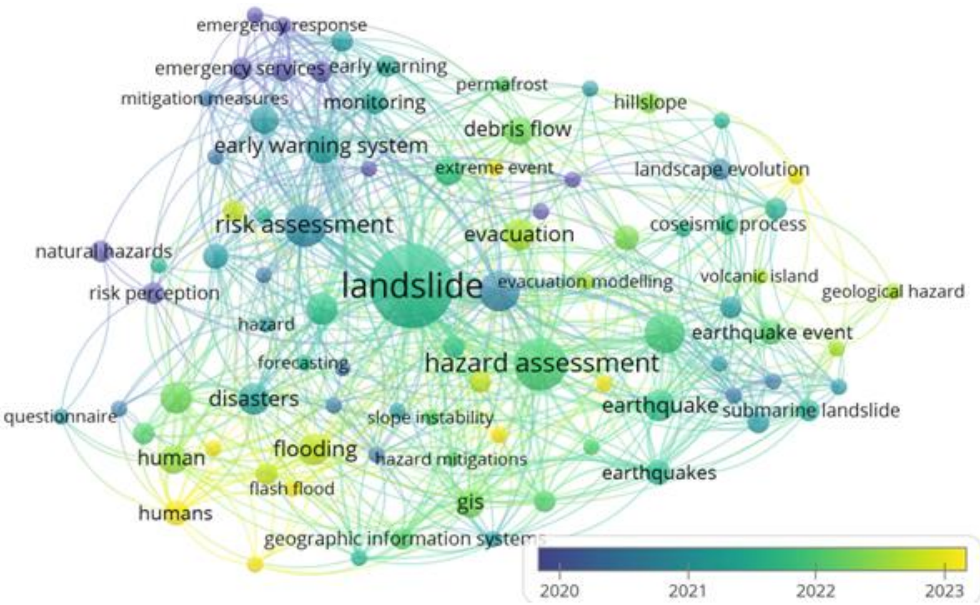

Fig. 5. Network visualization of landslide and evacuation research topics (2020-2023)

3.2 Landslide characteristics triggering evacuation in Indonesia & global case studies

Evacuation is not always the immediate or top priority during disasters, as not every disaster event necessitates evacuation. The decision to evacuate largely depends on the specific characteristics of the disaster and the behavior of the affected community. In some cases, the nature of the disaster may not pose an immediate threat to life, rendering evacuation unnecessary or impractical. However, in life-threatening situations, such as severe landslides or earthquakes, evacuation can significantly reduce fatalities and minimize the impacts on individuals and communities. The decision-making process surrounding evacuation is influenced by various factors, including human behavior, perception of risk, the urgency of the danger, and the logistics of movement (Aldahlawi et al., 2024; Bakhshian & Pastor, 2023). Understanding these factors is critical to improving the effectiveness of evacuation strategies and ensuring that communities are better equipped to respond to imminent threats.

One notable gap in current research is the limited focus on evacuation in response to landslides. A review of existing studies reveals that there is still a need for more in-depth investigation into how communities react to landslides and the decision-making processes involved. Although the dynamics of evacuation have been studied in relation to other types of natural disasters, such as floods and earthquakes, landslides present unique challenges that have not been sufficiently addressed in the literature (Bakhshian & Pastor, 2023). The lack of comprehensive studies on landslide characteristics further exacerbates the issue, as communities often lack the necessary information to assess the severity of a landslide event and determine whether evacuation is warranted. This lack of understanding can lead to confusion and delays in evacuating, which may result in unnecessary casualties and increased damage. Therefore, enhancing the understanding of landslide risks is essential for improving disaster preparedness and enabling communities to make informed decisions regarding evacuation.

The VOSviewer analysis of international collaboration in the field of landslide and evacuation research further underscores the need for a more coordinated approach to this critical area of study (Fig. 5). The network visualization of the research landscape highlights several key contributors, including China, India, the United States, Japan, and the United Kingdom. These countries are the core players in this research domain, as evidenced by their larger node sizes, which indicate a high volume of publications and citations in the field. This suggests that these countries are at the forefront of landslide research and are leading efforts to understand the dynamics of landslides, evacuation strategies, and community responses. Their leadership is instrumental in shaping the global discourse on disaster management and evacuation planning.

In contrast, Indonesia, a country that is highly susceptible to natural disasters, particularly landslides, is notably underrepresented in the research on landslide characteristics and evacuation responses. The relatively limited number of publications from Indonesia indicates an urgent need for more focused research in this area. Indonesia is often referred to as a "disaster research laboratory" due to its vulnerability to a range of natural disasters, including earthquakes, volcanic eruptions, and landslides. Given its high exposure to landslide risks, particularly in rural and mountainous areas, there is an imperative to increase research efforts aimed at understanding how communities in Indonesia respond to landslide threats and how evacuation strategies can be tailored to local contexts. By enhancing research on landslides and evacuation, Indonesia can better prepare for future disaster events and improve its disaster risk management strategies.

The findings from the VOSviewer analysis and the review of current literature highlight the need for greater collaboration and research in the field of landslide risk management and evacuation. By improving understanding of landslide characteristics and enhancing community preparedness, it is possible to reduce the devastating impacts of these natural disasters and save lives. Further research and international cooperation in this area are essential to ensuring that vulnerable regions are adequately equipped to respond to the growing threat of landslides.

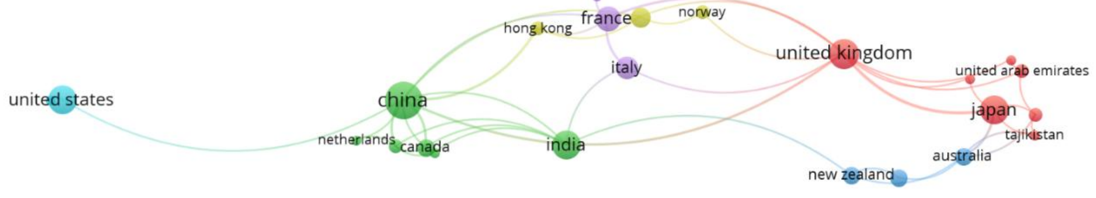

Fig. 6. International collaboration network in landslide and evacuation research

3.3 Landslide characteristics triggering evacuation in Indonesia

Banjarnegara Regency, located in Central Java Province, Indonesia, is one of the areas that has historically experienced a high frequency of landslides. The frequency of such events in the region has significantly escalated over the past decade. According to the Banjarnegara Regional Disaster Management Agency, the number of landslides reported in the area increased from 57 in 2007 to 76 in 2008, and further rose to 126 in 2009. However, the most dramatic increase occurred in 2010, when the number of landslides surged to 200. Over the last ten years (2014-2024), the region has witnessed a total of 175 landslide events, which have led to 119 fatalities and caused the displacement of 8,495 individuals (BNPB, 2024). The escalation of landslide incidents in Banjarnegara highlights the increasing vulnerability of this region to such natural disasters, particularly in light of its unique topographical and climatic characteristics.

In 2014, one of the most devastating landslides occurred in the Telaga Lele Hills, which resulted in a significant loss of life and widespread displacement. This event, as reported by Setiawan & Tanjung (2024), resulted in the deaths of 99 people, with 2,038 individuals displaced, and 13 people reported missing. The primary causes of this tragic event were linked to a combination of physical conditions that made the area particularly susceptible to landslides. The slopes in the region are extremely steep, with gradients reaching up to 45°, which is known to significantly increase the risk of soil movement, particularly during periods of heavy rainfall. Over the three days preceding the landslide, the area received intense rainfall, with an average daily rainfall intensity of 214.5 mm. This heavy precipitation saturated the soil, making it prone to failure. In addition, the altitude of the area, which exceeds 1,000 meters above sea level, further exacerbated the risk of landslides due to the combination of steep terrain and high rainfall accumulation.

The geographical characteristics of the Telaga Lele Hills region are also a major contributing factor to the occurrence and severity of landslides. The area is surrounded by a 15-hectare village, rice fields, and mixed gardens, with seasonal crops such as mustard greens and cabbage being cultivated on the steep slopes. These crops, though resilient to some extent, are not enough to prevent the destabilization of the soil in the face of extreme weather conditions. The hilly topography, combined with weak soil texture, further increases the vulnerability of this region to landslides. In total, the area affected by the landslide in 2014 spanned approximately 22.7 hectares (Fig. 6). This event underscores the critical need for better landslide risk management strategies in the region, including enhanced monitoring of weather patterns, early warning systems, and more effective land-use planning to mitigate the impact of such disasters in the future.

The devastating landslide in Banjarnegara serves as a stark reminder of the growing frequency and intensity of natural disasters in Indonesia, driven by a complex interplay of geological, climatic, and human factors. It also highlights the importance of improving disaster preparedness and response systems, especially in areas with high landslide risks, to minimize fatalities and displacement in the future. By better understanding the local conditions and investing in appropriate risk reduction measures, it is possible to mitigate the impact of such events and safeguard the livelihoods of those living in vulnerable areas.

Fig. 7. Landslide event location, Telaga Hills, Banjarnegara Regency
(Setiawan & Tanjung, 2024)

3.4 Landslide characteristics triggering evacuation in China

In 2018, a major landslide occurred in Boli Village, located in Taozi Town, Yanyuan County, Sichuan Province, in southwestern China. This event has drawn considerable attention due to the significant damage it caused to both infrastructure and agricultural land, yet it also highlighted the critical role of effective early warning systems and evacuation protocols in mitigating the impacts of natural disasters. Despite the destruction of 186 houses and approximately 300 acres of agricultural land, no casualties were reported among the 281 individuals at risk. This outcome was largely attributed to the swift and efficient evacuation facilitated by the early warning system, which allowed the local population to be evacuated in time before the landslide struck. The contrast between this case and some other landslide events, particularly in countries like Indonesia, underscores the importance of timely evacuation in reducing the death toll and the scale of destruction.

The landslide originated from a densely vegetated mountainous region with an elevation of over 3,346 meters above sea level. According to a field investigation by Hu et al. (2019), the landslide location is situated between two major geological faults, adding a layer of complexity to the regional geologic conditions. The landslide occurred as a result of various triggering factors, with rainfall being one of the primary contributors. Specifically, the region experienced a long-duration, low-intensity rainfall period from May 1 to July 18, accumulating a total of 817.4 mm. Additionally, the rainfall intensity was particularly high in the six days preceding the failure, with 260 mm of rain recorded, which significantly weakened the stability of the soil. This saturation of the soil, coupled with prolonged rainfall, triggered the massive landslide.

In addition to meteorological factors, the topographical and geological conditions of the area also played a crucial role in the landslide's occurrence. The terrain around the landslide site exhibits slopes ranging from 8 to 45 degrees (Fig. 7), which fall within a critical range for triggering landslides when subjected to significant external stresses such as heavy rainfall. The steep gradients in combination with high rainfall intensity significantly increased the likelihood of slope failure. The land's susceptibility to mass movement was exacerbated by the region's unique geologic structure, which included the presence of major fault lines that likely contributed to the destabilization of the land during periods of intense rainfall.

The landslide in Boli Village serves as an important case study in understanding the complex interaction between geological, meteorological, and human factors in natural disaster occurrences. Moreover, it emphasizes the vital role that early warning systems and evacuation plans play in reducing the loss of life during such events. The experience in Boli highlights that a proactive approach, combining effective monitoring of meteorological conditions, geological assessments, and swift evacuation procedures, can substantially minimize the devastating impacts of such disasters. This event also underscores the need for ongoing research and improvements in disaster risk management, particularly in regions vulnerable to landslides and other natural hazards.

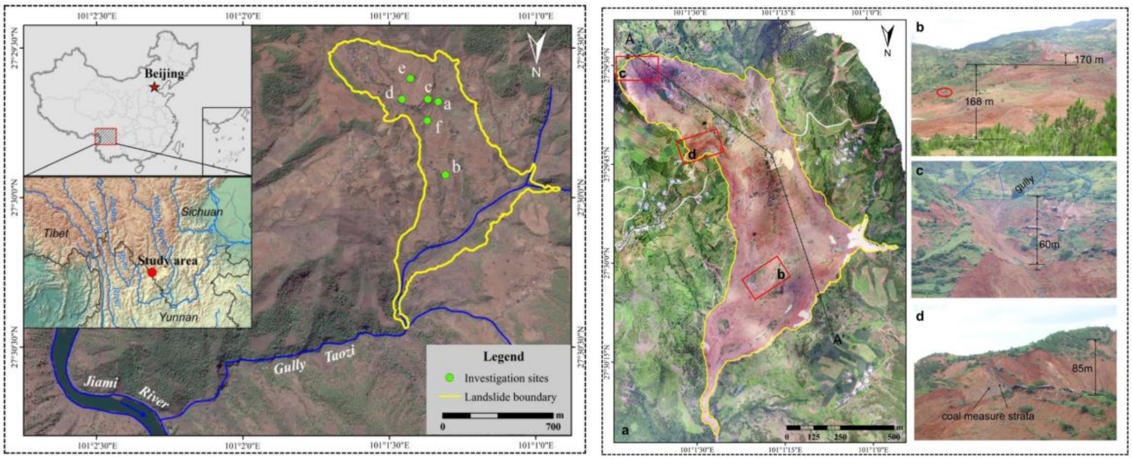

Fig. 8. Landslide event location, Sichuan Province, China
(Hu et al., 2019)

3.5 Landslide characteristics triggering evacuation in Himalayas Mountains, Nepal

On April 25, 2015, Nepal experienced a devastating earthquake, which marked the first significant seismic event in the Himalayan Subduction Zone in nearly seven decades. This powerful earthquake, known as the Gorkha earthquake, triggered widespread landslides, leading to catastrophic consequences for the affected regions (Liu, Li, Li, et al., 2023). According to Gnyawali & Adhikari (2017), the earthquake instigated 19,332 co-seismic landslides that covered an extensive area of 61.5 km^2 within the broader 20,500 km^2 region affected by the earthquake. These landslides occurred at elevations ranging between 1,000 and 3,000 meters above sea level, primarily in the transition zone between the High and Low Himalayas along the Main Central Thrust, a prominent fault line in the region. This area, characterized by steep slopes and fragile geology, is particularly vulnerable to landslides, and the seismic activity from the earthquake significantly exacerbated this risk.

The landslides triggered by the Gorkha earthquake had devastating human and environmental impacts. As reported by Subedi et al. (2019), the earthquake-related landslides resulted in the tragic loss of 8,970 lives, left 198 individuals missing, and caused serious injuries to 22,303 people (Subedi et al., 2019). The damage was widespread, with numerous communities across Nepal being affected. The different types of landslides observed during the earthquake varied in scale and severity, ranging from shallow disrupted slope failures to more destructive rockfalls, dry debris flows, and massive landslides. Among these, shallow disrupted slope failures were the most common, accounting for a significant portion of the landslide events. These types of landslides typically involve the destabilization of upper layers of soil and rock, leading to localized failures along slopes, often with less velocity but still significant enough to cause destruction in the affected areas.

The geological conditions of the region, particularly the steep slopes, played a crucial role in the occurrence of these landslides. Dominant slopes in the affected areas ranged between 30 and 45 degrees, a range that is particularly prone to landslide activity during seismic events (Liu, Li, Li, et al., 2023; Liu, Li, Nan, et al., 2023). The combination of steep terrain, fragile soil structures, and intense seismic forces created an environment where even relatively minor disturbances could trigger massive landslides. The interplay between the earthquake's seismic waves and the region's complex topography highlights the vulnerability of the Himalayan region to such natural disasters.

In addition to the immediate impacts, the landslides also caused long-term disruptions to the affected regions. Infrastructure such as roads, bridges, and buildings was severely damaged, making relief efforts difficult and further complicating recovery processes. The widespread displacement of communities and destruction of agricultural land led to significant socio-economic challenges, exacerbating the effects of the earthquake. As such, the 2015 earthquake serves as a stark reminder of the vulnerability of the Himalayan region to both seismic and landslide hazards, underlining the importance of better disaster preparedness, risk mitigation strategies, and improved infrastructure resilience.

The devastating impact of the Gorkha earthquake and the subsequent landslides also underscores the need for comprehensive geological assessments and monitoring in seismically active regions. Understanding the interplay between seismic events and landslide hazards is crucial for improving early warning systems and evacuation strategies, which can save lives and reduce the overall impact of such disasters. In particular, the case of the Gorkha earthquake highlights the importance of focusing on vulnerable mountainous areas with steep slopes and fragile soil structures in disaster management planning.

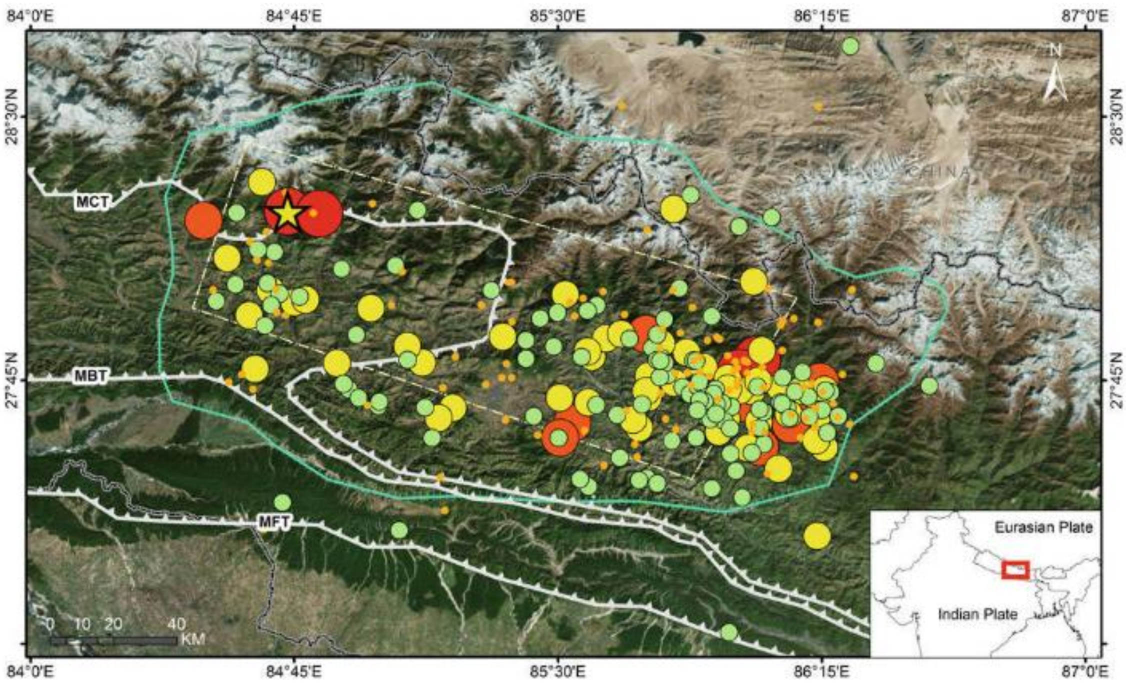

Fig. 9. Landslide location overlaying with seismic map in Himalayas (Gnyawali & Adhikari, 2017)

4. Conclusions

Physical characteristics and the preparedness of early warning systems are crucial in shaping community responses to landslides. This case study illustrates how a combination of steep slopes over 40 degrees, heavy rainfall intensity of more than 200 mm in one week, weak soil textures, and dense vegetation can trigger devastating landslides. However, landslides triggered by seismic activity result in significantly higher fatalities, and special attention is needed in areas prone to landslides and earthquakes, as happened in Nepal (highland and mountainous climate). In China (subtropic region), landslides are primarily triggered by moisture-saturated soils, which are vulnerable to ground motion, particularly during prolonged rainfall. In Indonesia as tropical region, landslides triggering evacuation predominantly occur in areas with highly erodible and unstable soils, exacerbated by high rainfall. Evacuation planning must be more adaptive and supported by GIS technology to identify high-risk areas. Globally, evacuation success relies on infrastructure, community awareness, and disaster preparedness. This study highlights the importance of crisis management strategies tailored to the specific landslide characteristics of each region, as well as the crucial role of community involvement and technology in ensuring effective evacuations.

Acknowledgement
Authors would like to express our sincere gratitude to the editorial team and reviewers for their invaluable contributions in evaluating and reviewing this scientific article. Their insightful comments, constructive feedback, and meticulous assessment have significantly enhanced the quality and rigor of this work.

Author Contribution
All authors have equally contributed to the conception, writing, and revision of this article, ensuring its accuracy and integrity.

Funding
This research received no external funding.

Ethical Review Board Statement
Not available.

Informed Consent Statement
Not available.

Data Availability Statement
Not available.

Conflicts of Interest
The authors declare no conflict of interest.

References

Aldahlawi, R. Y., Akbari, V., & Lawson, G. (2024). A systematic review of methodologies for human behavior modelling and routing optimization in large-scale evacuation planning. *International Journal of Disaster Risk Reduction*, *110*(January), 104638. https://doi.org/10.1016/j.ijdrr.2024.104638

Alexander, D. (2005). Towards the development of a standard in emergency planning. *Disaster Prevention and Management, 14*(2), 158–175. https://doi.org/10.1108/09653560510595164

Bakhshian, E., & Pastor, B. M. (2023). Evaluating human behaviour during a disaster evacuation process: A literature review. *Journal of Traffic and Transportation Engineering (English Edition)*, *10*(4), 485–507. https://doi.org/10.1016/j.jtte.2023.04.002

Berke, P. R., & Campanella, T. J. (2006). Planning for postdisaster resiliency. *The Annals of the American Academy of Political and Social Science, 604*(1), 192–207. https://doi.org/10.1177/0002716205285533

BNPB. (2024). *Indonesian Disaster Information Data*. https://dibi.bnpb.go.id/statistik_menurut_wilayah

Corominas, J., van Westen, C. J., Frattini, P., Cascini, L., Malet, J. P., Fotopoulou, S., & Catani, F. (2014). Recommendations for the quantitative analysis of landslide risk. *Bulletin of Engineering Geology and the Environment, 73*(2), 209-263. https://doi.org/10.1007/s10064-013-0538-8

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2008). Social vulnerability to environmental hazards. *Social Science Quarterly, 84*(2), 242-261. https://doi.org/10.1111/1540-6237.8402002

Dandridge, C., Stanley, T. A., Kirschbaum, D. B., & Lakshmi, V. (2023). Spatial and Temporal Analysis of Global Landslide Reporting Using a Decade of the Global Landslide Catalog. *Sustainability (Switzerland)*, *15*(4), 1–22. https://doi.org/10.3390/su15043323

Ermanto, Y. (2024). Landslide risk management using geospatial technique: comparative insights of China and Indonesia. *ASEAN Natural Disaster Mitigation and Education Journal*, *1*(2). https://doi.org/10.61511/andmej.v1i2.2024.289

Eslamian, S., Eslamian, F., Frameworks, N., & Resilience, B. (2021). Handbook of Disaster Risk Reduction for Resilience. In *Handbook of Disaster Risk Reduction for Resilience*. https://doi.org/10.1007/978-3-030-61278-8

Froude, M. J., & Petley, D. N. (2018). Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences, 18*(8), 2161-2181. https://doi.org/10.5194/nhess-18-2161-2018

Glade, T. (2003). Landslide occurrence as a response to land use change: A review of evidence from New Zealand. *Catena, 51*(3-4), 297-314. https://doi.org/10.1016/S0341-8162(02)00170-4

Gnyawali, K. R., & Adhikari, B. R. (2017). Spatial Relations of Earthquake Induced Landslides Triggered by 2015 Gorkha Earthquake Mw=7.8. *Advancing Culture of Living with Landslides*, *April*. https://doi.org/10.1007/978-3-319-53485-5

Hadmoko, D. S., Lavigne, F., Sartohadi, J., Hadi, P., & Winaryo. (2010). Landslide hazard and risk assessment and their application in risk management and landuse planning in eastern flank of Menoreh Mountains, Yogyakarta Province, Indonesia. *Journal of Natural Hazards*, *54*(3), 623–642. https://doi.org/10.1007/s11069-009-9490-0

Harris, D., Tuke, R., Smith, D., & Hughes, M. (2021). *Framework for evacuation routes*. NZ Transport Agency.

Highland, L. M., & Bobrowsky, P. (2008). T*he landslide handbook—a guide to understanding landslides.* U.S. Geological Survey Circular 1325.

Hu, G., Liu, M., Chen, N., Zhang, X., Wu, K., Raj Khanal, B., & Han, D. (2019). Real-time evacuation and failure mechanism of a giant soil landslide on 19 July 2018 in Yanyuan

County, Sichuan Province, China. *Landslides*, *16*(6), 1177–1187. https://doi.org/10.1007/s10346-019-01175-x

Lindell, M. K., & Perry, R. W. (2003). *Communicating environmental risk in multiethnic communities.* Sage Publications.

Liu, K., Li, Y., Li, H., Nan, Y., & Chen, Y. (2023). Distribution study of damage caused by the 2015 Mw7.8 Gorkha earthquake in Nepal. *Proc. SPIE 12988, Second International Conference on Environmental Remote Sensing and Geographic Information Technology*. https://doi.org/10.1117/12.3024150

Liu, K., Li, Y., Nan, Y., Li, H., & Wang, J. (2023, November). Exploration on the relationship between earthquake-triggered landslides and tectonics in the Himalayan Subduction Zone. In *International Conference on Remote Sensing, Mapping, and Geographic Systems (RSMG 2023)* (Vol. 12815, pp. 459-466). SPIE. https://doi.org/10.1117/12.3010307

Mei, E. T. W., Lavigne, F., Picquout, A., de Bélizal, E., Brunstein, D., Grancher, D., Sartohadi, J., Cholik, N., & Vidal, C. (2013). Lessons learned from the 2010 evacuations at Merapi volcano. *Journal of Volcanology and Geothermal Research*, *261*, 348–365. https://doi.org/10.1016/j.jvolgeores.2013.03.010

Mileti, D. S. (1999). *Disasters by design: A reassessment of natural hazards in the United States.* Joseph Henry Press.

Petley, D. N. (2012). Global patterns of loss of life from landslides. *Geology, 40*(10), 927-930. https://doi.org/10.1130/G33217.1

Pradhan, S. ., Vishal, V., & Singh, T. N. (2019). *Landslides: Theory, Practice and Modelling* (Vol. 50). Springer. http://link.springer.com/10.1007/978-3-319-77377-3

Setiawan, H. H., & Tanjung, M. I. (2024). Community-Based Landslide Disaster Mitigation on the Northern Slope of "Telaga Lele" Hill, Banjarnegara Regency, Indonesia. In *Landslide: Susceptibility, Risk Assessment and Sustainability: Application of Geostatistical and Geospatial Modeling* (pp. 547-569). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-56591-5_21

Subedi, S., Bahadur, M., & Poudyal, C. (2019). Impacts of the 2015 Gorkha Earthquake: Lessons Learnt from Nepal. In *Earthquakes - Impact, Community Vulnerability and Resilience* (p. 13). Intechopen. http://dx.doi.org/10.5772/intechopen.85322

Sugiarto, V., Ramdani, F., & Bachtiar, F. (2019). Modeling Agent-Oriented Methodologies for Landslide Management. *Journal of Information Technology and Computer Science*, *4*(2), 193–201. https://doi.org/10.25126/jitecs.201942129

Tierney, K. J. (2007). *Disaster preparedness and response: Research findings and guidance from the social science literature.* University of Colorado Institute of Behavioral Science.

UNISDR. (2015). *Sendai framework for disaster risk reduction 2015–2030.* United Nations Office for Disaster Risk Reduction. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

van Westen, C. J., Castellanos, E., & Kuriakose, S. L. (2006). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. *Engineering Geology, 102*(3-4), 112-131. https://doi.org/10.1016/j.enggeo.2008.03.010

Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2004). *At risk: Natural hazards, people's vulnerability, and disasters.* Routledge.

Zayn, A. R., Ramdani, F., & Bachtiar, F. A. (2020). Agent-based Modeling and Simulation for Evacuation of Landslides Natural Disaster. *Journal of Information Technology and Computer Science*, *5*(2), 194–206. https://doi.org/10.25126/jitecs.202052172

Biographies of Authors

Satria Indratmoko, Environmental Science, School of Environmental Science, Universitas Indonesia, Central Jakarta, Jakarta, 10430, Indonesia.

- Email: satria@ui.ac.id
- ORCID: 0000-0003-1195-6473
- Web of Science ResearcherID: N/A
- Scopus Author ID: 57200085389
- Homepage: https://scholar.google.com/citations?user=xNuJueIAAAAJ&hl=en

Raldi Hendro Koestoer, Environmental Science, School of Environmental Science, Universitas Indonesia, Central Jakarta, Jakarta, 10430, Indonesia.

- Email: ralkoest@gmail.com
- ORCID: 0000-0003-1701-0419
- Web of Science ResearcherID: N/A
- Scopus Author ID: 6508263908
- Homepage https://sinta.kemdikbud.go.id/authors/profile/5992062