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RESEARCH ARTICLE

Learning from the past: Vulnerability analysis and cascading hazard classification of the three major volcanic eruption in Indonesia

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Abstract. There is a significant gap in understanding the social impacts of three major volcanic eruption in Indonesia, namely Samalas, Tambora, and Krakatau in 1257, 1815, and 1883, respectively. Although these events have been widely studied in geological and volcanic contexts, the societal impacts and the associated cascading hazard has not been thoroughly compared. Therefore, this study aimed to investigate the community responses and impacts of the catastrophic events using historical documents that reflected societal memories, including Babad Lombok, Babad Sembalun, Babad Suwung, Syair Kerajaan Bima, and Syair Lampung Karam, as well as records from the Dutch East Indies period. The results showed that all documented social memories articulate the communities' reactions and the resultant consequences of the eruption. Furthermore, geological and volcanological data from previous studies were used to describe the characteristics of past vulnerability. Samalas exhibited the longest recovery process, while Krakatau resulted in the highest number of casualties due to its cascading hazard. All events were categorized within the M4 scale of cascading hazard, showing the complexity of the disasters. In conclusion, this study offered critical insights into Disaster Risk Reduction (DRR) programs, showing the necessity of integrating historical social memory into modern risk management strategies. By understanding past community responses, DRR initiatives can prepare for future volcanic events, ensuring a more resilient society.

1. Introduction

Indonesia is an archipelagic country home to numerous volcanoes. According to the catalog of volcanic eruption, the country has approximately 80 active erupting volcanoes (Siebert et al, 2015). Some of these events were classified as major eruption (volcanic explosivity index (VEI) >5) (Malawani et al, 2021; Newhall et al, 2018). In the modern human history of Indonesia, a minimum of three major eruption have caused global, regional, and local impacts (De Maisonneuve & Bergal-Kuvikas, 2020; Lavigne et al, 2013; Oppenheimer, 2003; Rampino & Self, 1982). A few examples include Samalas (1257 CE), the Tambora eruption (1815 CE), and the Krakatau eruption (1883 CE). Several geological and volcanological studies have shown these volcanoes' eruption processes. However, there are limited discussions on the socio-cultural impacts of the processes. This situation necessitates a social impact analysis of a disaster in the formulation of mitigation policies (Martin, 2020; Hizbaron et al, 2018). Practically, the social impact analysis can be addressed by examining vulnerability within the potentially impacted areas as well as understanding the process by which hazard is generated.

Comprehending the mutual interrelationship between vulnerability and the related hazard associated with past events, e.g., Samalas 1257, Tambora 1815, and Krakatau 1883, requires significant efforts. Due to the long interval since the eruption, obtaining access to social data and other information regarding past events is challenging (Martin, 2020; Tennant et al, 2021; Malawani et al, 2022). Historical documents might provide important information, as reported by (Malawani et al, 2022). Although the information about Tambora and Krakatau eruption in the nineteenth century is observable through the exploration of the East Indies documents during the occupation period in Indonesia (Oppenheimer, 2003; Verbeek, 1884), some events have limited documentation apart from locally written sources that are preserved (Malawani et al, 2022).

An analysis of past vulnerability is important to tracking the societal impact of previous volcanic eruption. A method designed to address these problems was developed by Martin (2020). Similar methods were also introduced by Riede (2019) and Torrence (2019). Vulnerability analysis primarily focuses on the social characteristics of communities exposed to hazard, but the geological features of the erupting volcano also require consideration. By reviewing previous study (Vidal et al, 2015; Suhendro et al, 2021; Paris et al, 2014; Sigurdsson & Carey, 1989; Giachetti et al, 2012), the physical-geological features of the Samalas (1257), Tambora (1815), and Krakatau (1883) eruption were examined. These features include magnitude, speed of onset, recurrence, duration, coverage area, and time of occurrence, and are useful in determining the typology of cascading hazard. The result of this study is expected to provide insight into how a major eruption produces multiple subsequent hazard as well as an overview of its past vulnerability in order to strengthen disaster preparedness.

2. Methods

Three main data sources were used as basic references to explore the history and impact of major volcanic eruption in Indonesia, namely historical manuscripts, previous studies, geological maps, and hazard maps, such as the *Kawasan Rawan Bencana*/KRB map (Disaster-Prone Area map). The first step was compiling data from historical manuscripts related to the three major eruption in Indonesia. These manuscripts contain primary sources providing information about social memories of communities affected by the eruption. Data for the 1257 Samalas eruption were obtained from Babad Lombok, Suwung, and Sembalun, as shown in Figure 1. Malawani et al, (2022) analyzed the ancient Lombok manuscripts to determine the impact of the Samalas eruption (1257). Geographical methods and field evidence were used to verify the accuracy of the manuscript accounts. Syair Kerajaan Bima was selected as a key reference to the related social memories of the Tambora eruption in 1815 (de Jong Boers, 1995; Tantri, 2019; Hamdan et al, 2023). The social memories of the 1883 Krakatau eruption were captured by Syair Lampung Karam (Aveling, 2016; Purnomo & Haryanto, 2022; Firdaus et al, 2022). Documents from the East Indies period are also useful as complementary sources for the Krakatau and Tambora eruption. The East Indies reports provided a detailed and systematic account of the events (chronological order), enabling a more comprehensive understanding of the impact on the environment and society. For example, Oppenheimer (2003) used contemporary accounts from various sources, such as Sir Stamford Raffles, East Indies documents, letters, and articles in the Asiatic Journal to describe the impact of the Tambora eruption (1815). An original report of the 1883 Krakatau event also summarizes the eruption process and its consequences (Verbeek, 1884).

The analysis of vulnerability to disasters in the past can be evaluated by considering physical and social variables (Martin, 2020). Physical variables include the geophysical aspects of natural processes, as shown in Table 1. These aspects include the intensity of the disaster, the thickness of ash deposits, the presence of pyroclastic flows, and the area of impact. Physical variables also cover the duration of direct and indirect hazard, ranging from short-term to long-term, such as pyroclastic flows lasting hours to days and volcanic ash that may persist for years. Social variables consist of community characteristics that affect vulnerability and ability to respond to and recover from disasters. These include the number of people affected, population, socioeconomic stratification, the complexity of decision-making processes, as well as evacuation networks. The variables will construct the final social variable, which is recovery duration.

Figure 1. Original palm leaf document of Babad Sembalun that records the social memory of people in Lombok facing the eruption of Samalas. (Photo by Franck Lavigne).

Table 1. Physical and societal variables for assessing past vulnerability.

Physical variable	Societal variable
VEI/magnitude	Population (direct hazard)
Fallout thickness	Fatalities
Pyroclastic density currents (PDCs)	Decision-making unit
Lahar	Subsistence/economy
Tsunami	Mobility
Duration of onset	Social m emory
Area coverage	Time to recover

The cascading hazard analysis considers several parameters, including case, effect, and escalation point (Alexander, 2018; Suppasri et al, 2021). The occurrence of disasters can be schematized by understanding the chains of cause-effect-escalation points. This can provide a useful framework for the development of disaster risk reduction (DRR) strategies. The cascading hazard are classified into six, namely Magnitude 0 (M0) to 5 (M5). M0 presents a single cause with one direct effect, while M1 includes one cause leading to a single sequence of effects. M2 describes one cause that produces multiple independent chains of effects. M3 includes two causes, each triggering multiple chains of effects, with a single escalation point. M4 includes two causes generating multiple effect chains and two or more escalation points. Lastly, M5 features multiple causes, several interconnected effect chains, and multiple escalation points.

The geological maps of the volcanoes were retrieved from the Ministry of Energy and Mineral Resources' database at https://geologi.esdm.go.id/, facilitating the determination of the physical characteristics. The three geological maps used are Sumbawa Sheet 1:250,000 (Tambora), Lombok Sheet 1:250,000 (Samalas), and West Java Sheet 1:500,000 (Krakatau). The KRB map is also helpful in examining contemporary disaster reduction strategies, and can be accessed through https://vsi.esdm.go.id/portalmbg/. Furthermore, this map is used to identify areas of potential volcanic activity, which can help inform emergency management planning and risk mitigation strategies. In this study, the available data were combined to examine the relevance of DRR in contemporary society, and another fundamental aspect is how past vulnerability can be explored (Figure 2).

3. An overview of the three major volcanic eruption

The 1257 eruption of Samalas volcano

Samalas volcano is located in the northern part of Lombok Island, in proximity to Rinjani volcano. The former summit of Samalas volcano has collapsed, forming a large caldera that is now filled with water and known as Segara Anak Lake. Barujari is a somma volcano situated within the caldera, forming a prominent feature of volcanic landscape and playing a central role in the ongoing geological activity of the region. This volcanic formation complex is called the Rinjani Volcanic Complex (RVC) (Figure 3). The major eruption of Samalas in 1257 was recently recognized as being among the most significant eruption in the last 2000 years, with a total eruption volume of up to 40 km^3 DRE and classified as volcanic explosivity index of 7 (Vidal et al, 2015). Based on the distribution of tephra driven by winds, it is suggested that this eruption probably occurred between May and October 1257 (Lavigne et al, 2013). This eruption occurred in four phases, namely the initial Plinian (P1), phreatomagmatic (P2), climactic Plinian phase (P3), and the collapse of the eruption column that produced pumice-rich pyroclastic density currents (P4) (Vidal et al, 2015). The Samalas tephra produced in the P4 phase is identified up to the slopes of Merapi (660 km to the west) and is 2-3 cm thick, previously referred to as Muntilan tephra (Alloway et al, 2017). The P3 and P4 phases produced the most far-reaching pumice and ash fall products compared to P1 and P2. Furthermore, the P3 fallout covered most of Lombok Island and several neighboring islands, such as Bali and Sumbawa, with a minimum of 5 cm thickness (Figure 3). The current volcanic sulfate deposit from the 1257 Samalas has the largest sulfate deposit in Antarctica for the last 2,000 years (Sigl et al, 2015). Some medieval historical records in Europe show that heavy summers and winters were colder than usual following the year 1257 (Guillet et al, 2017). The impact on local Lombok Island is described in Babad Lombok as the eruption buried a large part of the island and destroyed the capital city of Pamatan (Lavigne et al, 2013; Malawani et al, 2022). Some other references to the impacts caused by Samalas in other parts of Indonesia are unknown due to the absence of historical records or inscriptions from the kingdoms that existed in the archipelago at the time (Sastrawan, 2022; Alloway et al, 2017).

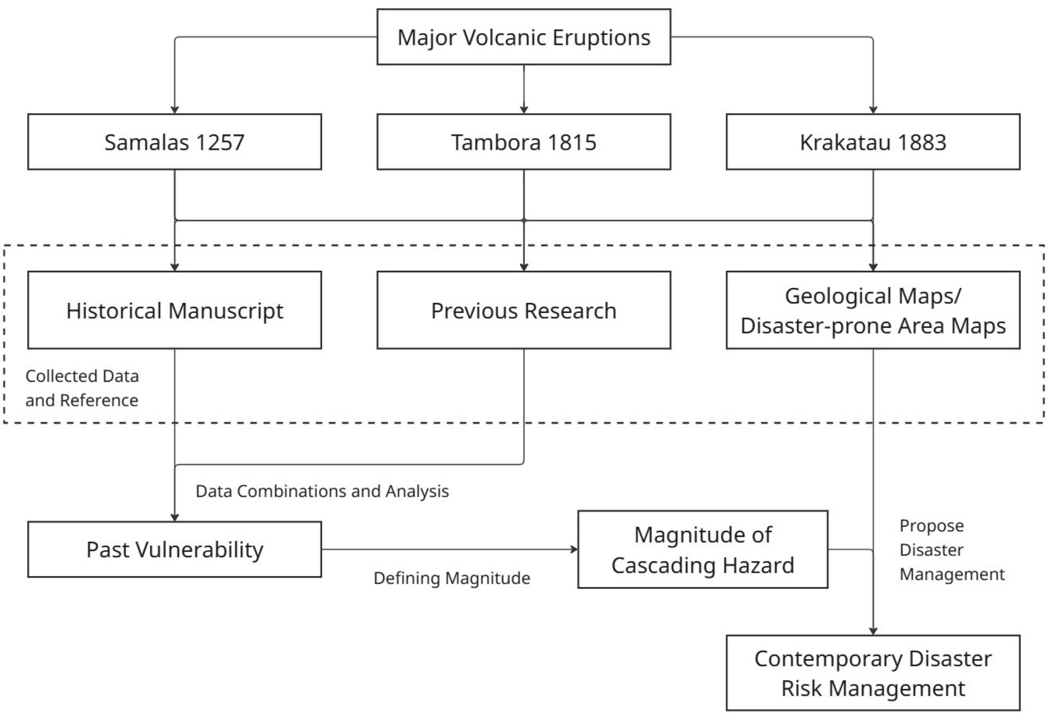

Figure 2. Study framework.

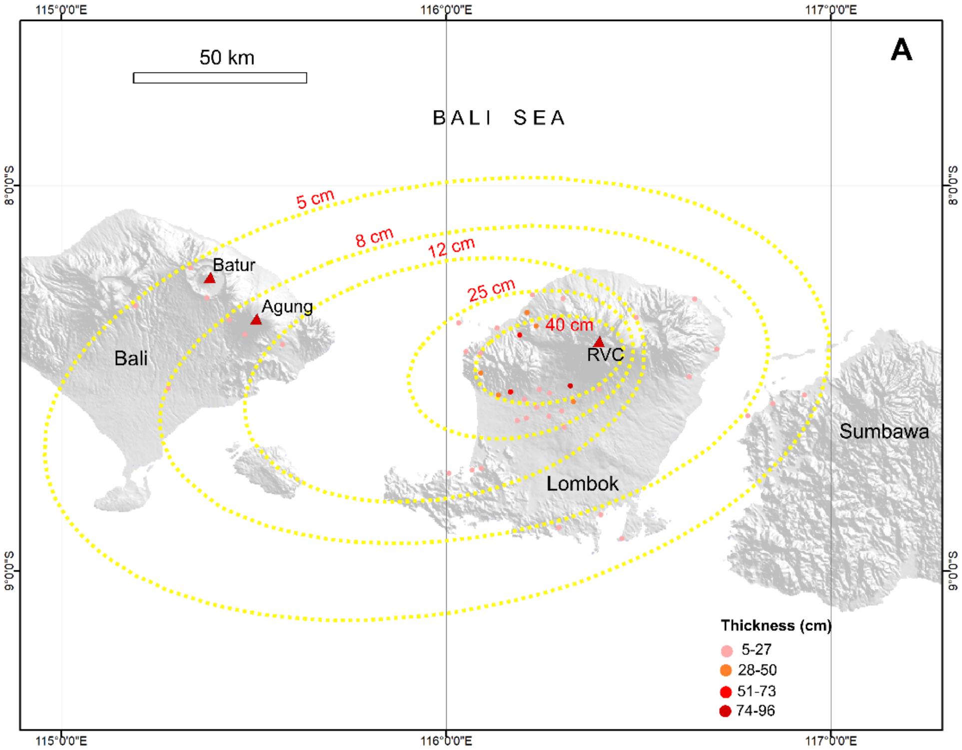

Figure 3. Isopach map of the airfall deposit from the 1257 Samalas eruption. Samalas volcano is showed by RVC (Rinjani Volcanic Complex). Source: Lavigne et al., 2013; Vidal et al., 2015.

The 1815 eruption of the Tambora volcano

In April 1815, Tambora volcano erupted violently with a maximum eruption column of approximately 43 km with a rate of 2.8 x 108 kg/s (Rampino & Self, 1982; Sigurdsson & Carey, 1989). Based on the stratigraphy of the proximal deposit, the 1815 eruption was classified into two main phases, namely (1) phase of tephra fall deposits, consisting of units F1, F2, F3, and F4, and (2) phase of pyroclastic flows (Sigurdsson & Carey, 1989). The magma chamber of Tambora experienced phenocrysts and temperature stratification before eruption. These conditions caused voluminous bubbles to rise, causing significant pressure and fractures on the surface (Suhendro et al, 2021). Magma rising through the fractures interacts with groundwater, resulting in phreatomagmatic eruption (F1 phase). The fracture path became more open, triggering a Plinian eruption (F2) due to high decompression. Another phreatomagmatic eruption (F3) occurred shortly after the first Plinian eruption. The second Plinian eruption was larger than F1 due to magma experiencing the greatest decompression of 30-32 MPa/s (Suhendro et al, 2021). The eruption duration of the Tambora eruption on the climax phase is approximately 24 hours (Self et al, 2004). This duration is longer than the 1257 Samalas eruption, which lasted non-stop from the initial Plinian phase to the caldera formation within 12-15 hours (Vidal et al, 2015). Based on the extent of the Plinian fallout material in Figure 4, the material deposits of Tambora 1815 (F4 unit) were directed to the west with a radius of approximately 95 km for a 5 cm isopach thickness. Tsunami events were also reported due to the ejection of pyroclastic flow material into the sea. In the middle of the night, a 1-2 meter tsunami was detected in Surabaya (± 500 km from the eruption center) (Oppenheimer, 2003). The 1815 Tambora cataclysm caused more than 12,000 victims, including in the list of the top 5 deadliest volcanic eruption since 1500 CE (Brown et al, 2017).

The 1883 eruption of the Krakatau volcano

Sixty-eight years after the eruption of Tambora, Krakatau in the Sunda Strait erupted again, breaking 203 years of dormancy (Hurlbut & Verbeek, 1887; Self, 1992). Krakatau had not suddenly erupted but was gradually marked by increasing activity (Hurlbut & Verbeek, 1887; Self, 1992). During its initial reactivity period (May 20 to August 25, 1883), volcanic activity occurred at the Perbuwatan vent through volcanic ash emissions and explosive eruption (Self, 1992). In June 1883, an explosive eruption destroyed the summit of Perbuwatan (Hurlbut & Verbeek, 1887). Pumice was reported floating in the sea around the Sunda Strait, disturbing navigation. The thick ash fall caused many ships to almost collapse, as the combined weight of ash and pumice deposits exceeded the structural limits (Hurlbut & Verbeek, 1887). The activity of Krakatau gradually decreased again until early August 1883. In mid-August 1883, an activity that initially occurred on the Perbuwatan vent manifested on the Danan vent, accompanied by the appearance of new fissures. The climax phase took place on August 26 and 27, 1883, marked by two major explosive eruption that produced columns exceeding 20 km in height, interspersed with smaller eruption throughout the period (Hurlbut & Verbeek, 1887). The eruption also caused a 0.3-0.4°C temperature drop in the northern hemisphere in 1884 and 1885 (Rampino & Self, 1982). In addition, tsunami events also occurred many times, culminating after the largest explosive eruption on August 27, 1883, in the morning. The Dutch East Indies government recorded 36,417 deaths due to the 1883 Krakatau eruption, 90% of which were caused by tsunamis (Figure 5) on the west coast of Java and southeast Sumatra (de Boer & Sanders, 2002). The Krakatau map presents tsunami propagation, while the Samalas and Tambora maps display tephra distribution. This difference reflects the broader impact area of the Krakatau tsunami compared to the more localized effects of airfall deposits.

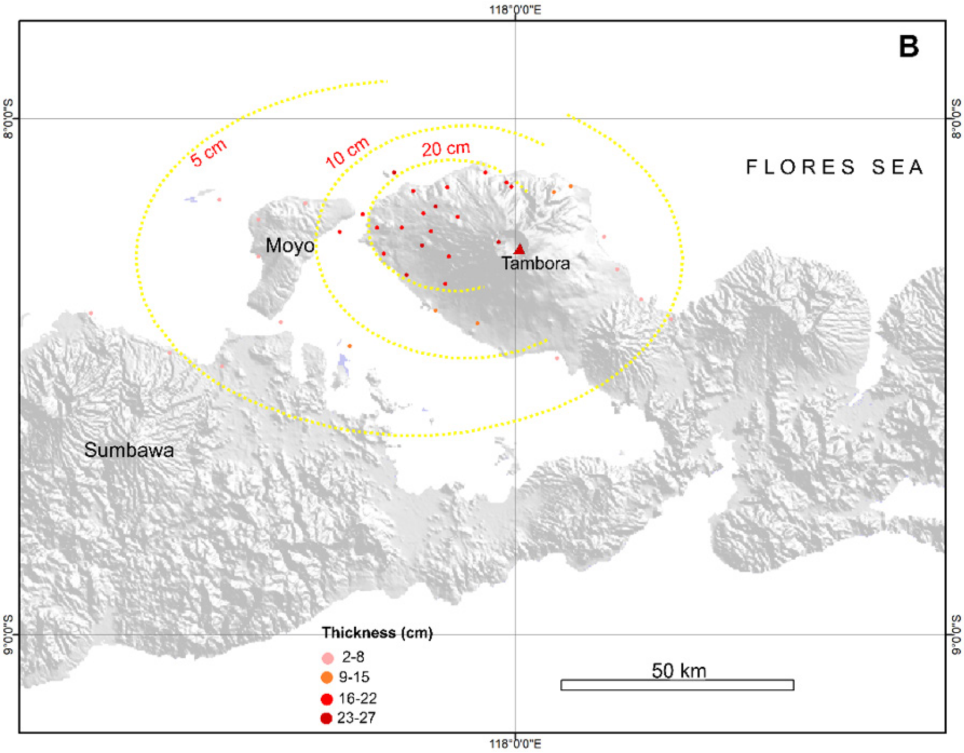

Figure 4. Isopach map of the airfall deposit from the 1815 Tambora eruption. Source: Sigurdsson & Carey (1989).

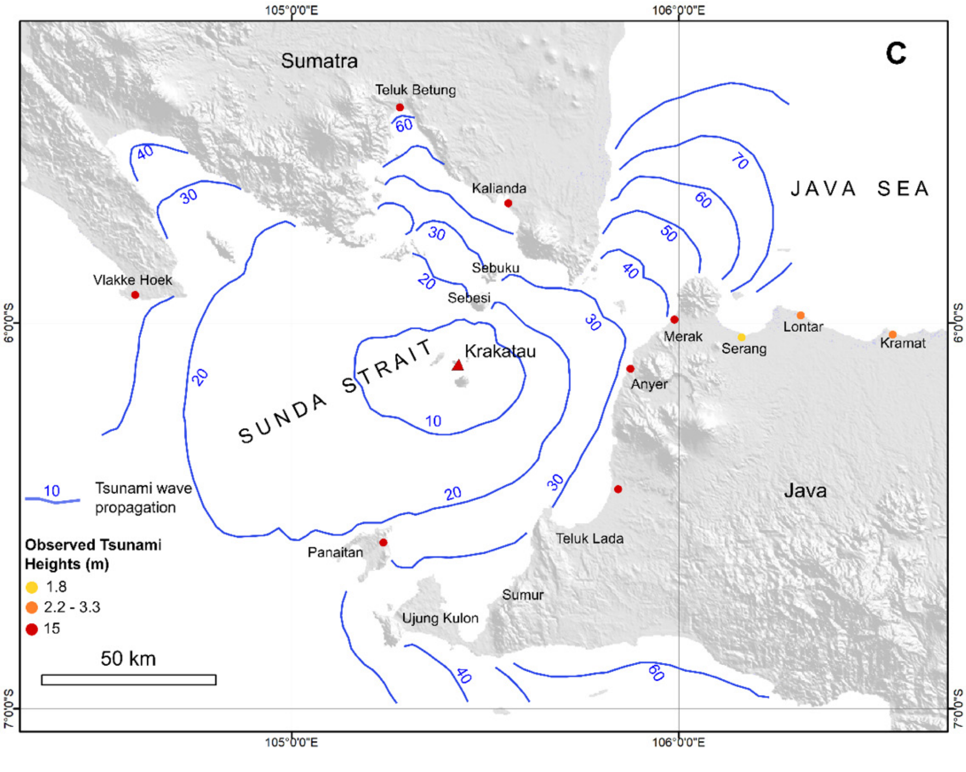

Figure 5. The tsunami generated by the 1883 Krakatau eruption. Tsunami propagation is shown in minutes. Source: Giachetti et al., 2012; Paris et al., 2014).

4. Results and Discussion

Social Memories

Human responses to volcanic eruption and the cascading hazard showed a vivid picture of chaos, desperation, and survival strategies. The document sources vividly showed human reactions to the eruption and its cascading hazard, showing a profound sense of urgency and emergency. According to Babad Lombok, Suwung, and Sembalun, the eruption of Samalas in 1257 CE caused massive destruction, with houses being swept into the sea and many lives lost (Table 2). The chaos was palpable as residents fled in all directions. Some reached higher ground, including Batek Selak Hill, while others became stranded or attempted to flee by boat. The royal family and other survivors attempted to escape using various methods, including boats, underscoring the severe impact of the eruption and the subsequent struggle for survival.

Table 2. Social memories of the Lombok inhabitants related to the 1257 Samalas eruption.

Babad Lombok	Babad Suwung	Babad Sembalun
"These flows destroyed Pamatan. Houses were destroyed and swept away, floating into the sea, and many people died"	"All of the inhabitants run around in chaos"	"They took refuge in Ngenang Village, at the bottom of Batek Selak hill"
"Stranded in Leneng (Lenek), dragged by debris and floating boulders, all the inhabitants ran."		
"Some of them escaped to the hill."		
"The rest of the royal family fled and took shelter at Jeringo; they were gathered there."		
"It is said that some of them embarked on boats, and they all escaped with their former leaders."		

Source : Malawani et al, 2022; Mutaqin & Lavigne, 2021.

Table 3. Social memories related to the 1815 Tambora and 1883 Krakatau eruption.

Syair Kerajaan Bima	**Interpretation**
Orangpun tiada yang berpindah, Masing-masing di negerinya ada	As a result of the eruption, people were confused and unsure of where to run or evacuate.
Berapa ratus hamba dan sahaya, Orang Bima tidak berdaya	Hundreds of people in the land of Bima are helpless.
Laparlah orang sekalian isinya, Lapar itu terlalu sangat. Tanah Bima hangus semua padinya	Everyone is starving. Hunger is severe, affecting everyone. Rice, agriculture all over Bima were damaged and destroyed.
Mahalnya makanan tiada tertanggung	Food prices are high, and most people are unable to afford basic food supplies.
Syair Lampung Karam	**Interpretation**
Hendak kemanalah pergi? Tempatnya kita sudahlah tinggi, Jikaulah air sampai kesini, Sudah kiamat isinya negeri	A critical situation when tsunami waves wipe out the country and there is nowhere to run, a situation where the community analogizes to an apocalypse.
daripada barang tidak perduli mencari tanah rampat yang tinggi kerana gelab tiada terperi melarikan nyawa daripada mati	Everyone tried to find high ground to evacuate, leaving their belongings behind as long as they all survived.
tatkala itu gelombang pun besar mengabiskan rumah, kayu, dan pasar licin seperti telur dikupas seperti rupa padang yang besar	After the tsunami swept through the area, houses, markets, and buildings were all washed away, leaving a completely flat surface, leaving no structures and no trees on the ground.

Source: de Jong Boers, 1995; Hamdan et al., 2023; Firdaus et al., 2022; Purnomo & Haryanto, 2022.

The Syair Kerajaan Bima and Lampung Karam showed the catastrophic aftermath of the eruption. Furthermore, the Syair Kerajaan Bima showed the pervasive helplessness and starvation among the Bima population in the face of the 1815 Tambora eruption, as agricultural land was destroyed, and food became scarce and prohibitively expensive. The disruption was very severe in such a way that the people of Bima faced extreme hunger. The Syair Lampung Karam described the aftermath of the 1883 Krakatau tsunami, where waves swept across the land, destroying structures and vegetation, leaving the area levelled and devoid of shelter. This apocalyptic imagery showed the extremity of the disaster, with survivors forced to prioritize lives over possessions. The historical accounts collectively showed the immediate human reaction to natural disasters and the long-term impacts on communities, as well as adaptive strategies in the face of overwhelming calamities.

Past Vulnerability Assessment

A total of 14 variables summarized key factors that shaped community vulnerability during the event. In addition to social factors, physical-geological factors were included to describe the volcanological conditions of the volcano and its surroundings. Social factors described for this assessment include population, decision-making unit, subsistence/economy, mobility, social memory, and time to recover. This assessment did not provide a ranking of high or low or a comparison of which is more vulnerable between the three events. The analysis could serve as a useful reference for assessing how current disaster management tools might address hazard and vulnerability in the event of a similar occurrence today. The three volcanic eruption of Samalas (1257), Tambora (1815), and Krakatau (1883) shared similar physical characteristics, namely a large VEI scale (>5) and identical hazard types. All these events experienced lahars except Krakatau because it directly flowed into the sea. A triggered tsunami occurred in both Krakatau and Tambora, but not in Samalas. In the 1883 Krakatau eruption, the tsunami was the most destructive hazard, responsible for the majority of fatalities through its inundation, while in Samalas and Tambora, most casualties resulted from volcanic ejecta (fallout, PDCs).

The data in Table 4 showed a significant correlation between the scale of the eruption and the number of fatalities. Krakatau, with the highest fatality count (36,000), was also the most powerful eruption. Although Samalas and Tambora were both catastrophic, the fatality rates were lower, influenced by factors such as population density and geographical setting. Each eruption featured a distinct set of decision-making units, reflecting differences in governance and response capacity. Samalas was under a kingdom's governance, while the East Indies government ruled during the events of Tambora and Krakatau. This variation influenced each case's response strategies. All three eruption profoundly impacted the local economies, which were primarily based on agriculture and, in some cases, fishing. The destruction of crops and infrastructure led to widespread famine and economic hardship. However, the extent of economic disruption varies depending on the specific circumstances of each eruption and the region's resilience. People were generally forced to migrate within or between areas in order to access safety and essential resources. The scale of displacement was related to the severity of the eruption, the availability of alternative livelihoods, and the recovery times following the eruption, which varied significantly. Samalas experienced the most extended recovery period, estimated at around 100 years. Tambora and Krakatau had shorter recovery times due to factors such as the availability of external aid, the resilience of the local population, and the pace of reconstruction efforts.

Cascading Hazard

The eruption of Samalas in 1257 posed new dangers with greater impact, thereby producing ash that forms a cover, causing solar dimming (Guillet et al, 2023). Figure 6 showed that solar dimming was considered the first escalation point as it majorly impacted the global climate. Following the statement of Guillet et al, (2017), there were cold summers in 1258 and 1259 in the northern part of the Earth. This impact on the climate led to the assumption that the eruption of Samalas contributed to the beginning of the Little Ice Age (Miller et al, 2012). In addition, the results of the eruption in the form of pyroclastic density currents acted as the most dangerous cause. Malawani et al, (2021) assumed a high number of casualties from the event, based on the Babad Lombok, which recorded that Pamatan City (the capital of Lombok) had a population exceeding 10,000 at the time of the Samalas eruption. The Babad Lombok also described how the eruption buried the civilization in Pamatan City, forcing residents to evacuate both to escape the danger and to establish a new settlement elsewhere (Malawani et al, 2021; Lavigne et al, 2013; Malawani et al, 2022). Pyroclastic density current also entered the ocean, triggering small tsunamis and causing coral destruction. Another effect of pyroclastic density current was sedimentation by lahar, which had a major impact on morphological change (Mutaqin et al, 2019a; Malawani et al, 2023). Furthermore, an eruption produced lava flows that caused forest fires based on the narration of Babad Sembalun. The event was classified as magnitude (M4) based on the causes, effects, and escalation points present, which was a disaster with substantially complex consequences.

Table 4. Comparison of vulnerability characteristics from the three major volcanic eruption.

Variable	Samalas 1257	Tambora 1815	Krakatau 1883
VEI/magnitude	7[1]	7[2]	6[2]
Fallout thickness	40 cm [1,3]	30 cm [4]	2 m [5]
PDCs	Present [1,3]	Present [6]	Present [5]
Lahar	Present [7]	Present [6]	No [8]
Tsunami	Present (very small)[7]	Present (small)[9]	Present[10,11]
Duration of onset	Hours to a day[1]	Days [4, 9]	Weeks [8]
Area coverage	Inter-island (fallout) [3]	Inter-island (fallout, tsunami) [4,9]	Inter-island (tsunami) [8,10,11]
Population (direct hazard)	Lombok	Sumbawa	Java, Sumatra
Fatalities	>10,000[12]	12,000[9]	36,000[13,14]
Decision-making unit	Kingdom[12]	Government [9]	Government[8]
Subsistence/economy	Agriculture, fishery[12,15]	Agriculture[9,14]	Agriculture, fishery, trade[16]
Mobility	Intra-region, inter-region[12,13]	Intra-region[9,17]	Intra-region[8]
Social memory	Oral, *babad* document [12]	Oral, written tale, East Indies note[11]	Oral, written tale, East Indies note[8,11]
Time to recover	~100 years[12,17]	30-50 years[18]	20-30 years[19]

Reference:
[1]Vidal et al., 2015; [2]De Maisonneuve and Bergal-Kuvikas, 2020; [3]Lavigne et al., 2013; [4]Sigurdsson and Carey, 1989; [5]Hurlbut & Verbeek, 1887 ; [6]Suhendro et al., 2021; [7]Mutaqin et al., 2019a; [8]Verbeek, 1884; [9]Oppenheimer, 2003; [10]Giachetti et al., 2012; [11]Paris et al., 2014; [12]Malawani et al., 2022; [13]de Boer & Sanders, 2002; [14]Brown et al., 2017; [15]Mutaqin and Lavigne, 2021; [16]Firadus et al., 2022; [17]Malawani et al., 2025; [18]de Jong Boers, 1995; [19]Brata et al., 2013.

In 1815, the produced ash from the eruption of Tambora formed a mantle that caused a solar dimming and caused disruption of the global climate (Oppenheimer, 2003). Global climate disruption was characterized by the 'one year without a summer' event that occurred in parts of Europe and America in 1816 (Brázdil et al, 2016; Raible et al, 2016). In addition, Oppenheimer (2003) reported that this eruption resulted in the burial of civilization and major casualties in Sumbawa and Lombok. Eruptions produce pyroclastic flows that enter the sea and cause tsunamis. The tsunami triggered by the Tambora eruption caused intra-regional destruction, which was not observed during the Samalas eruption, and was considered an escalation point. According to Oppenheimer (2003) and Stothers (1984), the tsunami due to the Tambora eruption had a maximum height of 4 meters in Sanggar and reached other places, such as Bima, Besuki, and Surabaya, with wave heights of 1-2 meters. Pyroclastic flows also led to sedimentation, as seen in the 1257 Samalas eruption. This accumulation of material contributed to subsequent morphological changes. Although the number of causes and effects in the Tambora eruption is less than the Samalas eruption, it falls under magnitude 4 (M4) in the cascading hazard classification due to the complexity of its impacts (Figure 7).

The 1883 Krakatau eruption ejected a pumice fall that accumulated into a pumice raft (Verbeek, 1884), which was selected as an escalation point due to its criticality. Pumice rafts caused risky impacts on marine life, damage to ships, and disruption of navigation (Redick, 2023). Meanwhile, the ash cover produced by the Krakatau eruption caused climate change, such as a significant increase in rainfall and a decrease in average temperature (Gil-Guirado et al, 2021). The explosive eruption of Krakatau also caused a collapse and ejected pyroclastic material that entered the ocean, thereby triggering a large tsunami with an initial run-up height up to 41 meters (Mutaqin et al, 2019b; Madden-Nadeau et al, 2021). The major impact caused by this tsunami was a considerable number of fatalities, resulting in a 36,000 death toll (Brown et al, 2017; Self, 1992), and destroying the majority of Krakatau island (Deplus et al, 1995). This phenomenon became a big history of tsunamis in Indonesia triggered by volcanic eruption. Therefore, the Krakatau eruption tsunami was considered an escalation point based on the magnitude of the loss effect. Similar to Samalas and Tambora, Krakatau eruption had more than one escalation point and complex effects, thereby classified as a magnitude level 4 (M4). Figure 8 shows the cascading hazard classification of the 1883 Krakatau Volcano eruption.

The cascading hazard magnitude classification explained how causes, effects, and escalation points interact with each other in a disaster. The magnitude level also explained the

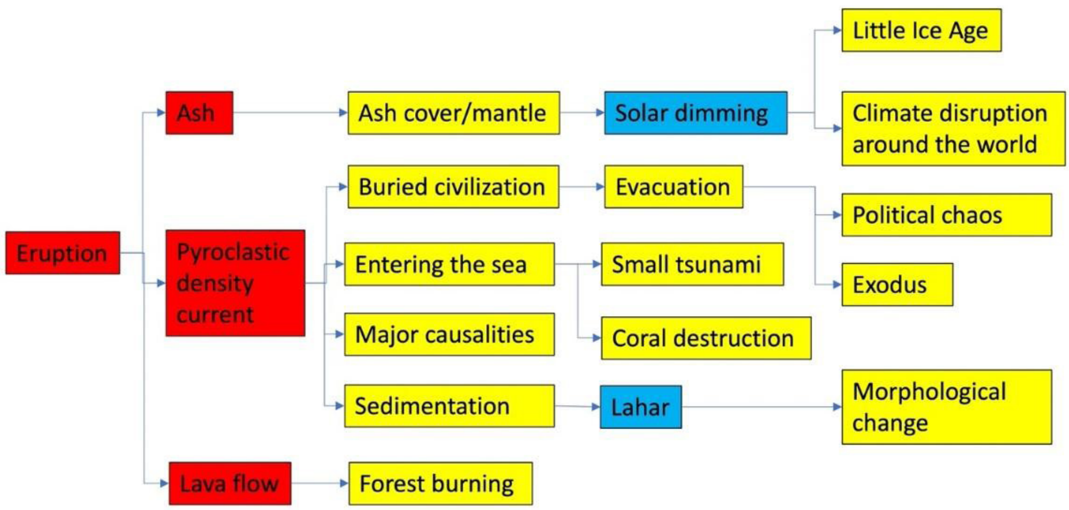

Figure 6. Schematic process and cascading hazard of the Samalas Volcano eruption in 1257. (Red: cause; yellow: effect; blue: escalation point).

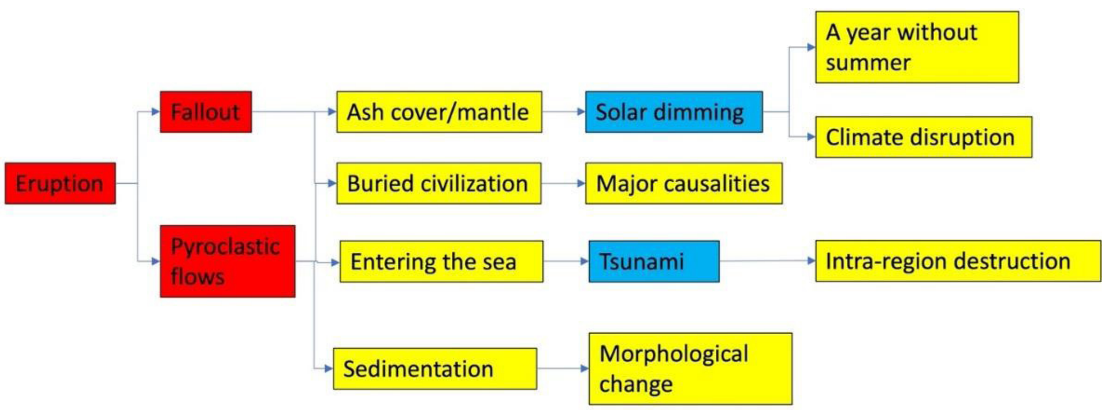

Figure 7. Schematic process and cascading hazard of the Tambora Volcano eruption in 1815. (Red: cause; yellow: effect; blue: escalation point).

extent of a disaster's impact on environmental, social, political, and economic conditions at both local and global scales (Suppasri et al, 2021; Alexander, 2018). Information about the dynamics and impacts of disasters could be used as a reference for policymakers in developing DRR strategies, specifically in mitigation and community preparedness.

Contemporary Disaster Risk Management

The eruption of Samalas in 1257 CE was a significant volcanic event, and its impact was felt across the region. The magma chamber responsible for this eruption was still active, sustaining current volcanic activity at Barujari somma-volcano and Rinjani (Figure 9). However, the possibility of eruption matching the previous magnitude remained very low, as current activity at both sites appears stable. Volcanic system remains under surveillance to detect any changes that might signal increased hazard potential. In contemporary times, Rinjani volcano attracted a significant number of climbers and tourists, contributing to a high visitor density. Additionally, densely populated areas, such as Sembalun, located near the summit, are at considerable risk. The combination of high visitor traffic and the presence of nearby populated areas increased vulnerability to volcanic hazard. Despite the stability of the current volcanic activity, the high density of visitors and the proximity of populated areas necessitated an elevated focus on DRR measures. Effective DRR strategies should address both the immediate and longer-term risks associated with potential future eruption. Enhancing community awareness, preparedness, and effective evacuation planning were key to minimizing potential impacts from future eruption of Rinjani.

Tambora remained an active caldera volcano with the potential for eruption similar in scale to the catastrophic event of 1815. However, the tendency of occurrence was currently assessed as low. The DRR efforts in the region were primarily structured around managing hazard at a low to medium level (Figure 10). This method may not adequately prepare for a worse-case scenario resembling the 1815 eruption, which had global climatic impacts due to its massive scale. Historically, local disaster planning had often focused on existing scenarios rather than preparing comprehensively for a repeat of the 1815

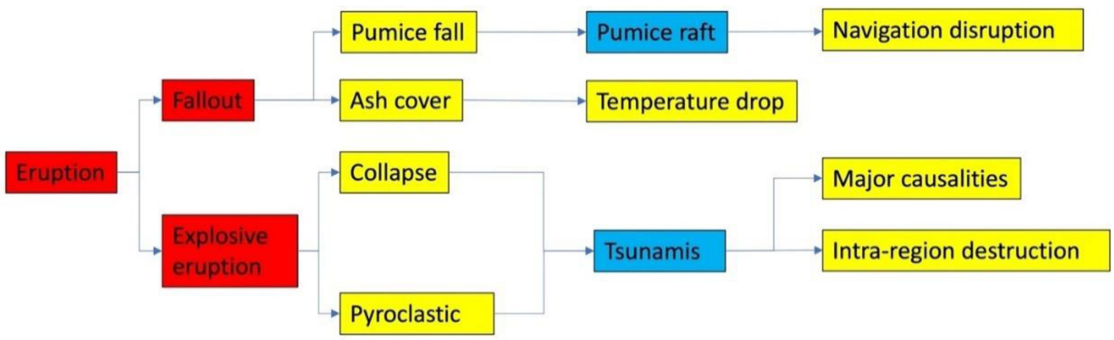

Figure 8. Schematic process and cascading hazard of the Krakatau Volcano eruption in 1883. (Red: cause, yellow: effect, blue: escalation point).

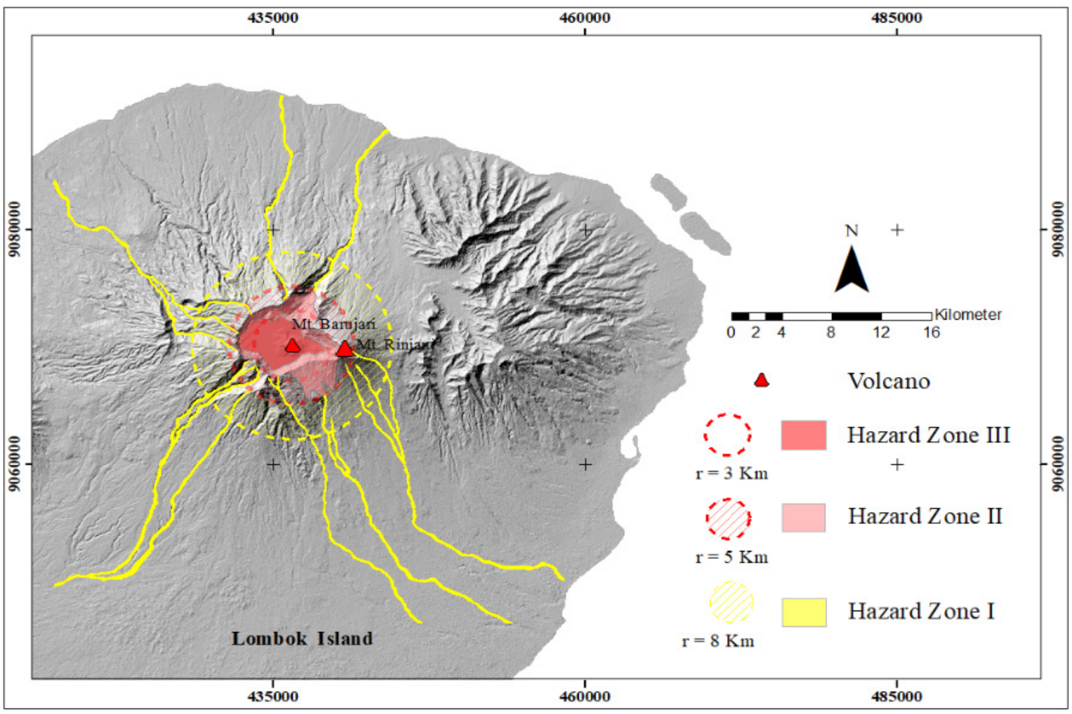

Figure 9. Disaster-prone area (KRB map) of the Samalas-Rinjani volcanic complex. The database of the KRB map can be accessed through https://vsi.esdm.go.id/portalmbg/.

eruption. This eruption was the most powerful in recorded history, leading to widespread devastation and climatic effects that persisted for years. Considering the potential magnitude of the cascading event (M4), it was important to incorporate a worst-case scenario based on the 1815 eruption into local disaster planning. This entailed not only enhancing evacuation protocols and emergency response capabilities but also developing strategies to mitigate broader socio-economic impacts and ensure resilience in affected communities. Local legends, such as prohibitions against living along the coast in certain locations near Tambora, offered insights into historical perceptions of volcanic risk (Mutaqin & Lavigne, 2019). These customs were based on the collective memory of tsunamis caused by volcanic events, showing a deep awareness of natural hazard among communities. Drawing from this cultural knowledge could support disaster planning by reinforcing scientific results and strengthening community participation and readiness.

Krakatau continued to pose significant hazard to the surrounding region, particularly through tsunami events

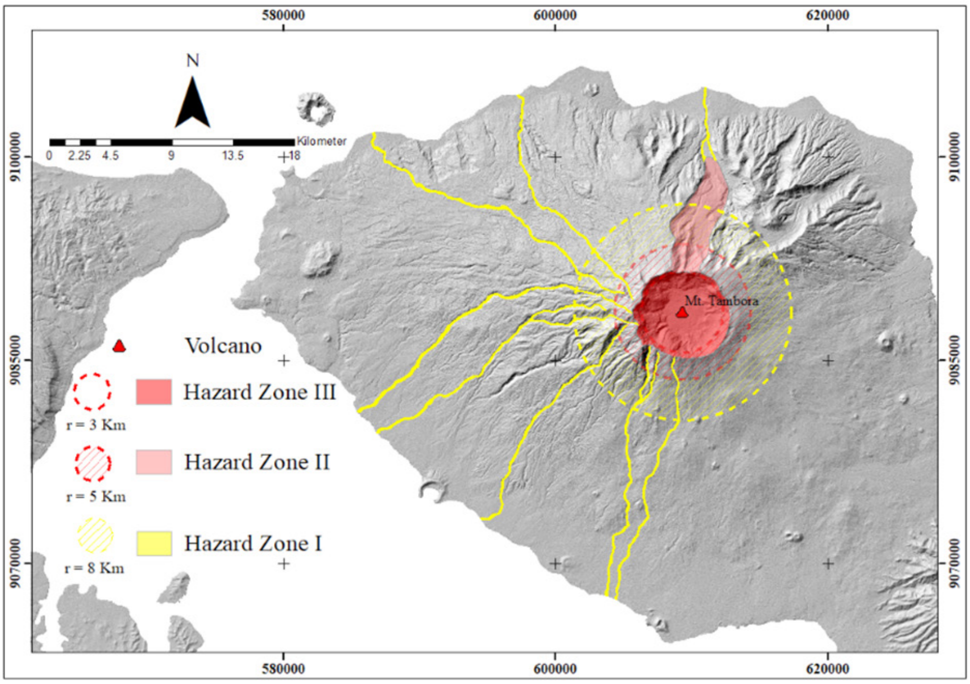

Figure 10. Disaster-prone area (KRB map) of the Tambora volcano. The database of the KRB map can be accessed through https://vsi.esdm.go.id/portalmbg/.

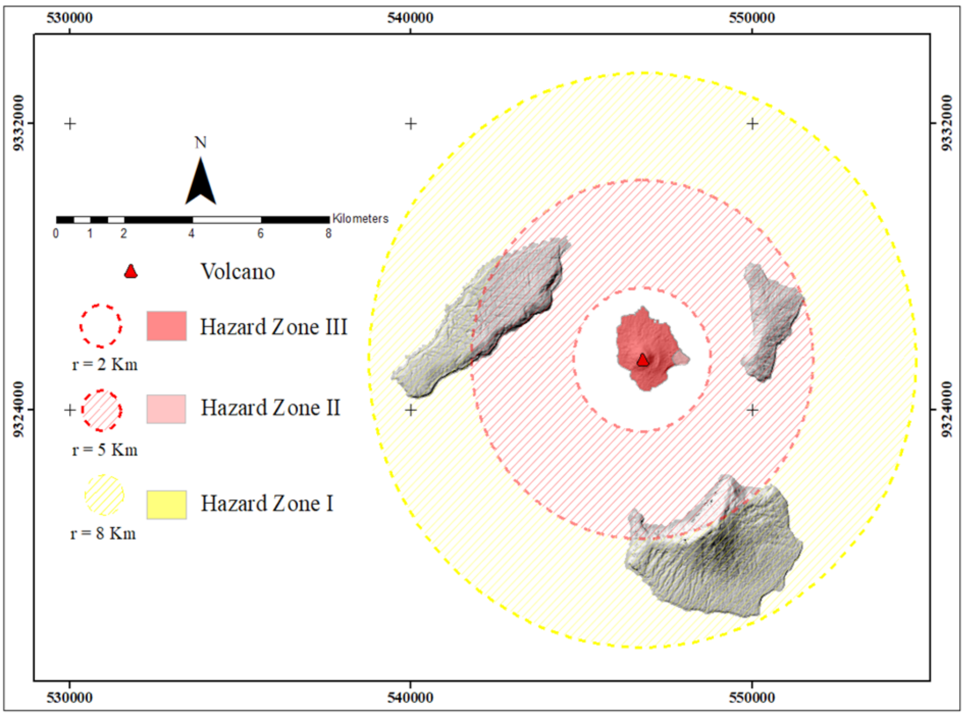

Figure 11. Disaster-prone area (KRB map) of the Krakatau volcano. The database of the KRB map can be accessed through https://vsi.esdm.go.id/portalmbg/.

triggered by volcanic activity, as shown in Figure 11. Krakatau currently has no potential for volcanic explosivity index (VEI) 6 eruption. However, the risk of tsunamis in the Sunda Strait remained high, as shown by the 2018 event that impacted coastal communities. This event showed the volcano's ongoing hazard potential and underscored the importance of robust DRR strategies in the area. The eruption was not as massive as the 1883 event, but it can generate a significant tsunami due to underwater landslides. This event prompted a reassessment of tsunami hazard embedded within DRR plans for Krakatau, showing the need for updated hazard zones based on a thorough understanding of volcanological processes. To effectively manage risks associated with Krakatau, it is essential to integrate advanced volcanological insights into hazard assessments and mitigation strategies. This was carried out by leveraging modern monitoring technologies to detect precursory signals of volcanic unrest and improve early warning systems for both volcanic eruption and associated tsunamis. Learning from past events, such as the 1883 eruption and subsequent tsunamis, provides critical historical context for understanding the volcano's behavior and refining the predictive models.

5. Conclusion

In conclusion, this study shows the critical need to understand the social impacts of Indonesia's major volcanic eruption, namely Samalas, Tambora, and Krakatau in 1257, 1815, and 1883, respectively. By examining historical documents that capture societal memories and analyzing data from previous study, this study uncovers the diverse community responses, past vulnerability, and the cascading hazard associated with the disasters. The results show that while Samalas experienced the longest recovery period, Krakatau had the highest casualties and economic loss due to its multiple hazard. Moreover, the analysis of past vulnerability descriptions and cascading hazard provides valuable insights for evaluating current DRR programs, particularly in the context of existing volcanic hazard maps. There is a need to incorporate potential hazard arising from cascading events in hazard map to foster a collective awareness. Learning from past events allows for the establishment of a DRR that focuses on aspects of community preparedness and resilience to deal with future volcanic hazard. This can help to build a strong foundation for disaster response and reduce the resulting impact.

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