Eruption on Indonesia’s volcanic islands: a review of potential hazards, fatalities, and management

A Hidayat¹, M A Marfai²* and D S Hadmoko²

¹ Department of Geography, Faculty of Geography, Universitas Gadjah Mada, Sekip Utara, Bulaksumur, 55281 – Indonesia
² Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Sekip Utara, Bulaksumur, 55281 – Indonesia

* arismarfai@ugm.ac.id

Abstract. Among the 17,504 islands in Indonesia, there are a number of volcanic islands with active volcanoes amid human inhabitation. These conditions can be dangerous when the volcano erupts. This paper provides a review of eruptions on Indonesia’s volcanic islands, especially in potential hazard, fatalities, and management. There were 22 Indonesia’s volcanic islands with records of volcanic eruptions during the Holocene era. Seventy percent of them are classified as active and have a high potential to endanger the surrounding population who generally live on small islands. More than 150,000 people have been evacuated in 25 volcanic unrest of 9 volcanic island during 1966 to 2017. The largest human fatalities from eruption on volcanic island was caused by volcanic tsunami. Since 416 to 2018 there were 19 volcanic tsunami events on Indonesia’s volcanic islands, resulting in 41,328 death tolls. With this review, we hope that our knowledge of volcanic eruption on Indonesia’s volcanic island can be improved and the community living around the volcanoes can be more prepared to face a volcanic crisis that can occur at any time.

1. Introduction
Volcanic eruptions are one of the most dangerous natural hazards on earth because their impact can disrupt the social and economic activities of the community [1, 2] and even cause loss of life [3]. The impact of eruptions on small volcanic islands, including several eruption events or products like pyroclastic flows, flank collapses, phreatomagmatic explosions, incandescent lava flows, and volcanic tsunamis, can be vast due to their small size and surrounding marine environments [4]. As an archipelagic country, Indonesia has 17,504 islands [5]. The formation of these many islands is inseparable from geologic processes happening in Indonesia. As widely known, Indonesia is a subduction zone of three tectonic plates, namely the Eurasian plate, the Indo-Australian plate, and the Pacific plate. From this plate collision zone, a belt consisting of up to 400 volcanoes emerged, and 130 of them are classified as active [6]. The distribution of volcanoes along the subduction zone is presented in Figure 1.

Volcanic islands are volcanoes that erupted on the seabed with the summits appearing above sea level [7]. Various materials spewed out by volcanoes are deposited repeatedly every time an eruption event occurs and eventually form an island. Volcanic islands generally develop into or are parts of island arcs in tectonic systems. According to Condie [7], they appear near oceanic ridges or in oceanic basins. The easily recognizable features of these islands are their shape and the genesis of the rocks. The shape generally resembles a cone, although, on some volcanic islands, the cone may have been lost due to eruptions [8]. The genesis of the rocks can be easily identified from rock outcrops, which
are the products of volcanic activities like lava deposits, lahar sedimentation, and tephra layers. The size of the islands ranges from <1 to approximately 10,000 km² [7]. In Indonesia, a small island, as clearly defined in Indonesia Coastal and Small Island Management Act of 2014, is an island with an area of less than or equal to 2000 km² that includes ecological unity [9].

Among the volcanic islands in Indonesia, some still have active volcanoes (such as Ternate Island and Siau Island) while others have dormant and even inactive ones (such as Tidore Island). More than a few volcanic islands have active volcanoes and human occupation on their slopes, e.g., in Ternate, Rokatenda, and Una-Una Island. This type of volcanic islands poses a higher risk than the ones with inactive volcanoes. Eruptions on volcanic islands that are deemed phenomenal are the Krakatoa Eruption in 1883, which caused a tsunami and claimed 36,500 lives [2, 6, 11, 12]. High fatalities are also the results of pyroclastic flows, as in the eruption of Mount Pelee in Martinique in 1902 that led to the deaths of 29,000 people [3, 13]. Since the 1700s, eruptions on volcanic islands have claimed more than 100,000 lives [4]. The direct causes of loss of life are pyroclastic flows, lava, or landslides/flank collapses, while the indirect ones are volcanic tsunamis.

In general, there are only a few studies of eruptions on volcanic islands in Indonesia, both in terms of hazards and mitigations. Research on Indonesia’s volcanic islands in a broad spectrum of topics and methodologies has been performed on, for instance, Siau Island with focuses on capacity in dealing with natural hazards [14] and agroforestry on a small volcanic island [15]. Another study on Ternate Island emphasizes the modeling of evacuation pathways [16], the characteristics of Gamalama eruptions [17], and physical and social vulnerability [18]. Most volcanic island studies are about Krakatoa Volcano or the Child of Krakatoa [11, 12, 19, 20]. This review comprehensively discusses eruption events and their impact on Indonesia’s volcanic islands. Volcanic hazard assessment is necessary to support volcanic risk management [21]. With this review, the locations of Indonesia’s volcanic islands that have the potential to experience eruptions in the future can be mapped, which can increase knowledge of eruptions on these islands and their impact as part of disaster preparedness.
2. Methods

2.1. Data collection and processes

Historical data of volcanic activities and management were compiled from various relevant literature such as Journal, International Volcanic Database [23], National Geophysical Data Center / World Data Service [13], National Disaster Management Agency, and National Database of Volcano from Center of Volcanology and Geological Hazard Mitigation (CVGHM). The spatial distribution of volcanoes was obtained from volcano database by Simkin and Siebert [10].

2.2. Data analysis

This review was descriptively analyzed in term of eruption, social impact, fatalities, potential hazard, and management in Indonesia’s volcanic islands. The authors identify the data from various sources and comparing one to another to validate the data. This review also discussing potential volcanic hazard in the future and the challenges of volcanic crisis on small volcanic island.

3. Results and Discussion

3.1. Indonesia’s volcanic islands

Indonesia is the largest archipelagic country in the world and consists of 17,504 islands [22]. Based on the results of the identification, which considered the genesis and existence of volcanoes that have erupted since the Holocene era, there are 22 volcanic islands in Indonesia [34]. In this study, the term of volcanic island is an island with an area of less than or equal to 2000 km² that the majority consist of volcanic landform. The volcanic islands in Indonesia and their volcanoes are listed in Table 1.

| No | Islands       | Coordinates         | Volcano Names | Elevation (masl) | Latest Eruptions | Status  |
|----|---------------|---------------------|---------------|-----------------|------------------|---------|
| 1  | Anak Krakatau | 6.10°S, 105.42°E    | Krakatoa      | 813             | 2019             | Active  |
| 2  | Api Siau     | 2.78°N, 125.4°E     | Karangetang   | 1797            | 2019             | Active  |
| 3  | Banda        | 4.52°S, 129.9°E     | Banda Api     | 596             | 1988             | Active  |
| 4  | Damar        | 7.12°S, 128.6°E     | Wurlali       | 868             | 1892             | Active  |
| 5  | Gunungapi    | 6.64°S, 126.6°E     | Wetar         | 282             | 1699             | Active  |
| 6  | Hiri         | 0.9°N, 127.32°E     | Hiri          | 630             | ?                | Dormant |
| 7  | Kayoa        | 0.07°N, 127.4°E     | Tigaalulu     | 422             | ?                | Dormant |
| 8  | Komba        | 7.79°S, 123.6°E     | Batu Tara     | 633             | 2015             | Active  |
| 9  | Makian       | 0.32°N, 127.4°E     | Makian        | 1357            | 1988             | Active  |
| 10 | Manok        | 5.54°S, 130.3°E     | Manuk         | 257             | ?                | Dormant |
| 11 | Mare         | 0.57°N, 127.4°E     | Mare          | 308             | ?                | Dormant |
| 12 | Moti         | 0.45°N, 127.4°E     | Moti          | 927             | ?                | Dormant |
| 13 | Nila         | 6.73°S, 129.5°E     | Nila          | 781             | 1968             | Active  |
| 14 | Palue        | 8.32°S, 121.7°E     | Rokatenda     | 875             | 2013             | Active  |
| 15 | Sangiang     | 8.2°S, 119.07°E     | Sangeangapi   | 1949            | 2019             | Active  |
| 16 | Sangihe      | 2.3°N, 125.37°E     | Ruang         | 725             | 2002             | Active  |
| 17 | Serua        | 6.31°S, 130.0°E     | Legatala      | 608             | 1921             | Active  |
| 18 | Siau         | 3.69°N, 125.4°E     | Awu           | 1318            | 2004             | Active  |
| 19 | Ternate      | 0.8°N, 127.33°E     | Gamalama      | 1715            | 2018             | Active  |
| 20 | Teun         | 6.97°S, 129.1°E     | Teon          | 728             | 1904             | Active  |
| 21 | Tidore       | 0.66°N, 127.4°E     | Tidore        | 1750            | ?                | Dormant |
| 22 | Una Una      | 0.16°S, 121.6°E     | Colo          | 404             | 1983             | Active  |

Source: Hidayat et al. [34]
The number of volcanic islands in Indonesia, particularly those with volcanoes that erupted before the Holocene, is far higher than this figure, but this study experienced difficulty in identifying or affirming which islands fell into this category due to unavailability of supporting data. Also, this research only selected volcanic islands with volcanoes that erupted in the Holocene era under the consideration that they pose significant threats to the surrounding communities and the fact that most of the identified volcanic islands have active volcanoes. Out of the 22 recognized volcanic islands, 16 (73%) have active volcanoes, and the rest (6 islands) have dormant ones. Volcanic islands in the southern part of Indonesia are formed in the subduction zone between the Indo-Australian Plate and the Eurasian Plate, while the ones in the eastern part lie on the subduction zone between the Pacific and Eurasian Plates (Figure 2). They mostly appear not far from the oceanic crust (<15 km), and only some are located more than 25 km from it. Volcanic islands in Indonesia generally evolve from stratovolcanoes with summits at 257 to 1949 masl. Sangeangapi Volcano on Sangiang Island has the highest summit, i.e., 1949 masl. Following this height is Karangetang Volcano on Api Siau Island with a summit at 1797 masl. Meanwhile, Manuk Volcano on Manuk Island has the lowest summit, that is, 257 masl (Table 1).

Figure 2. The distribution of Indonesia’s volcanic islands with volcanoes that erupted in the Holocene era [34]

3.2. Potential volcanic hazards on volcanic islands
Volcanic eruptions are a natural phenomenon that involves explosions, lava flows, pyroclastic flows, gas emissions, and tephra falls. However, they can also be associated with secondary disasters, such as volcanic earthquakes, volcanic landslides, and lava. The danger of eruptions on volcanic islands is not much different from eruption events elsewhere, but volcanic islands are often small in size and have various limitations that may worsen the impact. The examples of these limitations include locations that are difficult to reach, vulnerability to ecological damages, high dependence on imports, and limited natural resources, supplies of clean water, space for evacuation, and transportation and communication [24]. Potential hazards on volcanic islands depend on the events or products of eruptions. These various events or products and their potential impacts on society and the environment are as follows:
3.2.1. Explosive eruptions, pyroclastic flows, lava flows, and tephra falls

Volcanic islands that are generally small in size and surrounded by oceans are in serious dangers of volcanic eruptions, lava flows, pyroclastic flows, and tephra falls. According to Gaudru [4], pyroclastic flow is the most destructive and deadly event resulting from volcanic eruptions. Pyroclastic flow, or better known as Pyroclastic Density Currents, is a current of a mixture of volcanic gases and fragmented rocks that flows down the volcanic slopes at the speed of up to hundreds of kilometres per hour with high temperatures (300°C – 700°C) [25]. PDCs will destroy anything on their path. They occurred during the eruptions of Karangetang Volcano on Api Siau Island in 1976 and Colo Volcanic on Una-Una Island in 1983 [23].

Another dangerous product of eruptions is incandescent lava flows. Lava is molten rocks with temperatures ranging from 650 °C to 1200 °C that is released by volcanoes during eruptions. It can travel from less than 1 km to several tens of kilometres depending on its chemistry, temperature, effusion rate, viscosity, and topography [26]. The speed of lava flow also varies from several meters to tens of kilometres per hour before it finally cools and solidifies. In Indonesia, lava flows formed during the eruptions of Banda Api Volcano on Banda Island in 1988. Exceptional ones were evident during the 1773 Gamalama Volcano Eruption on Ternate Island as they caused 40 deaths.

Aside from pyroclastic and lava flows, eruptions can produce hazardous tephra falls. Tephra is a general term for volcanic rock fragments that are released into the air by volcanic explosions and carried up by hot gases in the eruption column [25]. Based on its size, tephra is classified into volcanic ash (fragments < 2 mm), lapilli (2-64 mm), blocks (angular fragments, > 64 mm), and bombs (round fragments, > 64 mm). Large-sized tephra (i.e., bombs or rocks) usually falls not far from the crater, whereas the smaller one, lapilli, tends to be found farther away. As for the smallest fragments, i.e., volcanic ash, they can be transported by winds hundreds to thousands of kilometres away from the crater.

Since tephra can spread far from its source, it can cause extensive impact on humans and the environment, such as disruptions to the health of humans and pets, flight activity, and key infrastructure (transportation, telecommunications, and water and drainage networks), as well as damages to buildings and agricultural land and commodities. Thick volcanic ash can cause damage to housing infrastructure and clog irrigation channels. Although tephra bombs and blocks usually land within 5 km from the crater, they may travel up to 10 km. The most adverse consequences of large-sized tephra are its direct impacts; for instance, it can blow holes in the roof, kill people or livestock, and severely damage plants [26].

3.2.2. Lahars

Lahars are a good hydro-volcanic event that occurs during and after eruptions with the characteristics of large discharge flow, high sediment concentration, and poor sorting [27, 28]. Lahars occurring during eruptions are often referred to as primary or syn-eruptive lahars, while the ones forming afterward are secondary or post-eruptive. The combination of generally steep stratovolcano slopes that contain less compact material and wet tropical climate with high rainfall creates an ideal condition for lahars [29]. Because of the limited area of volcanic islands, lahars pose high risks of death and damage to infrastructure. Records show that they flew down the slopes of Awu Volcano on Siau Island in 1701, 1856 and 1892 and Makian Volcano on Makian Island in 1760 and occurred sometime after the 2011 Gamalama Volcano Eruption on Ternate Island [23].

3.2.3. Volcanic earthquakes, sector collapses, and volcano-triggered tsunamis

Volcanic earthquakes occur due to the movement of magma. This motion produces pressure changes in the rocks surrounding magma and, at some point, it can break them (trigger an earthquake) or move aseismically (through creep movement) [26]. Volcanic islands are a volcanic building resulting from repeated fast placement of magmatic products in a limited area. As a consequence, each volcanic structure with a significant height (≥1000 m) is deemed not robust (brittle). Volcanic earthquakes can trigger sector collapses, avalanches, and rockfalls, which are gravitational movements from some
portions of the volcanic slopes [12]. If sector collapses and landslides occur in the sea, they can trigger volcanic tsunamis.

Tsunamis are waves or a series of long-period water waves produced by unavoidable disturbances in marine or lake environments and can affect coastal ecosystems [6]. The examples of these disturbances are underwater earthquakes, landslides, or volcanic eruptions, the collapse of the seafloor, or bombs or meteorites landing in the sea. Tsunamis can be triggered by several eruption mechanisms, e.g., underwater explosions, airwaves generated by volcanic blasts, pyroclastic flows or lahars entering the sea, the collapse of the underwater caldera, subaerial failure, and submarine failure [12].

There is a long history of volcano-triggered tsunamis in Indonesia. Based on written data in the year 416, the volcanic island Krakatoa erupted and then triggered a tsunami. However, the details on the incident are still in question [6, 13, 30, 31]. Eruptions on volcanic islands that trigger tsunamis appear to have an enormous impact on people living on them and the nearby islands. The Krakatoa eruption in 1883 was the most phenomenal disaster on Indonesia’s volcanic islands that caused a tsunami and claimed 36,000 lives. Overall, eruptions on volcanic islands that induced the occurrence of tsunamis in Indonesia are listed in Table 2.

| No | Locations                      | Days | Months | Years | Causes of tsunami                  | Fatalities (human) | References |
|----|--------------------------------|------|--------|-------|------------------------------------|--------------------|------------|
| 1  | Krakatoa, South Lampung        | 416  |        |       | Questionable                       | [6, 13, 30, 31]     |            |
| 2  | Gamalama, Ternate Island       | 18   | 7      | 1608  | N/A                                | [13, 30]            |            |
| 3  | Teon Volcano, Banda Sea        | 11   | 11     | 1659  | Pyroclastic flows?                 | [30]                |            |
| 4  | Gamalama, Ternate Island       | 9    | 5      | 1772  | N/A                                | 35                  | [13]       |
| 5  | Gamalama, Ternate Island       | 2    | 2      | 1840  | Questionable                       | [6, 13, 30]         |            |
| 6  | Awu, Sangihe Island            | 2    | 3      | 1856  | Pyroclastic flows                  | 3,000              | [6, 11, 13, 31] |
| 7  | Ruang, North Sulawesi          | 3    | 3      | 1871  | The collapse of the lava dome       | [6, 11, 13]         |            |
| 8  | Krakatoa, South Lampung        | 27   | 8      | 1883  | Pyroclastic flows                  | 36,000             | [6, 11, 13, 30, 31] |
| 9  | Krakatoa, South Lampung        | 2    | 8      | 1884  | Underwater explosion?              | [13, 30]            |            |
| 10 | Banua Wuhi, Sangihe Island     | 6    | 9      | 1889  | Underwater explosion?              | [6, 11, 13, 30]     |            |
| 11 | Awu, Sangihe Island            | 7    | 6      | 1892  | Pyroclastic surges?                | 1,532              | [13, 30]   |
| 12 | Banua Wuhi, Sangihe Island     | 14   | 3      | 1913  | Pyroclastic surges?                | [13]                |            |
| 13 | Banua Wuhi, Sangihe Island     | 18   | 7      | 1918  | Underwater explosion               | [13, 30]            |            |
| 14 | Banua Wuhi, Sangihe Island     | 3    | 4      | 1919  | Underwater explosion               | [13, 30]            |            |
| 15 | Rokatenda, Flores Sea          | 7    | 8      | 1927  | Underwater explosion               | 226                | [13, 31]   |
| 16 | Rokatenda, Flores Sea          | 28   | 3      | 1928  | Underwater explosion               | [6, 13, 30]         |            |
| 17 | Ilaverung, Lembata Island      | 4    | 8      | 1928  | Volcanic landslide?                | 98                 | [6, 13, 30] |
| 18 | Ilaverung, Lembata Island      | 17   | 8      | 1979  | Volcanic landslide                 | [11, 13, 30]        |            |
| 19 | Krakatoa, South Lampung        | 22   | 12     | 2018  | Volcanic landslide?                | 437                | [13, 20]   |

From 1966 to 2017, 25 eruption events on nine volcanic islands required the evacuation of 158,816 people (Table 3). Evacuations of residents on volcanic islands in Indonesia are generally inter-island. Only a few of them are within the affected island because generally volcanic islands in Indonesia are small, meaning that nearby islands are feasible options for evacuations. The evacuations due to dangerous volcanic activities and other natural hazards are significantly different because the duration in the former is far more uncertain than the latter. The displacement of people will influence the social and economic conditions of the communities on small volcanic islands. For this reason, disaster-related stakeholders must set a higher limit of acceptable risk than the case of evacuation from hazardous areas on large islands that likely has little to no social or economic impact [4].
### Table 3. The number of evacuated people due to eruptions on Indonesia’s volcanic islands

| No | Months | Years | Volcanoes       | Number of Evacuated People | Evacuation Destination | Causes                                                                 | Additional Information |
|----|--------|-------|-----------------|----------------------------|------------------------|----------------------------------------------------------------------|------------------------|
| 1  | 8      | 1966  | Awu             | 11,000                     |                        | Explosions                                                           |                        |
| 2  | 10     | 1976  | Karangetang     | 1,800                      |                        | Pyroclastic and lava flows                                           |                        |
| 3  | 8      | 1980  | Gamalama        | 40,000                     | Tidore, Halmahera, & Hiri Islands | Incandescent material falls, tephra falls, forest fires            | Ash thickness reached 15 cm |
| 4  | 2      | 1981  | Rokatenda       | 1,850                      | Safe zone Pulauweh Island | Explosions                                                           |                        |
| 5  | 7      | 1983  | Colo            | 7,000                      |                        | Explosions, pyroclastic flows                                       |                        |
| 6  | 8      | 1984  | Karangetang     | 20,000                     |                        | tephra falls, lava flows                                            |                        |
| 7  | 9      | 1984  | Karangetang     | 4,500                      | Api Siau Island         | Ash falls and pyroclastic density current                           | From the south to the west flanks |
| 8  | 8      | 1985  | Sangeang Api    | 1,250                      | Sumbawa                | Explosions                                                           |                        |
| 9  | 1      | 1986  | Sangeang Api    | 1,242                      | Sumbawa                | Gas explosions, incandescent lava fragments                        |                        |
| 10 | 2      | 1988  | Gamalama        | 3,500                      | Halmahera              | Thick ashfalls                                                      |                        |
| 11 | 7      | 1988  | Makian          | 15,000                     | Moli                   | Pyroclastic flows                                                   |                        |
| 12 | 4      | 1988  | Banda Api       | 1,800                      | Neira                  | Bombs, lava flows                                                   |                        |
| 13 | 4      | 1988  | Banda Api       | 6,000                      | Neira & Lontar Islands | Bombs, lava flows                                                   | Some evacuated to safer locations in Neira Island, and some to Lontar Island |
| 14 | 5      | 1988  | Banda Api       | 7,000                      | Ambon Island           | Bombs, lava flows                                                   | Evacuated from Gunungapi, Neira, and Lontar Islands |
| 15 | 6      | 1988  | Banda Api       | 1,800                      | Ambon, Seram, & Lontar Islands Bombs, lava flows |                           | Most refugees were allowed to return to Banda Neira and Lontar Islands |
| 16 | 4      | 1992  | Karangetang     | 452                        |                        | Pyroclastic flows                                                   |                        |
| 17 | 12     | 1992  | Karangetang     | 452                        |                        | Hot mudflow and ash                                                 |                        |
| 18 | 1      | 1993  | Karangetang     | 452                        |                        | Rumbling sounds and ejection of lava fragments                      |                        |
| 19 | 7      | 1997  | Karangetang     | 400                        |                        | Explosions and pyroclastic flows                                   |                        |
| 20 | 10     | 2002  | Ruang           | 1,000                      | Nearby islands         |                                                                       | From the villages in the west to other locations |
| 21 | 5      | 2004  | Awu             | 20,000                     |                        | Explosions                                                          |                        |
| 22 | 2      | 2011  | Karangetang     | 1,200                      | Api Siau               | Pyroclastic flows                                                   | From the villages in the west to other locations |
| 23 | 8      | 2013  | Rokatenda       | 3,903                      | Flores                 | Pyroclastic flows                                                   |                        |
| 24 | 2      | 2014  | Sangeang Api    | 7,328                      | Sumbawa                | Explosive eruption column of ash and sulfur dioxide, ashfall        |                        |
| 25 | 2      | 2017  | Karangetang     | 339                        |                        | Incandescent materials, pyroclastic flows                           | From Ulu, Salili, Belali, and Tarorane Villages to other locations |

Total 158,816

Source: Global Volcanism Programs [23]
3.3. Volcanic crisis management and challenges for small volcanic islands in Indonesia

Indonesia has had a lot of experience in dealing with large-scale eruption disasters, such as the eruptions of Merapi Volcano in 2010, Mount Sinabung in 2012, and Mount Agung in 2018. In terms of volcanic crisis management, stakeholders of disaster management take into account recommendations from the Center for Volcanology and Geological Disaster Mitigation (Pusat Vulkanologi dan Mitigasi Bencana Geologi—PVMBG). From seismological monitoring posts, PVMBG collects data and monitors any volcanic activities to determine the status of the hazard (Figure 5). It issues four alert levels as a response to volcanic events in Indonesia, namely (i) normal active, (ii) advisory, (iii) watch, and (iv) warning. It is also responsible for producing Maps of Disaster-Prone Areas (Kawasan Rawan Bencana—KRB) for each active volcano. They contain information about the danger zones, ranked from the most to the least dangerous, namely KRB III, KRB II, and KRB I.

![VSAT DATA TRANSMISSION SYSTEM](image)

**Figure 5.** Indonesia’s volcano monitoring networks. There are 12 monitoring regions, each of which observes 2-7 volcanoes (satellite images and connecting lines indicate signal transmission to the headquarters of PVMBG in Bandung). Map modified from Andreastuti et al. [6].

Information on volcanic activities is monitored by the observation posts, and then the records are transmitted to the PVMBG headquarters in Bandung. In Bandung, the data is then analyzed to determine alert status and risk reduction measures and is regularly reported to disaster management stakeholders in both national and local levels. The stakeholders in eruption disaster management are PVMBG, National Disaster Management Agency (Badan Nasional Penanggulangan Bencana—BNPB), local governments in the regency, district, and village levels, volunteers of
Indonesian Red Cross Society (Palang Merah Indonesia—PMI) and Search and Rescue team (SAR), National Search and Rescue Agency (Badan Nasional Pencarian dan Pertolongan—BASARNAS), Indonesian National Armed Forces (Tentara Nasional Indonesia—TNI), and Indonesian National Police (Kepolisian Negara Republik Indonesia—POLRI). In an emergency (alert levels III and IV), PVMBG can directly inform the situation of the volcano to the heads of the affected regions so that they together with the Regional Disaster Management Agency (Badan Penanggulangan Bencana Daerah—BPBD) can immediately coordinate any parties involved in handling the crisis, including the rescuers (TNI, POLRI, BASARNAS, and volunteers from SAR, PMI, and Youth Disaster Preparedness Unit or Taruna Siaga Bencana—TAGANA), to plan and carry out evacuation if necessary.

In the case of small volcanic islands, there are many obstacles in their disaster management. Constraints in communication can have fatal consequences for disaster risk reduction efforts. Moreover, there is an insularity factor (i.e., an area that is difficult to access) due to limited transportation facilities and infrastructure or any constraints in territorial waters [24]. In this situation, the fastest response is locally sourced, i.e., the communities know more about the terrain conditions and the safe location for temporary evacuation before outside assistance arrives. Increasing the capacity of communities on small volcanic islands is therefore necessary [33]. Also, specific contingency plans for people relocation by sea to other islands are required and must be continuously tested and evaluated to ensure that they can work should a crisis emerge. Exploring cooperation in inter-island disaster management or establishing a disaster-safe sister island for an eruption-prone one is critical in disaster risk reduction.

4. Conclusions

There is a real need to conduct studies on volcanic islands in Indonesia where population and economic activities continue to grow and, at the same time, increase their vulnerability to eruption impacts. To develop a strategy for disaster risk reduction on volcanic islands, an understanding of the hazardous areas and past eruption events and their adverse effects on volcanic islands in Indonesia is necessary. Information on Maps of Disaster-Prone Areas on volcanic islands must be updated and consider the results of current scientific studies. Furthermore, the preparedness of people living around volcanoes on volcanic islands has to be improved, one of which is by cooperating with communities in adjacent islands (sister islands) to face a crisis that can occur at any time.

Acknowledgments

The first author acknowledges the Indonesia Endowment Fund for Education (LPDP) for its financial support (PRJ-2912/LPDP.3/2016). The authors acknowledge the Republic of Indonesia’s Ministry of Research, Technology, and Higher Education for funding received for 2019 National Competitive Research Grant—Doctoral Dissertation Research Scheme, especially in collecting data. Authors would like to thank World-class University Program, Universitas Gadjah Mada, for supporting the part of the publication process. Finally, the authors also would like to thank anonymous reviewers for their helpful comments on this paper.
References

[1] Bird D K, Gisladottir G and Dominey-Howes D 2010 Volcanic risk and tourism in southern Iceland: Implication for hazard, risk, and emergency response education and training. J. Volcanol. Geotherm. Res. 189 33–48

[2] Brown S K, Jenkins S F, Sparks R S J, Odber H and Auker M R 2017 Volcanic fatalities database: analysis of volcanic threat with distance and victim classification Journal of Applied Volcanology, 6 (1) https://doi.org/10.1186/s13617-017-0067-4

[3] Doocy S, Daniels A, Dooling S and Gorokhovich Y 2013 The Human Impact of Volcanoes: a Historical Review of Events 1900-2009 and Systematic Literature Review PLOS Currents Disasters. Edition 1. doi: 10.1371/currents.dis.841859091a706e1eb8a30f4fd7a1901

[4] Gaudru H 2005 Potential Impacts of Eruption on Volcanic Islands: Global Approach for Volcanic Risk Mitigation SVE/ROP Geneve

[5] Martha S 2017 The Analysis of Geospatial Information for Validating Some Numbers of Islands in Indonesia Indonesian Journal of Geography 49 (2) 204 – 211

[6] Mutaqin B W, Lavigne F, Hadmoko D S and Malawani M N 2018 Volcanic Eruption-Induced Tsunami in Indonesia: A Review IOP Conf. Ser.: Earth Environ. Sci. 256 012023

[7] Condie K C 2016 The Crust (Chapter 2 in Earth as an Evolving Planetary System (Third Edition) Academic Press 9–41. https://doi.org/10.1016/B978-0-12-803689-1.00002-X

[8] Velmurugan A 2008 The Nature and Characters of Tropical Islands (Chapter 1) in Editor(s): Sivaperuman C, Velmurugan A, Singh A K and Jaisankar I Biodiversity and Climate Change Adaptation in Tropical Islands Academic Press 2008 Pages 3-30 ISBN 9780128130643, https://doi.org/10.1016/B978-0-12-813064-3.00001-6

[9] Law No. 1 of 2014 about amendments to Law No. 27 of 2007 on coastal areas and small islands management (Pengelolaan wilayah pesir dan pulau-pulau kecil) Kementerian Hukum dan Hak Asasi Manusia Lembaran Negara Republik Indonesia Tahun 2014 Nomor 2

[10] Latter J H 1981 Tsunamis of volcanic origin: Summary of causes, with particular reference to Krakatau, 1883. Bulletin Volcanologique. 44 (3), 467–490 https://doi.org/10.1007/BF02600578

[11] Paris R, Switzer A D, Belousova M, Belousov A, Ontowirjo B, Whelley P L and Ulyrova M 2014 Volcanic tsunami: A review of source mechanisms, past events and hazards in Southeast Asia (Indonesia, Philippines, Papua New Guinea). Natural Hazards 70 (1), 447 – 470 https://doi.org/10.1007/s11069-013-0822-8

[12] NGDC/WDS (National Geophysical Data Center / World Data Service) 2019 Significant Volcanic Eruptions Database. National Geophysical Data Center NOAA doi:10.7289/V5JW8BSH [14 May 2019]

[13] Rampengan M M F, Boedihardhanto A K, Law L, Gaillard J C and Sayer J 2014 Capacities in Facing Natural Hazards: A Small Island Perspective. International Journal of Disaster Risk Science 5 (4) 247–264 https://doi.org/10.1007/s13753-014-0031-4

[14] Rampengan M M F, Boedihardhanto A K, Margules C, Sayer J, Law L, Gaillard J C, Linh T T M 2016 Agroforestry on an Active Volcanic Small Island in Indonesia: Prospering with Adversity Geographical Research 54 (1) 19–34 https://doi.org/10.1111/1745-5871.12148

[15] Syiko S F, Ayu R T and Yudono A 2013 Evacuation Route Planning in Mount Gamalama, Ternate Island-Indonesia Procedia Environmental Sciences 17 344–353 https://doi.org/10.1016/j.proenv.2013.02.047

[16] Hendrajaya L, Surono and Handayani G 1996 A short note on basic behavior of the mount Gamalama's eruption Jurnal Matematika dan Sains I (2) 1 – 14
[18] Mei E T W, Sari I M, Fajarwati A and Safitri D 2017 Assessing the Social Economic and Physical Vulnerabilities to Gamalama Volcano Proceeding 1st International Conference on Geography and Education (ICGE 2016) Atlantis Press 33–40 https://doi.org/10.2991/icge-16.2017.7

[19] Camus G, Gourgaud A and Vincent P M 1987 Petrologic evolution of Krakatau (Indonesia): Implications for a future activity Journal of Volcanology and Geothermal Research 33 (4), 299–316 https://doi.org/10.1016/0377-0273(87)90020-5

[20] Giachetti T, Paris R, Kelfoun K and Oنتوئيریو ب 2012 Tsunami hazard related to a flank collapse of Anak Krakatau Volcano, Sunda Strait, Indonesia Geological Society, London, Special Publications 361 79–90 https://doi.org/10.1144/SP361.7

[21] Marfai M A, King L, Singh L P, Mardiatno D, Santohadi J, Hadmoko D S and Dewi A 2008 Natural hazards in Central Java Province, Indonesia: An overview Environmental Geology 56 (2) 335–351 https://doi.org/10.1007/s00254-007-1169-9

[22] BIG (Badan Informasi Geospasial) 2019 Jumlah Pulau Indonesia Sebanyak 16.056 Pulau Masih Bisa Bertambah Lagi http://www.big.go.id/berita-surta/show/rujukan-nasional-data-kewilayahan-luas-nkri-8-3-juta-kilometer-persegi [16 May 2019]

[23] Bacharudin R, Martono A and Djuhara A 1996 Disaster prone Zone Map of Gamalama Volcano, Ternate, Maluku, Scale 1: 25.000 Bandung: Volcanological Survey of Indonesia

[24] Wilkinson E, Lovell E, Carby B, Barclay J and Robertson R E A 2016 The Dilemmas of Risk-Sensitive Development on a Small Volcanic Island Resources 21 (5) DOI :10.3390/resources5020021. Licensee MDPI, Basel, Switzerland

[25] Andreastuti S, Paripurno E T, Gunawan H, Budianto A, Syahbana D and Pallister J 2017 Character of community response to volcanic crises at Sinabung and Kelud volcanoes Journal of Volcanology and Geothermal Research https://doi.org/10.1016/j.jvolgeores.2017.01.022

[30] Sadly M, Trytomo R, Prasetya T, Daryono, Angrah S D, Budiarta, Setiyono U, Priyobudi, Yatimantor T, Hidayanti, Angraini S, Rahayu R H, Yogaswara D S, Julius A M, Apiyani M, Harvan M, and Simangunsong G 2018 Katalog Tsunami Indonesia Tahun 416 – 2017 Badan Meteorologi Klimatologi dan Geofisika. ISBN 978-602-52407-0-6

[31] Mercer J, Dominey-Howes D, Kelman I and Lloyd K 2007 The potential for combining indigenous and western knowledge in reducing vulnerability to environmental hazards in small island developing states Environmental Hazards, 7 (4) 245–256 https://doi.org/10.1016/j.envhaz.2006.11.001

[32] Andreastuti S, Paripurno E T, Gunawan H, Budianto A, Syahbana D and Pallister J 2017 Character of community response to volcanic crises at Sinabung and Kelud volcanoes Journal of Volcanology and Geothermal Research https://doi.org/10.1016/j.jvolgeores.2017.01.022

[33] Hidayat A, Marfai M A and Hadmoko D S 2019 Pemetaan pulau vulkanik kecil di Indonesia: Studi pendahuluan untuk manajemen bencana erupsi Jurnal Planoearth 4 (2) 95 - 101