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Reviewing the Impact of Earthquakes on Flood Occurrence: Insights from Kota Belud, Sabah, Malaysia

K. Sharir[1] and R. Roslee[2†]
[1]Faculty of Engineering (FKJ), Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
[2]Faculty of Science & Natural Resources (FSSA), Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
†Corresponding author: R. Roslee; rodeano@ums.edu.my

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ABSTRACT

This study investigates the trends and processes of flooding in Kota Belud, Sabah, Malaysia, following the 2015 Ranau Earthquake. The earthquake caused landslides that altered river systems and significantly impacted flood patterns. Using an interdisciplinary methodology, we examined geological processes, river morphology, sediment dynamics, and erosion mechanisms to understand the correlation between geological forces and flooding. The investigation spanned a decade (2010-2020), revealing an increase in flood incidents post-earthquake. Key findings include the impact of sediment dynamics on river behavior, the role of river morphology, and the importance of erosion and sedimentation in flood timing. This research offers valuable insights into disaster management strategies, emphasizing the need for understanding geological influences on flood susceptibility.

INTRODUCTION

In the complex interplay of Earth's geological forces, the relationship between seismic events and hydrological phenomena can change landscapes, disturb communities, and modify natural processes (Chen et al. 2015). One significant problem related to earthquakes is flooding, especially in regions where seismic activity intersects with complex drainage systems. This connection between tectonic movements and hydrological responses is both fascinating and crucial, necessitating further research to fully understand it.

Our study delves into the relationship between earthquakes and floods, explicitly focusing on Kota Belud, Sabah, Malaysia, in the aftermath of the 2015 Ranau Earthquake. This location, where geological forces intersect with drainage systems, offers an ideal context for investigating how earthquakes can initiate flooding events. The aftermath of the Ranau Earthquake, marked by landslides, erosion, and debris flow, has significantly altered flood patterns in this area (Rosli et al. 2021, Tongkul 2017, Yusoff et al. 2016).

The primary objective of this study is to unravel the complex interactions between seismic activity and hydrological responses, specifically the increased flooding in Kota Belud following the 2015 Ranau Earthquake. This research aims to answer the following questions: How do geological processes, triggered by seismic events, alter flood patterns? What role do sediment dynamics and river morphology play in post-earthquake flooding?

OBJECTIVES

The main objectives of this study are:

1. To investigate the impact of the 2015 Ranau Earthquake on flood patterns in Kota Belud.
2. To analyze the role of sediment dynamics and river morphology in post-earthquake flooding.
3. To develop insights for disaster management strategies based on the findings.

METHODOLOGY

We employed a combination of field surveys, remote sensing techniques, and GIS analysis to collect data on river morphology, sediment deposition, and flood events. Instruments included LiDAR for topographical mapping, sediment traps for measuring deposition rates, and flow meters for assessing river discharge. Data were collected from various sources, including the Department of Irrigation and Drainage and the National Disaster Management Agency, ensuring a comprehensive analysis (Fig. 1).

RESULTS

Our results indicate a significant increase in flood events post-earthquake, even with lower rainfall intensities. Sediment deposition in river channels was identified as a major factor influencing flood patterns. Borehole analyses revealed varying sediment thickness downstream, correlating with increased flood frequency. Detailed tables and figures illustrate the spatial distribution of floods and sedimentation patterns, supporting our findings.

Flood Distribution

The objective of flood distribution is to assess the areas impacted by floods and identify locations that consistently experience flood events. This study also plays an important role in identifying places that are frequently prone to flood occurrences. Flood distribution data, commonly referred to as flood inventory, and all the factors that influence flooding are essential when generating flood susceptibility maps. Moreover, the flood inventory map is used to determine factors that contribute to flood recurrence.

To assess the distribution of floods, we employed data collected from on-site inspections conducted between 2018 and 2022. Incorporated into the analysis are data obtained from several government entities such as the Department of Irrigation and Drainage, the National Disaster Management Agency, the Civil Defence Force, and the Kota Belud District Council.

A total of 217 flood events were recorded within the study area over a decade from 2010 to 2020. These events affected 48 different locations (Department of Irrigation and Drainage Sabah 2020). Out of these places, 30 had repeated flood events happening multiple times over this period as specified in Table 1. These specific locations are considered hotspots because they are very prone to flooding.

Fig. 2 depicts the spatial distribution of flood occurrences for the five-year periods before (2010-2015) and after (2015-2020) the 2015 Ranau Earthquake. Surprisingly, the number of areas affected by floods increased from 87 to 130 after the earthquake, even though the timeframe of five years remained consistent before and after the seismic event. The changes in flood patterns pre- and post-earthquakes can be associated with sedimentary deposits caused by landslides triggered by earthquakes which pile in river channels leading to a decrease in river depth. Furthermore, erosion processes occurring in drainage development zones exacerbate this

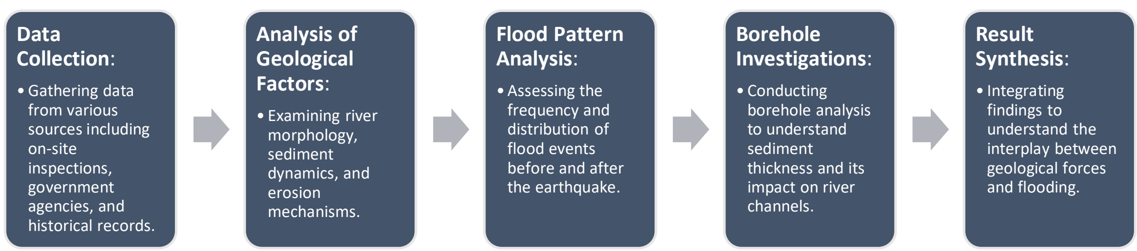

Fig. 1: Methodology flowchart.

Table 1: Flood hot-spot location.

Location	No. of events	Location	No. of events	Location	No. of events
Kg Bobot	13	Kg Tombol	2	Kg Limatok	2
Kg Gunding	12	Kg Pirasan	2	Kg Linau	13
Kg Jawi-Jawi	2	Kg Sangkir	2	Kg Lingkodon	17
Kg Keranjangan	6	Kg Sembirai	18	Kg Menunggui	18
Kg Kesapang	2	Kg Siasai	13	Kg Merabau	2
Kg Kota Bunga	3	Kg S. Punggur	2	Kg Pgkln Abai	6
Kg Labuan	7	Kg Tg Pasir	4	Kg Wakap	5
Kg Lebak Engad	11	Kg Tg Wakap	2	Kota Belud	4
Kg Lebak Moyoh	15	Kg Taun Gusi	3	Padang Pekan	5
Kg Lentigi	2	Kg Tawadakan	2	Pasar Tani	5
Total number of repeating locations					30

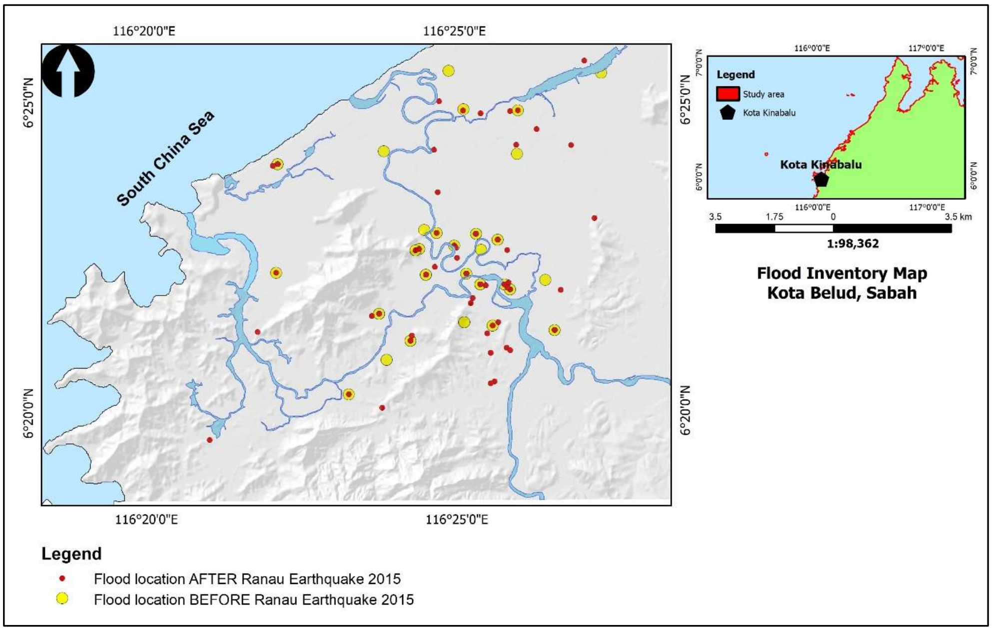

Fig. 2: The flood hot-spot location.

issue. Together, these factors contribute to an increase in flood episodes after an earthquake, even if the amount of rainfall is not unusually great.

Analysis of Flood Trends

The research we conducted in Kota Belud, Sabah, examines the complex connection between sedimentation and flooding that occurs after an earthquake. An examination of data collected from government entities, including the Department of Irrigation and Drainage Sabah and the Department of Meteorology Malaysia, indicates a significant pattern: a rise in the occurrence of floods after the 2015 Ranau Earthquake. It is noteworthy that this trend encompasses flood occurrences that happen at precipitation intensities lower than the standard heavy rain threshold of 60 mm per hour set by the National Flood Forecasting and Warning Centre.

To obtain a broader understanding, we compare the daily precipitation data from the years before the earthquake (1996, 2008, and 2014) with the years after the earthquake (2015, 2016, 2017, and 2018). This analysis reveals a significant change in flood patterns as floods are now occurring even with lower levels of rainfall. Significantly, an occurrence of flooding in August 2015 characterized by a rainfall intensity of 17 mm (classified as moderate rain) and other incidents in 2016, such as the severe rainfall event in May (55.5 mm), defy traditional assumptions. The observed variation can be ascribed to alterations in the flow patterns of the river caused by the deposition of sediment due to seismic activity, erosion, and the collapse of slopes in the upper areas, specifically in the Kadamaian River and Wariu River basins. Our analysis reveals how seismic events can significantly change river behavior by affecting sediment dynamics, leading to post-earthquake flooding scenarios.

Geological Factors in Flood Occurrence

The flow of water within the drainage systems is a key geological force that causes erosion, transportation, and deposition of material across landscapes. Almost every part of our world shows evidence of erosion or sediment accumulation caused by rivers. Understanding these geological processes is extremely important as they can greatly impact the frequency and severity of floods in a certain area. To thoroughly examine these processes, this part will be divided into several important elements: river morphology, drainage order, erosion and its impact on sediment deposition, and the movement and settling of sediment that is unique to the area being studied.

Unveiling the River Morphology

Learning about river morphology and how it changes over time is important before getting into the more complicated parts of flood research. A comprehensive study of the properties of rivers and drainage systems is crucial due to their close connection with flood events. To structure our research, we categorize the river basin into three main zones:

1. Zone 1: The Erosion Zone functions as a source of sediment in the upstream section, exerting geological pressures that result in erosion.

2. Zone 2: The Sediment Transport Zone, is located in the middle of the river's course. This area is frequently affected by erosion and sedimentation processes.
3. Zone 3: The Sedimentation Zone, is the area downstream where sediment accumulates, playing a crucial role in the river's environment.

The study area encompasses five main rivers: Sungai Wariu, Sungai Tempasuk, Sungai Kadamaian, Sungai Abai, and Sungai Gurong-Gurong. There are three essential river basins: Tempasuk, Kadamaian, and Wariu. The rivers demonstrate various phases of development, with Sungai Kadamaian and Sungai Wariu being mature rivers in lowland and hilly regions, displaying extensive plains and integrated drainage systems. On the other hand, Sungai Kuala Abai and Sungai Tempasuk are categorized as matured rivers located further downstream, characterized by distinctive attributes such as sandbanks and valleys with ridges. This initial investigation establishes the foundation for a comprehensive examination of the interaction between geological characteristics and flood patterns in the area, highlighting the significance of comprehending river development.

Analyzing River Order and its Significance in Flood Studies

Analyzing river order provides valuable insights into flood dynamics. Higher-order rivers indicate increased flow, which is crucial for flood studies, while lower-order rivers are significant due to their potential to disrupt the drainage system. Our study area, lacking rapid urbanization, experiences predominantly natural disturbances in Orders 1 and 2, aligning with earlier findings of landslide-prone terrain in the upper Kadamaian River basin (Fig. 3). These geological features impact river dynamics, providing critical insights into flood susceptibility.

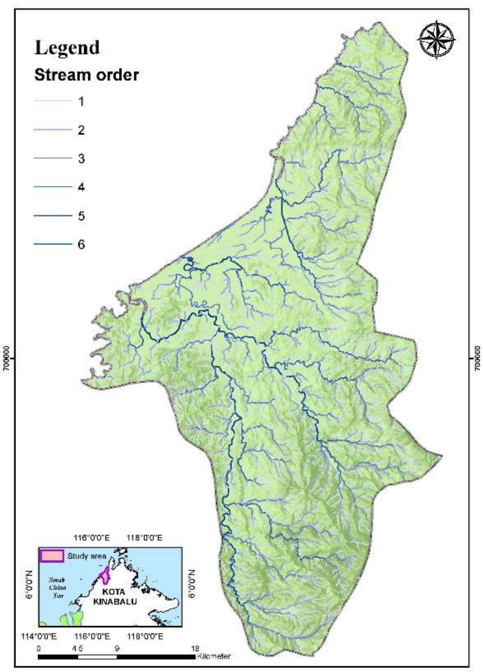

Fig. 3: The order of stream network.

Erosion and its Impact on Sediment Deposition

For our investigation into the erosion dynamics in the Kota Belud district, we utilize the Revised Universal Soil Loss Equation (RUSLE) to evaluate erosion rates. This approach considers factors such as precipitation, the susceptibility of soil to erosion, the characteristics of the slope, the kind of cultivation, and the effectiveness of erosion control measures. The results of our study depicted in Fig. 4 classify soil erosion into five distinct categories, ranging from very low to very high.

Most of Kota Belud, specifically 63.29% or 87,657 hectares, experiences a very low erosion risk. However, a significant portion, 26.17% or 36,245 hectares, suffers a very high danger of erosion. The medium-risk zones encompass 4.52% of the total land area, equivalent to 6,260 hectares. The low-risk regions cover 3.69% of the land, around 5,111 hectares. Lastly, the high-risk areas account for 2.33% of the land, a total of 3,227 hectares.

In 2021, Roslee and Sharir confirmed that the Kadamaian River Basin in south-eastern Kota Belud is a significant area at risk of land loss. Areas adjacent to main rivers, particularly the specific location we are studying, exhibit elevated rates of erosion. The heightened erosion close to rivers leads to sediment build-up in riverbeds, impeding efficient drainage during periods of intense precipitation. The complex interplay between erosion, sediment deposition, and river dynamics provides a valuable understanding of the susceptibility of the study area to flooding.

Sediment Dynamics: A Key Player in Post-Earthquake Flooding

Sedimentary deposits originating from the physical or chemical breakdown of rocks within the Earth's crust comprise a diverse range of particle sizes, from block-sized to colloidal dimensions (Joe et al. 2019, Quigley & Duffy 2020). When water serves as the vehicle for transporting these sediments, they are referred to as fluvial or river sediments (Rentschler & Salhab 2020). In nature, these sediments are a natural by-product of erosional processes that occur within drainage systems (Liu et al. 2020). However, an excess accumulation of these sediments beneath the drainage

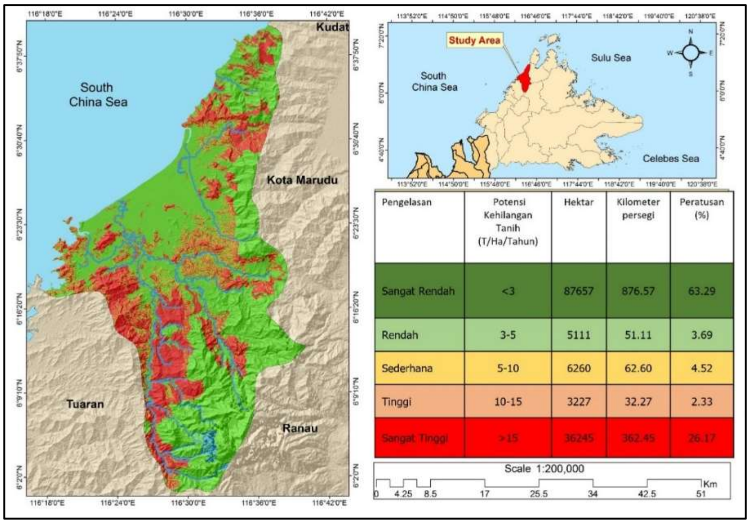

Fig. 4: The potential of soil erosion in Kota Belud.

system can have profound implications. Specifically, it can lead to the shallowing of river channels, thereby impeding their capacity to accommodate water during precipitation events, ultimately culminating in flooding (Sharir et al. 2022).

To gain a better grasp of the situation, we selected the daily rainfall data from the three years before the 2015 Ranau Earthquake for comparison with the years following the earthquake. Specifically, we chose 1996, 2008, and 2014 to represent the pre-earthquake events, while 2015, 2016, 2017, and 2018 represent the post-earthquake events. The selection of these assessment years was based on the availability of the information provided. The daily precipitation data is compared to the occurrence of floods in the study area. The rainfall data is constrained by a threshold value of 60 mm, representing the intensity range used to measure the amount of rain within an hour. This value is provided by the National Flood Forecasting and Warning Centre (Table 2).

Based on the rainfall data depicted in Fig. 5a, it was observed that the flood event before the 2015 Ranau Earthquake surpassed the established threshold for measuring heavy rainfall (>60 mm). In 1996, there were no reports of flooding. However, a flood was documented on February 17, 2008, with a recorded rainfall of 104.7 mm. Compared to 2014, one year before the earthquake, the highest recorded flood occurred on October 8, 2014, with a precipitation level of 86.5 mm.

Table 2: Rainfall intensities classification.

Rainfall intensities	Range (mm/hour)
Light	1-10
Moderate	11-30
Heavy	30-60
Extremely Heavy	>60

Source: National Flood Forecasting & Warning Center (2021).

The flood patterns observed during the monitoring periods of 2015, 2016, 2017, and 2018 showed changes following the impact of the earthquake (Fig. 5b). According to the recorded data, flood episodes happen not just when it rains more than 60 mm, which is considered heavy rain, but also when it rains less than that amount. Based on the information provided, there was a single flood event in 2015 following the August 2015 earthquake with a rainfall of 17 mm, falling into the moderate rain category. In 2016, there were three flood occurrences recorded in May (with heavy rainfall of 55.5 mm) and September (with rainfall of 19.5 mm and 16 mm, falling into the moderate rain category). In 2017, five flood events were detected, all of which were caused by very heavy rain. These events occurred in August, September, and December, with rainfall intensities ranging from 17 mm to 46 mm, classified as moderate to heavy rain. In 2018, there were three flood events recorded in January, June, and July, with rainfall intensities ranging from 15 mm to 45 mm, also classified as moderate to heavy rainfall.

The difference in flood patterns pre- and post-the 2015 Ranau Earthquake can be linked to the deposition of sediments, which reduces the river's depth as a consequence of the mountain's collapse caused by seismic activity, as well as the erosion that takes place in the surrounding drainage basin region. Consistent with previous research, it has been observed that soil erosion has a significant impact in the upper region of the river basin, specifically in the Kadamaian River and Wariu River basins. Erosion and

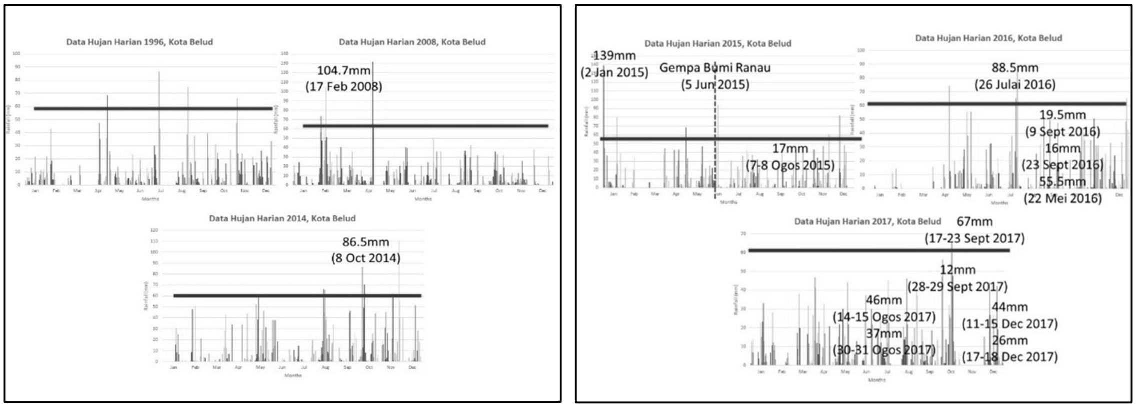

Fig. 5: Daily rainfall and flood records for the year before (a) and after (b) the 2015 Ranau Earthquake.

slope instability in the upper section of the drainage system result in the accumulation of sediment on the river bed in the middle and lower sections. The field survey results indicate that sediments deposited in the downstream section of the Kadamaian River, Tempasuk River, and Abai River have created a substantial and compact layer as a result of the parent rock's high clay content. The river in the area of Kota Belud experienced shallowing as a result of sediment transportation and deposition on its bed after the earthquake.

In our pursuit to unravel the intricate dynamics of sediment accumulation within the river system, we conducted extensive borehole investigations spanning from the upstream to the downstream regions. These boreholes provided critical insights into the various soil types, physical attributes, and engineering properties at each location, shedding light on the intricate nature of sediment deposition. Our study, however, places a special emphasis on Layer 1, known as the Fluvial Deposit Layer, as it is the focal point for assessing deposit thickness-a key factor linked to the upstream river collapse around Mount Kinabalu and erosion processes.

The data collected from these boreholes reveal a compelling trend: sediment thickness increases as one moves further downstream along the river (Table 3). This phenomenon significantly impacts the region's flood dynamics, extending beyond heavy rainfall events. The accumulation of thick sediment deposits at the riverbed contributes to the shallowing of river channels, ultimately constraining their capacity to manage water during precipitation events effectively. It is worth noting that in BH2-Pekan Kota Belud, technical constraints in the field rendered the precise measurement of sediment thickness challenging, with a recorded value of 15.32 meters. Nevertheless, this discrepancy could be attributed to the unique geographical location of BH2, situated at the confluence of two major rivers—the Kadamaian River and the Wariu River-both originating from Mount Kinabalu. The collision of these river systems in the BH2 area leads to the accumulation of sediment transported from upstream, further enhancing our understanding of flood hazard dynamics within the region, a topic we delve into in the subsequent section.

Table 3: Fluvial sediment thickness for each borehole.

Borehole	Location	Thickness of sediment (meter)
BH 1	Kg Melangkap	4.50m
BH 2	Pekan Kota Belud	15.32m
BH 3	Kg Sembirai	10.50m
BH 4	Kg Kulambai	25.5m

CONCLUSIONS

This comprehensive investigation explores the complex relationship of geological phenomena that impact floods in Kota Belud, Sabah, specifically following the occurrence of the 2015 Ranau Earthquake. The area encountered escalated environmental difficulties, such as increased floods, landslides, soil erosion, and debris flow. The scope of our analysis was centered on the incidence of floods before and after earthquakes, to pinpoint the underlying reason for the increased severity of flooding.

The investigation begins with an examination of the geological elements that influence flooding. The hydrological flow within drainage networks, regulated by geological factors, influences the processes of sediment erosion, transit, and deposition. Rivers' complex shape and dynamic behavior were studied to understand flood dynamics. The study examined fundamental elements such as river order, drainage patterns, and erosion mechanisms to comprehend the complex correlation between geological characteristics and flooding.

The concept of river order, which is crucial in geomorphology, provides valuable insights about the volume and intensity of river flow. Rivers of higher order signify augmented water flow, whilst rivers of lower order necessitate care due to their capacity to damage drainage systems. The Revised Universal Soil Loss Equation (RUSLE) identified Kota Belud as being prone to soil erosion, with a heightened risk near large rivers, including the Kadamaian River Basin.

The occurrence of post-earthquake floods was impacted by the movement of sediment, resulting in an unforeseen change in flood patterns that occurred at lower levels of rainfall. The accumulation of material caused by seismic activity resulted in changes to the flow of the river, making it difficult to control the water during rainfall. The examination of boreholes determined the thickness of sediment downstream, providing insights into the occurrence of floods and highlighting the accumulation of materials in shallower sections of the river channels.

Our research has clarified the complex relationship between geological variables and floods in Kota Belud. Gaining knowledge of sediment dynamics, river behavior, and erosion mechanisms is essential for understanding the occurrence of floods that happen after an earthquake. This work contributes to the understanding of regional flood risks, facilitating the formulation of efficient measures to mitigate the impact of disasters and supporting at-risk populations in their efforts to prepare for catastrophic events.

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ORCID DETAILS OF THE AUTHORS

K. Sharir: https://orcid.org/0000-0002-0679-2913
G. Mukherjee: https://orcid.org/0000-0002-4501-7477