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Natural Hazards
https://doi.org/10.1007/s11069-024-06671-5

ORIGINAL PAPER

Deadliest natural disaster in Balinese history in November 1815 revealed by Western and Indonesian written sources

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Received: 19 December 2023 / Accepted: 6 May 2024

Abstract

In November 1815, the deadliest "natural" disaster in Balinese history was caused by the exceptional combination of multiple natural hazards that occurred simultaneously and cascaded in the present-day province of Buleleng. This major disaster, which is thought to have claimed more than 10,000 lives, has never been scientifically analyzed. The study conducts an in-depth analysis of this cascading disaster, from the root causes and chronology of natural hazards to their environmental and societal effects, by thoroughly examining all available written sources about this event, whether colonial or Indonesian. Seven months after the Tambora eruption, a magnitude 7.3 earthquake, which occurred in the Bali Sea off the northern coast of the island, triggered a very large landslide on the northern flank of the Buyan-Bratan caldera. The initial mass movement evolved into a cohesive debris flow that reached the sea after traveling up to twenty kilometers through Banyumala River Valley and Singaraja City downstream. According to historical accounts, fifteen villages were buried or devastated by the debris flow. The large volume of sediment entering the sea triggered a local tsunami along Buleleng's coast. This geohistorical approach offers a comprehensive overview of various sources describing Singaraja's situation before the crisis, the hazard succession, the cascading hazard intensities, and the short- to long-term impacts on Buleleng. Based on the written sources, Bali took around fifteen years to recover from the 1815 disasters.

Keywords Cascading disaster · Earthquake · Landslide · Debris flow · Tsunami · Tambora eruption

1 Introduction

With recurrent earthquakes and 120 active volcanoes according to the Global Volcanism Program (GVP) database, the Indonesian archipelago is the most geodynamic region in the Indian Ocean and consequently is one of the countries most exposed to geohazards

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Published online: 20 June 2024

and multi-risks. Over recent years, Indonesia has been hit by a series of disasters that have severely disrupted the functioning of communities, resulting in widespread human, material, economic, or environmental losses and impacts beyond the capacity of the affected society to cope (UNISDR 2009). Among these disasters are the 2004 Sumatra earthquake and tsunami, which had a death toll of 225,000 (Dayton-Johnson 2006), and the 2006 Bantul earthquake near Yogyakarta in Java, which claimed more than 5,700 lives (Elnashai et al. 2007; Nichols 2007). More recently, the 2017 Agung volcanic unrest crisis and eruption is estimated to have cost the Indonesian economy more than $692 million (BNPB 2017), and Lombok's successive earthquakes in 2018 killed 562 people and displaced more than 400,000 people (BNPB 2018). The recurrence of physical phenomena, known as natural hazards, that may cause loss of life, injury, property damage, social and economic disruption, or environmental damage (UNISDR 2009), has heightened awareness of disasters within Indonesian society. Prevention, mitigation, and risk management have become a priority for government institutions. However, while the threat posed by these natural hazards to society is considered, recent events have underlined the difficulty of effectively managing multi-risks. This involves addressing all probabilities of a natural hazard and its negative impacts, considering interactions between hazards and also between vulnerabilities (Gallina et al. 2016). These processes are complex and multidimensional, in which different hazards can threaten the same exposed elements (temporal coincidence, e.g., the eruption of Pinatubo in 1991 aggravated by a typhoon generating major lahars, Major et al. 1996; Self et al. 1996) or serial hazards may occur at the same time or in short succession, so-called cascade hazards (e.g., the Krakatau eruption in 2018, whose flank collapse triggered a tsunami; Grilli et al. 2019). Cascading effects display complex dynamics in which the impact of an initial physical event triggers a sequence of events that cause multiple physical, economic, social, and cultural disruptions (Pescaroli and Alexander 2015). A cascading disaster is an extreme event in which cascading effects increase over time, triggering unexpected, high-impact secondary hazards (Pescaroli and Alexander 2015). The occurrence and magnitude of these cascading events are still poorly understood, and current knowledge is insufficient. In a cascading event, the multi-hazards can represent a serial linear sequence such as earthquake-landslide (e.g., Padang disaster in 2009: BNPB 2009; Wilkinson et al. 2012) or eruption-lahars (e.g., 2010 eruption of Merapi whose pyroclastic density current (PDC) deposits and volcanic fallout were remobilized by syn-and post-eruptive lahars; Surono et al. 2012; De Bélizal et al. 2013). Hazards can also occur in a parallel sequence, with the consequences of each one interacting, such as during the Palu earthquake in 2018, which simultaneously produced a tsunami, soil liquefaction, landslides, and a local tsunami triggered by a submarine landslide (e.g., Sassa and Takagawa 2019; Widiyanto et al. 2019). Another example is the tropical cyclone Seroja in 2021, whose torrential rains caused landslides and flooding, killing 272 people and causing economic losses of $475 million in Indonesia and East Timor (Latos et al. 2023). The dendroid event chain is a complex structure of parallel-serial hazards, where the initial hazard has generated several sequences of secondary and tertiary hazards (interconnected or not) magnifying the chain effects. This was the case of the Tohoku earthquake and tsunami in Japan in 2011, which generated a parallel series of hazards such as the nuclear power plant accident followed by radioactive contamination, fires, soil liquefaction, and subsidence following the earthquake (e.g., Mimura et al. 2011; Norio et al. 2011). Similarly, the 2004 Indian Ocean earthquake triggered a tsunami, fires, and soil liquefaction (e.g., Lay et al. 2005). Therefore, communities and critical infrastructures are more exposed to these multiple hazards, which can cause cascading effects of vulnerabilities. These cascading disasters and risks represent a new challenge for citizens and stakeholders in multi-risk management in Indonesia (Gallina et al. 2016; Pescaroli and Alexander 2017).

Recent multi-dimensional disasters serve as benchmarks for studying the cascading effects of hazards and impacts. Studies on historical Indonesian cascading disasters are still rare and limited to large-scale events that marked the archipelago's history (Sastrawan 2022), and whose consequences were global, such as the 1257 Samalas eruption (e.g., Lavigne et al. 2013; Mutaqin and Lavigne 2019), the 1815 Tambora eruption (e.g., De Jong Boers 1995; Oppenheimer 2003), or the 1883 Krakatoa eruption (e.g., Dörries 2003; Paris et al. 2014). However, Indonesian history is full of cascading disasters that have received little or no study, e.g. the 1856 Gunung Awu eruption triggered a coastal landslide, that caused a tsunami (Bankoff et al. 2021) or the cascading disaster that occurred on 22 November 1815 in the Buleleng kingdom, an event which is locally known as "*Zaman Gejer Bali*," or "the time when Bali shook". A major earthquake struck the Buleleng region, off the north coast of Bali (Fig. 1, 8°20'06" S, 115°05'17" E). The offshore earthquake would have triggered a tsunami and a huge landslide on the northern flank of the Buyan-Bratan caldera (Fig. 1a), which evolved into a massive debris flow that devastated various valleys and Singaraja-Sukasada villages, and caused fatalities of a large number of Balinese (Soloviev and Go 1974; Nordholt 1996; Harris and Major 2017). Little is known about these multi-risk sequences and their impact on Balinese society, already shaken by the cataclysmic Tambora eruption seven months before this disaster and forced to adapt to sudden events (e.g., De Jong Boers 1995; Oppenheimer 2003). The purpose of this paper is to fill this knowledge gap through the exegesis of historical accounts. These documents reflect the direct or indirect experiences of an author or witnesses to a past disaster, and shed light on legendary accounts and myths passed down from successive generations (Garrison et al., 2018; Principe et al., 2004; Trigo et al., 2010). The more or less long-term impact of disasters is reflected in textual sources, revealing the undocumented background of major disasters. This exegesis of historical sources and oral testimonies inscribed in family memories reveals crucial information for the cascading impacts of future disasters on a local and regional scale (e.g., Malawani et al. 2022). This study presents an opportunity to understand how cascading natural hazards interact with human societies, and how these cascading natural events affect a community on a local scale to better prepare the population for future disasters.

This deadliest natural disaster in recorded Balinese history has not been scientifically investigated in detail. This article aims to document this disaster in the Buleleng kingdom and report the results of a first-order analysis based on a geohistorical approach to the exegesis of written documents relating to the November 1815 event. This paper examines a wide range of rarely used historical documents of European (colonial) and Balinese origin, which can make a significant contribution to our understanding of the disaster. The local impact of the 1815 Gejer Bali disaster can be traced in several Western written documents and three main Indonesian texts, each with varying details (Tables S1 and S2 in Supplementary Material). We provide an overview of different sources describing Singaraja's situation before the disaster, the chronology and intensity of cascading hazards, and finally the short-, medium-, and long-term impacts on the Buleleng kingdom.

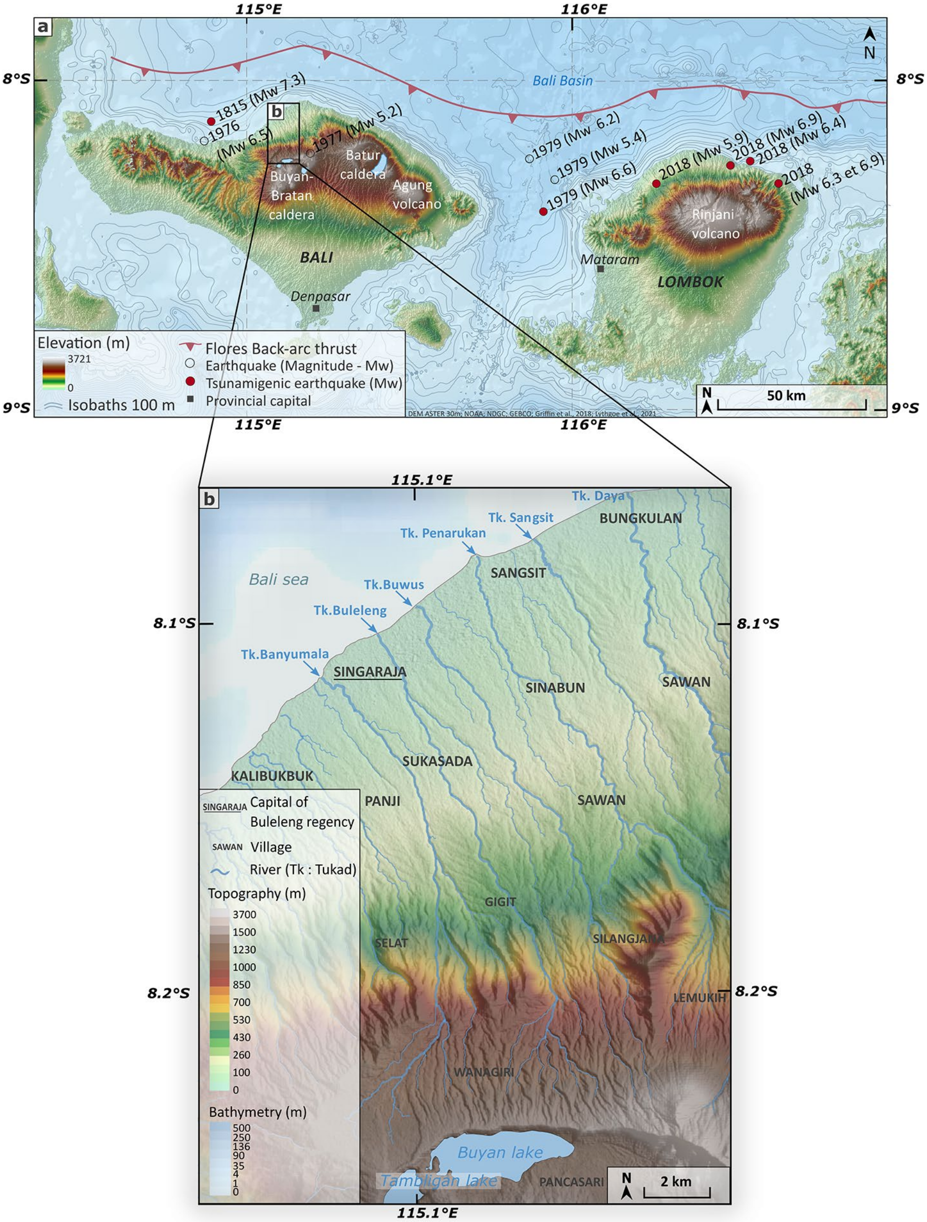

Fig. 1 **a.** 1815, 1976, 1979, and 2018 earthquake epicenters recorded in the western region of the Flores Back-Arc Thrust Fault zone. **b**. Location map of the Singaraja-Sukasada area in Buleleng Regency, where the Gejer Bali disaster occurred

2 Context and study area

With its neighboring islands of Lombok and Sumbawa, Bali is part of the volcanic arc of the Lesser Sunda Islands, which was created during the Miocene subduction of the Indo-Australian plate (Hall 2002; Koulali et al. 2016). Thus, earthquakes in southern Bali are distributed along the Java trench, like the 1917 event of M6.6, which killed 1,500 people due to landslides principally (Soloviev and Go 1974). North of Bali, the Flores Back-Arc thrust (FBT) triggered several strong earthquakes, e.g., in 2018 in Lombok, in 1979, in 1976, and in 1815, whose epicenters are located in the Bali Sea or the Lombok Strait (Fig. 1a; Soloviev and Go 1974; McCaffrey and Nabelek 1987; Harris and Major 2017; Nguyen et al. 2015; Griffin et al. 2019; NOAA Database 2021). The Flores Back-Arc thrust belt is a south-dipping fault with an east-west strike that follows the north coast of the Lesser Sunda Islands (Fig. 1a; Silver et al. 1983, 1986). In this region, earthquakes can be generated by tectonic fault movement or by volcanic activity (Felix et al. 2021).

Landslides are frequently secondary seismic hazards and constitute a major geological risk in Indonesia, such as during the 2009 Padang earthquake in Sumatra, or the 1917, 1976, 1979, and October 2021 earthquakes in Bali (Muhari 2021; Soloviev and Go 1974; Stover and Hake 1979). The Indonesian archipelago is therefore considered one of the world's landslide hazard hotspots, with some of the highest landslide risks in Eastern Asia (Nadim et al. 2006). In the mountainous region of Buleleng, authorities and Balinese communities deal regularly with the threat of landslides, as during the rainy season. Several mudslides have blocked the new shortcut Singaraja-Denpasar road, which has just been completed and is heavily used, burying houses, stores, and construction machines (Eka Saputra et al. 2016; Diara et al. 2022).

The Lesser Sunda Island region is known for its volcanoes, whose activities have left deep traces on Indonesian society, including the Agung eruption in Bali in 1963 (Volcanic Explosivity Index - VEI 4+; Fontijn et al. 2015; Rampino and Self 1984) and the Samalas eruption in Lombok in 1257 (VEI 7; Lavigne et al. 2013; Mutaqin and Lavigne 2019). The Tambora eruption in April 1815 (VEI 7; Oppenheimer 2003; Self et al. 1984), occurred in Sumbawa, 300 km east of Bali, seven months before the earthquake-triggered landslide and debris flows that devastated Buleleng in November of that year. PDCs and tephra fallout killed 12,000 people in Sumbawa, and more than 49,000 people died in Lombok and Sumbawa from the indirect consequences of the eruption due to famine and epidemics (Oppenheimer 2003). The volcanic plume spread to the western part of the archipelago over a distance of more than 1,400 km and covered Bali with 20 to 30 cm of ash (Kandlbauer and Sparks 2014). However, the impact of this eruptive crisis on the Balinese people is rarely presented in the literature (Vickers 1989; Oppenheimer 2003). Against this backdrop of environmental upheaval, the inhabitants of Buleleng face a new telluric crisis.

These 1815 natural disasters took place against a tense political backdrop, with the beginning of the 19th century marked in Bali by internal rivalries between the island's main kingdoms and attempts at political interference by rival European powers in the archipelago. Although Buleleng, one of the main kingdoms, was prosperous in the 18th and early 19th centuries, it regularly fought over land and resources with other kingdoms, such as Jembrana, Klungkung, and Karangasem (Fig. 2; Agung 1991; Nordholt 1996). Additionally, the archipelago's two greatest European powers, the British and the Dutch, were also present. Before the 1810s, the Dutch (formerly the Dutch East India Company - VOC) were already

Fig. 2 A Dutch map of Bali and its nine kingdoms in 1850. Dutch translation into Indonesian: Badong = Badung / Banglie = Bangli / Beliling = Buleleng / Dianjar = Gianyar / Djembrana = Jembrana / Karang Assam = Karangasem / Klong Kong = Klungkung/ Tabanan = Tabanan / Mengawei = Mengwi (Spanier 1850)

interested in Bali due to the slave trade during the 18th century, managed through agents such as Chinese and Bugis traders settled near harbors like Singaraja. In the early 19th century, French traders were also active in Bali in search of enslaved people (Creese 2016). It is estimated that between 1650 and 1830, 1,000 enslaved people were exported from Bali each year (Schulte Nordholt 1996; Creese 2016). From 1811 to 1816, Java was in the hands of British lieutenant-governor Stamford Raffles, who wished to establish trade relations with the Balinese kings, particularly in Buleleng, Bali's major commercial place (Hanna 2004). In 1816, the British ceded Java back to the Dutch, who sent the high-ranking civil servant H.A. van den Broek to Bali in 1817–1818 to establish commercial (especially slave trade and later recruitment of soldiers) and political links with the Balinese kings (Vickers 1989; Agung 1991). It is in this particular historical context that the European and Balinese forces at work in 1815 faced two successive natural disasters and their consequences, i.e., the Tambora eruption with little-known effects on Bali, and the Buleleng earthquake with its multiple cascading hazards, whose impact left its mark on Balinese society.

3 Methods

We examined various historical sources of Western and Indonesian origins that have rarely been exploited to provide a better understanding of the nature and timing of the Gejer Bali disaster. We also provide reliable descriptions of the social and economic impacts that reveal the scope of the disruption. This type of study is often limited to earthquakes, eruptions, and tsunamis, as these kinds of disasters most frequently appear in written records (e.g., Cahyono 2012; Malawani et al. 2022; Reid 2013; Sastrawan 2022). Based on selected written extracts concerning the hazard and the consequences of the disaster, and to provide a detailed chronology of events, we categorized the results of this research into three periods, i.e., pre-, onset-, and post-disaster. The exegesis of the narrative sources was based on different angles, i.e. a geographical approach to map the villages impacted by the flow and its trajectory described in the accounts, and a linguistic approach by determining the literal meaning of some toponyms to identify and map the names mentioned in the sources. Several other sources were used to determine the location of the toponyms, such as a recent topographic map (from https://tanahair.indonesia.go.id/portal-web/) and the 1885 Dutch Colonial Map of Buleleng and Jembrana (from https://digitalcollections.universiteitleiden.nl/). The last-mentioned is the oldest and largest scale map (local) to be found in the Dutch archives. The maps were used to identify those villages that had their names changed or had undergone a transformation as a result of Dutch retranscription. Finally, a historical approach was taken by comparing chronological accounts between different colonial sources but also cross-checking with local narrative sources and historians from Universitas Pendidikan Ganesha (UNDIKSHA) in Singaraja. For convenience, the historical source descriptions quoted in the Results section are presented translated in English; however, the original versions are provided in Tables S1 and S2 of Supplementary Material.

3.1 Western (colonial) written sources

The historical documents most used in this study are Dutch and British written accounts. The British presence in Southeast Asia at the beginning of the 19th century, and the Dutch presence in Indonesia, provided many detailed reports and accounts of Balinese society, which attracted the Westerners' curiosity and economic interests. We used different types of documents mainly published in the 19th century (Table S2 in Supplementary Material): (i) newspapers published by colonial authorities e.g., *Java Government Gazette*, *Bataviaasch Courant*, *Singapore Chronicles* and *Commercial Register* digitized (https://www.delpher.nl/) (ii) colonial administrative reports or letters, e.g., Van den Broek's accounts, visiting Bali in 1918, are drawn in part from van der Kemp's 1899 publication of the commissioner's archived reports and correspondence (Creese 2016), or even resident controller Bloemen Waanders' report on Singaraja from 1855; (iii) travel reports by scientists, mercenaries or navigators describing geographical features, ethnography, religion, customs e.g., botanist Zollinger, missionaries Medhurst and van Eck. Table S1 in Supplementary Material summarizes the publication contexts of the works cited in the Results section, providing a better appreciation of the relevance and information origins gathered by the British and Dutch witnesses. Most of the nineteenth-century documents used are freely available digitally on Google Books or have been consulted at the Ecole Française d'Extrême Orient (EFEO) library, and at the Special Collections of Leiden University Libraries. Historical documents such as those by Raffles (1817) or Ross (1816) were more widely used to describe the Tambora eruption's timing and its consequences, but are used in this study to highlight Buleleng's social and economic context before the disaster. The other accounts listed in Table S1 in Supplementary Material were mostly used for ethnographic descriptions of Bali, to introduce European leaders to Balinese life. However, the November 1815 disaster left its mark on the Balinese people. Decades later, various accounts of the events are recurrent in 19th-century presentations of Bali but are rarely exploited to document disasters (e.g., Nguyen et al. 2015; Soloviev and Go 1974).

3.2 Characteristics of Indonesian written sources

This study's second type of historical document is local Indonesian accounts (Table S3 in Supplementary Material). After Japan, Java-Bali is the second most abundant region in terms of written sources on tectonic events before the modern period (Reid 2023). Commonly found in Java, Bali, and Lombok, a *babad* compiles historical writing that recounts the chronicles or history of the past, and contains myths and legendary elements (Ras 1986). The *babad* can present different types of knowledge, laws, history of dynasties, cultural events (Sastrawan 2016), or natural disasters such as the *Babad Lombok* describing the pre-, onset- and post-eruption conditions of Samalas in 1257 (e.g., Malawani et al. 2022; Mutaqin and Lavigne 2019). They are usually written decades or even centuries after the events they describe (Sastrawan 2022). These texts are second-hand written accounts based on oral traditions and community memories. They are rewritten many times, with new information from multiple sources, and it is rare to find detailed accounts of natural disasters written before the twentieth century (Sastrawan 2022).

Three main indigenous sources were analyzed in this study. The first one that mentions the November 1815 disaster is the *Babad Buleleng*, written in 1920 in Old and Middle Javanese language, which is commonly used in the historical Balinese literature (Worsley 1972; Tatu 1999; van der Meij 2017). This *babad* exists in several versions, but in this study, we have used the published version edited and translated by Worsley (1972). The *Sejarah Buleleng* (Panji Sakti 1956) recounts the filiations since the 17th century between the descendants of the *Ki Gusti Panji Sakti* royal family, who reigned over the Den Bukit (Buleleng) region. The disaster is depicted in another text called *Babad Raya Anglurah Panji Sakti* (1954), which talks about the major events associated with that same royal family. These first two texts are available from the EFEO library. Finally, a book called *Sejarah Buleleng* (The History of Buleleng – 1956) compiles important facts about the provincial history of Singaraja and Sukasada in particular (Fig. 1b). Written in Indonesian in 1956, it focuses on the colonial period and the conflictual relations between the Balinese and Dutch in the 19–20th centuries. However, the *Babad Raya Anglurah Panji Sakti* (1954) and the *Sejarah Buleleng* (Panji Sakti 1956) widely overlap in the events they depict, and borrow many details of the 1815 Gejer Bali disaster from the Dutch or British nineteenth-century original sources. Indeed, Western writing may have been recopied in *lontar*, stored in the public collections of the Gedong Kirtya library in Singaraja (Creese 1995), where we found the *Sejarah Buleleng* chronicle. Further documents and *babad* refer to the Gejer Bali events without providing relevant and detailed information (e.g., Korn 1 to 5 in Hägerdal 2006).

4 Results

4.1 The Buleleng kingdom before the November 1815 disaster

Dutch administrator H. A. van den Broek, visiting Bali in 1818, described Buleleng, and Singaraja in particular, as a major harbor town, considered "the commercial center of the island" (van den Broek 1835). A few years earlier, when Raffles briefly visited Buleleng in 1815, he underscored Bali's strategic location, particularly Buleleng on the north coast. Located at the crossroads of the archipelago's shipping lanes, between Bangka (Sumatra), the Celebes, and Borneo, Raffles wanted to set up hub harbors in the archipelago to promote a free-trade policy that would ultimately, however, be thwarted (Bastin 1954; Raffles 1817). At the beginning of the 19th century, Buleleng and its harbor of Singaraja were a central market in the intra-island exchange of opium, rice, livestock, and especially enslaved people, which had been traded on the island by the Chinese since the 10th century (Raffles 1817; Vlekke 1945). Types of enslaved people included criminals, Balinese unable to pay the obligations and debts owed to the sovereigns, or people captured during slave raids during battles between kingdoms (Vlekke 1945). They were then sold or exchanged in Buleleng, the main Balinese market of the time. As van den Broek writes (1835), the slavery system provided the essential income for Buleleng: "Before the abolishment of the slavery trade, Boléling and its subordinates made a large income for the Prince, both from the enslaved people, which he sold annually and from those brought to him from Ceram, for which he exchanged rice, which he was abundantly supplied with by the Javanese slave traders (mostly Chinese)". Trade was managed mainly by the Chinese and Bugis (Muslim merchants from Sulawesi) under the authorization of the local ruler of Buleleng, who levied a tax on all trade (Agung 1989). Even though the Chinese presence in Bali dates back to at least the 10th century, their exact timing of arrival in Buleleng remains unknown (Lombard-Salmon and Sidharta 2000; Aryana 2018). The Bugis settled in the Kampung Bugis in Singaraja during the 17th century (Sukmarini et al. 2023). The Chinese and Bugis communities lived together in the *Pabean* Buleleng District (*Pabean* meaning "customs station" in Balinese), today known as *Banjar Pabean* (*banjar* meaning hamlet). According to Raffles' and van den Broek's descriptions, Singaraja was the capital of the Buleleng kingdom, but under the control of the Karangasem kingdom in the early 19th century (Figs. 1 and 2). A flourishing trading post in the Buleleng Harbor and productive farmland made it a prosperous kingdom (Agung 1989). At the time, Buleleng was one of the island's most populous kingdoms. Bali's population was estimated at between eight to nine hundred thousand in 1815–1817 (Raffles 1817; van den Broek 1835). The Buleleng kingdom's population is estimated at 30,000 men, "whose teeth have been filed down" after puberty (this corresponds to a Balinese purification rite that marks the transition from teenage to adulthood, to eliminate negative human traits: Ernawati 2012; Raffles 1817). As the British commander Raffles points out, this figure is underestimated and does not take into account women and children under the age of fifteen, or enslaved people. This was the only pre-event population estimation and indicated the population size at the time. To compare with this figure, the Karangasem and Tabanan kingdoms (Fig. 2) had approximately 50,000 and 40,000 men respectively (Raffles 1817).

Buleleng's landscapes can be divided into two main units: the coastal plains, which brown, black silty soil "is very fertile and cultivated with rice fields everywhere"; and "the more inland areas consist primarily of barren cliff mountains, […] covered with brushwood, and otherwise totally infertile" whose volcanic soil is red and clayey (Broek 1835 in Table S2 in Supplementary Material). Living conditions in Bali were dramatically affected by the Tambora eruption in April 1815, as the *Bataviaashe Courant* wrote on October 26, 1816, "Reports from the eastern part of the island give us the sad certainty that the grim consequences, which the eruptions of the fire-spitting mountains on Sumbawa have had for the inhabitants of that island, are also now being felt throughout its vast expanse on the island of Bali." From the Lombok Strait (east of Bali) to Banyuwangi (Java, west of Bali), Bali was covered by 20 cm to 30 cm of ash, according to historical reports of the time (Ross 1816). Residents of Bali and Lombok were killed by falling buildings unable to withstand the weight of volcanic fallout (van den Broek 1835). All the vegetation was suffocated by ash, and the Bali inhabitants "were obliged to remove the ash as much as they could before they could cultivate the land" (Medhurst 1830). In this backdrop of slow post-Tambora eruption recovery, another shock hit Bali.

4.2 The November 1815 Buleleng disaster revealed by written sources

On 22 November 1815, the estimated M7.3 Buleleng earthquake (Nguyen et al. 2015; Griffin et al. 2019) triggered a major landslide. The combination of seismic forces and pre-earthquake rainfall destabilized the northern flank of the Buyan-Bratan caldera (Fig. 1). Sediments remobilized by this large-volume collapse, and perhaps by other adjacent landslides, coalesced to form a massive debris flow that traveled up to twenty kilometers through the Banyumala River Valley until reaching the coast of Singaraja downstream. The debris flow matrix was composed of fine sediment and large megaclasts. According to historical accounts, fifteen villages were buried or devastated by the debris flow, as shown in Fig. 4. The entrance of a large volume of sediment into the sea was reported to have triggered a local tsunami. This could have affected coastal villages in Buleleng region, including at least two villages to the east of Singaraja (Fig. 4). 10,253 fatalities were reported in this earthquake-landslide-debris-flow-tsunami sequence. In the following section, the hazards and their impacts are described and discussed in more detail.

4.2.1 A disaster triggered by a cascade of multiple natural hazards

4.2.1.1 Earthquake, the initial hazard. The main detailed European descriptions of 22 November 1815 events first appeared in the Java Government Gazette on December 16, 1815 (Hubbard 1815), and in the Singapore Chronicles and Commercial Register on July 15, 1830 (Medhurst 1830 in Table S2 in Supplementary Material). According to the Java Government Gazette, the disaster began with an earthquake felt at 10 PM, followed by aftershocks for almost an hour. The shocks were felt as far away as Surabaya, on the northeast coast of Java. Based on available historical evidence of earthquake damage, Modified Mercalli Intensity (MMI) values have been determined (Nguyen et al. 2015). An MMI 8 was assigned to structural damage and partial or total collapse of buildings in Buleleng (Griffin et al. 2019). Through analysis of historical reports, statistical analysis, and modeling, Griffin et al. (2019) estimated a magnitude of 7.3 (Mw) for the November 1815 earthquake from a Bayesian model (with a 95% confidence interval of 7.1–7.6). Event modeling locates the epicenter at 27 km depth, about 10 km north of the Buleleng coast (114.9°E, -8.1°S; Fig. 1.a; Griffin et al. 2019).

4.2.1.2 Slope failure and landslides in Buleleng mountains. The seismic tremors were followed by muffled sounds coming from the interior of Buleleng's mountains. The noises were compared to those of the explosion of a mountain, later misinterpreted as a volcanic eruption by Western visitors like Zollinger (1849) or van Eck (1878) and repeated in oral traditions. The sounds echoing in the highlands originated from the collapse of a section of the mountain overlooking Buleleng because of the seismic tremors, as indicated in Java Government Gazette: "The mountain burst with a tremendous explosion." The mountain collapse was often explained in contemporary accounts as the rupture of one of the walls of the Buyan or Tamblingan caldera lakes (Fig. 1). Medhurst (1830) mentions "the force of the water of the upland lake, which was bursting out its sides" (Table S2in Supplementary Material). The mountain would have split open and a breach would have formed, allowing the lake waters to spill into the valleys, carrying everything in their path (Zollinger 1849 in Table S2 in Supplementary Material). Oral transmissions describe a vertical water column passing over the caldera ridges and reaching the coast. However, texts mention heavy rainfall in the day and night before 22 November (mentioned in several sources, e.g., Zollinger 1849; Eck 1878; Vriesman 1884; *Babad Raja Anglurah Panji Sakti*; Tables S2 and S3 in Supplementary Material). There it is not inconceivable that the water-saturated slopes had been weakened by the seismic tremors of the night earthquake, causing a massive landslide.

4.2.1.3 Landslide-triggered debris flows fed by heavy rainfall. The combination of the driving forces of the earthquake and the heavy rains that preceded the tremors led to the destabilization and remobilization of an enormous volume of sediment and water. This mass movement, generated by the slope failure, evolved into a voluminous debris flow that carried boulders up to 15 m to 30 m in diameter, as suggested in this passage: *"*several immense rocks some 50 or 100 feet square were dislodged from their places, which was carrying with them abundance of smaller stones, earth and water did not stop in their course till they were precipitated into the sea*"* (Medhurst 1830 in Table S2 in Supplementary Material). The debris flow progressively eroded the riverbed and banks, and incorporated boulders in its path, growing in size as it progressed (bulking effect). Details of the debris flow depth are available from three sources. In *Bijdragen tot de kennis van het Eiland Bali*, written by Dutch administrator Bloemen Waanders in 1868, whose information comes from his stay in Singaraja in 1855, a flow depth of 10 to 12 feet, i.e., 3 to 3.6 is mentioned. In *Sejarah Buleleng* (Panji Sakti 1956), the debris flow depth is reported as 20 to 40 feet, i.e., 6 m to 12 m. Sirikan (1956) mentions a flow depth of 12 to 40 feet, i.e., 3.6 m to 12 m. For the latter author, no indirect sources (whether oral transmission or Western archives) are mentioned. In summary, the debris flow depth is estimated at between 3 m and 12 m, depending on the observation's location in the watershed.

Seventeen villages were buried or severely destroyed in the path of the flow, as indicated in Bloemen Waanders' text: "when there was a terrible mountain collapse, during which the flourishing *desa* [villages] of Kedoe, Mendala, Gendis, Tepok Basa, Sambangan, Bangkang, Galéran, Pandji, Pebantenan, Brattan, Bandjar Mandowan, Bandjar Tengah, Bandjar Badoeng, Bandjar Boengkoelan, Soeka Sadi, Boeleleng and Pabéjan were totally or partially buried by an overwhelming earth slide". Not all these village names appear on current maps, or even on the 1885 Dutch Buleleng map (Fig. 3). Some have changed their name, been merged into a single village, or no longer exist. Table S4 in Supplementary material comments on the specific features of some localities mapped in Fig. 4. Kedu in the Buleleng mountains (Figs. 3 and 4) has become a sparsely populated hamlet, whereas it was a large

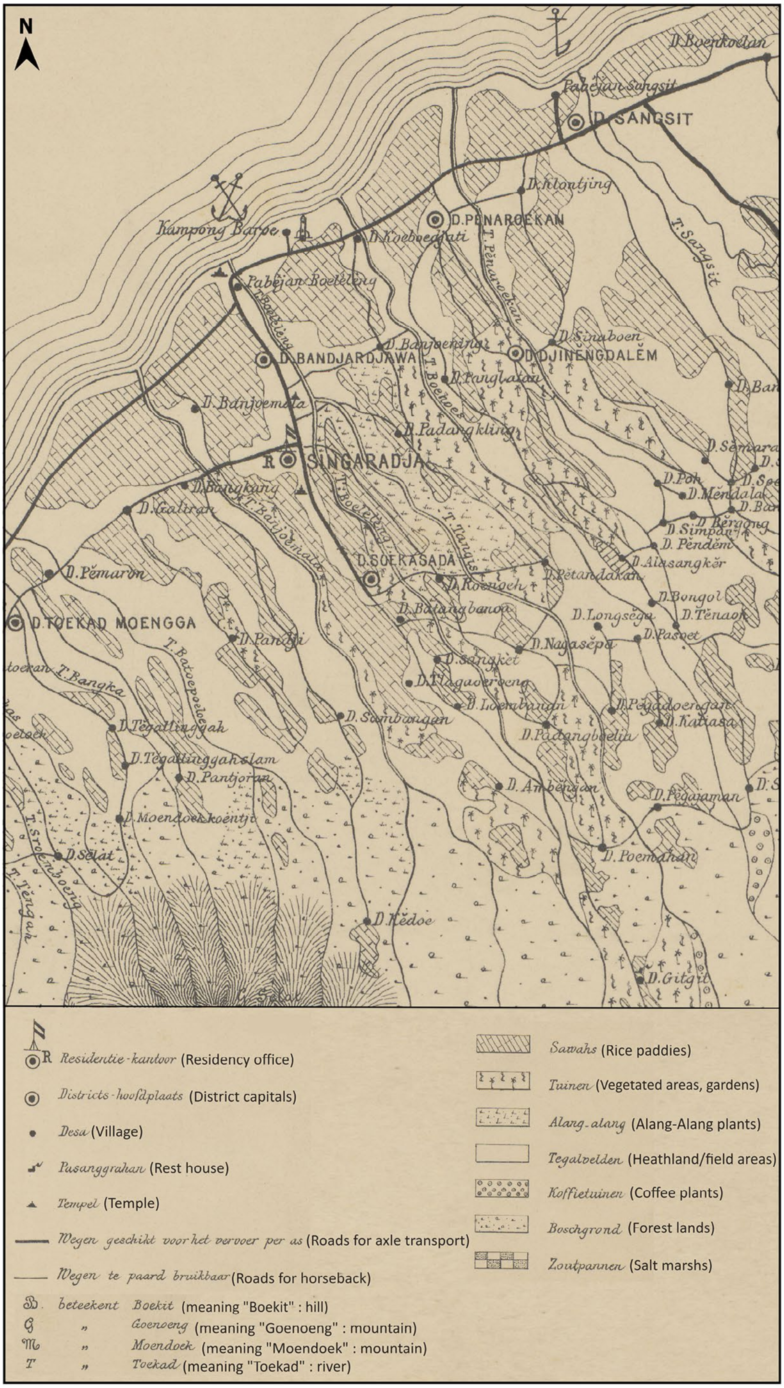

Fig. 3 Map of a portion of the Buleleng kingdom produced in 1885 by the Indonesian surveyor Raden Mas Ronodirdjo at the request of the Dutch governor F.A. Liefrinck. Map at 1:80,000 scale (Ronodirdjo and Liefrinck 1885)

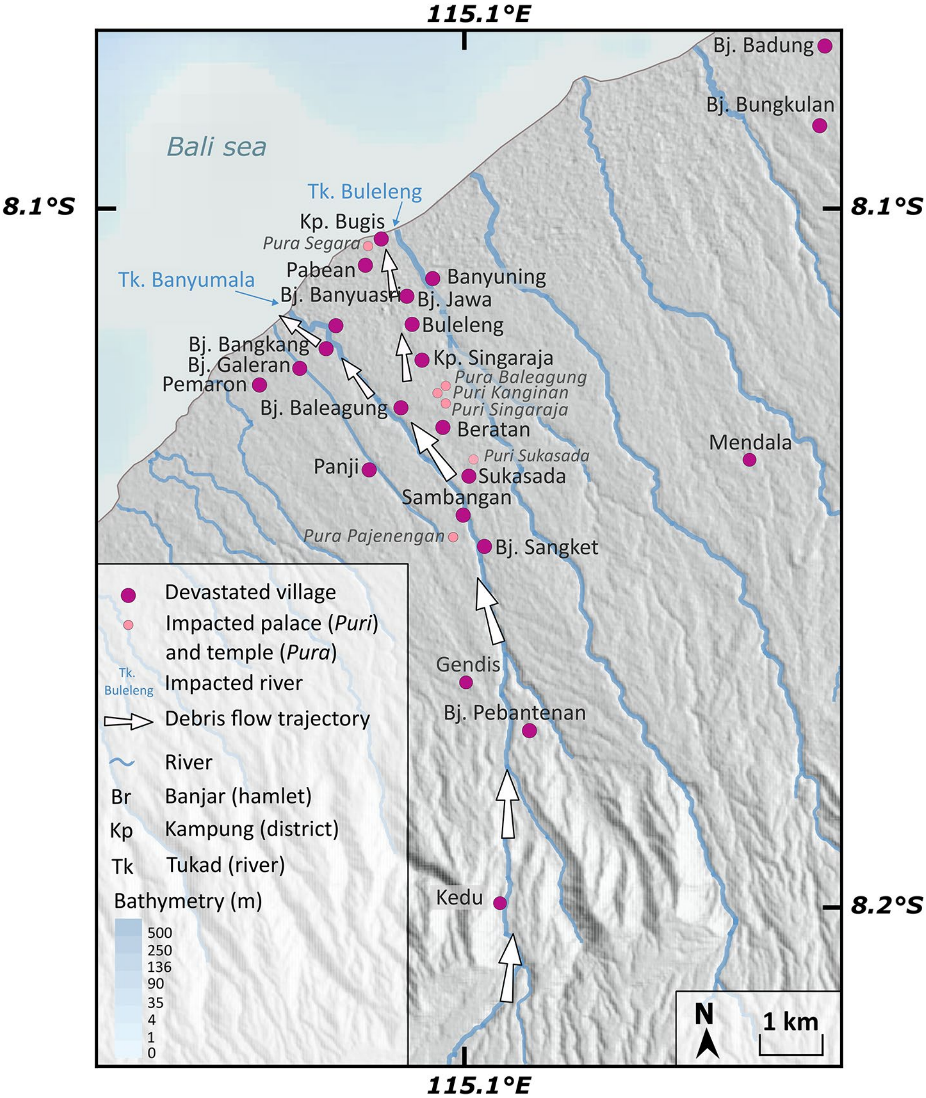

Fig. 4 Map of villages affected by the Gejer Bali disaster in 1815, according to Bloemen Waanders (1868), the Babad Raya Anglurah Panji Sakti (1954), the Sejarah Buleleng (Panji Sakti 1956) and oral traditions

village before the disaster, which according to van Eck (1878) would have been populated by over a thousand men. In the *Sejarah Buleleng* (Panji Sakti 1956), the Bloemen Waanders list is completed with the hamlets of Cengana (belonging to the Sambangan village), Banjar Jawah and Banyuning (Figs. 3 and 4). The Banjar Banyuasri and Baleagung hamlets in Fig. 4 were added to the villages devastated by the debris flow according to an interview with I Gusti Ngurah Panji Anom, 13th generation of the Sukasada royal family.

From the landslide source, at the walls of the Buyan or Tamblingan caldera lake, the debris flow would have extended for over twenty kilometers to reach the Singaraja coast downstream where blocks would have been engulfed by the sea. The mapping of the villages affected by the debris flow (Fig. 4) shows the trajectory of the debris flow, which mainly flowed through the Banyumala River valley. The Banyumala etymology, meaning "dirty, polluted water or water causing trouble," suggests that the river's destructive activity was recurrent and that this type of debris flow already could occurred in the Banyumala Valley before 1815.

The Bloemen Waanders report also describes how the flow split in two downstream: "As if by a miracle the stream split in two just before the Bale Agung at Boeleleng, one part taking a westerly direction, the other an easterly one. As if with renewed force the [debris] slide pushed northward, the eastward through the ravine of the river Boeleleng, the westward through that of the Banjoemalo." Further downstream from the Banyumala River, where the slope reduces, the debris flow could have followed the pre-event topography and split into two directions: continuing westward to the eponymous village near the coast, towards the Bangkang and Pemaron villages, but also branching off to the east towards the Buleleng River, towards the Banyuning Village (Fig. 3). The debris fan may have redefined Singaraja's hydrographic network as we know it today.

4.2.1.4 The tsunami's origin. According to Bloemen Waanders, after splitting, the two flows joined at the Pabean harbor settlement: "they rejoined with fearful violence at Pabéjan and did not plunge into the sea until after they had completely submerged that beautiful and large Muslim encampment". However, as far as the latter information is concerned, the Java Government Gazette and Singapore Chronicles and Commercial Register descriptions of the disaster differ from those of Bloemen Waanders, whose account is given some forty years after the events (Table S2 in Supplementary Material). In reality, the Pabean District (harbor) destruction would not have been caused by the two flows joining together, but by a tsunami, as can be confirmed by the two newspaper contemporary descriptions: "On the fall of so large a mass, the water rose suddenly and overflowed the country to a considerable extent, and in retiring, which it did almost immediately swept everything before it. The fallen mountain forms a promontory projecting a considerable distance into the sea" (Java Government Gazette, 1815); "the sea, agitated by the plunging of the rocks into its waves, burst the bounds which nature had assigned it, and came pouring over the land in return" (Medhurst 1830). In these historical documents, the tsunami is only mentioned after the debris flows have penetrated the sea. According to these two quotes, the large volume of sediment and boulders entering the sea would have triggered a tsunami, just as the PDCs entering the sea triggered a tsunami during the Plinian eruption of Tambora in 1815 (Gertisser and Self 2015). The volume of sediment reaching the sea pushed the water northwards and along the coasts on either side of the debris flow, westwards and eastwards. For example, two coastal villages located further east of the area affected by the debris flow, namely Bungkulan and Badung, were devastated during the tsunami (Fig. 4). Although the earthquake was felt in Lombok, Surabaya (Java) and Bima (Sumbawa), no records of a tsunami occurring in November 1815 on the Java and Lombok coasts have been mentioned in any known tsunami-earthquake databases or written sources (Soloviev and Go 1974; Harris and Major 2017). The lack of any significant tsunami reaching the nearby coasts suggests that it was a local tsunami affecting mainly the Buleleng coast. Regarding the tsunami's run-up, the *Sejarah Bali* mentions a height of 2 to 3 m (Sirikan 1956), but so far no tsunami deposits have been found. The Bugis, Chinese and Arab trading communities closest to the Buleleng harbor in the Pabean District were also affected by the tsunami, as Medhurst reports (1830): “thus were the remaining houses upon the sea-beach, which had escaped the mountain’s crash, suddenly swept away by the foaming billows; the walled and tiled buildings of the Chinese were immediately overturned, and the light bamboo dwellings of the Bugguese [Bugis] were carried wholesale to about a gun-shot distance from the place where they once stood.”

4.2.2 Death toll and property losses

4.2.2.1 Uncertainty over death tolls. A month after the disaster, the Java Government Gazette reported that “the number of lives lost on the occasion amounts to upwards of 1200,” without specifying whether the deaths were caused by the debris flow, the tsunami, the earthquake, or all the telluric hazards combined. Medhurst’s account (1830) mentions a thousand deaths. The death toll takes on a different dimension in Bloemen Waanders’ account (Table S2in Supplementary Material), which mentions 12,000 victims. This figure is clarified by the Balinese note (the *pangelingeling*) provided by Vriesman (1884): “Tally: the number of subjects of the Prince G’de Karang (Asem) killed, those buried by the flow, amounted to 10,253 souls.” The *Sejarah Buleleng* (Panji Sakti 1956) reports that 1,512 people were killed (Table S2 in Supplementary Material). However, it seems difficult to distinguish between victims of debris flows and victims of tsunamis when several hazards cascade over a restricted area in a very short space of time (the Pabean district and the villages on either side). These discrepancies will be discussed in Discussion section. According to the *Babad Buleleng*, six members of the Sukasada royal family were among the victims (Worsley 1972) buried by the debris flow, namely I Gusti Ngurah Jlantik, Ki Gusti Bagus Jlantik Banjar (prime minister of Buleleng, died in Galiran), Ki Gusti Wayan Panji, Ki Gusti Wayan Panebel and Ki Gusti Nyoman Panarungan (both died in Sukasada).

4.2.2.2 Losses of buildings with important functions. The debris flow buried several buildings with political (palace—*puri*), religious (temple—*pura*) and cultural functions that were very important at that time (*Babad Raya Anglurah Panji Sakti; Sejarah Buleleng*). The Puri Sukasada, built in 1584, and its market were buried and now lie under rice fields (Sastrodiwiryo 1994). Other smaller palaces and temples, such as Puri Kanginan, Pura Panjenangan, Pura Dalem Buleleng, Pura Segara, and Pura Baleagung, were devastated by the flows (Fig. 4; Dwipayana 1954). According to Bloemen Waanders (1868), the flow split into two at the latter temple (Fig. 4; Table S2 in Supplementary Material).

The post-disaster landscape of Buleleng was transformed, as Medhurst describes it (1830): “In the morning, the country presented a most desolate prospect, and along the track of the mountain’s fall, nothing appeared but a stripe of red earth which mixed with the water that had come with it, from the mountain, was so stiff and clayey, that hardly possible to proceed forward.” In the flow path, men, fields, plantations, and cattle are covered by this thick clay mud. The multi-metric blocks transported and scattered across the valleys followed the path taken by the devastating debris flow until they reached the Singaraja coast and were engulfed by the sea (Table S2 in Supplementary Material).

4.3 Medium- and long-term impact of the disaster

4.3.1 Medium-term difficulties for Bali (1816–1820)

The Tambora eruption in April 1815 had a dramatic impact on Balinese society, particularly in the Buleleng region, affected by the Gejer Bali disaster seven months later. The impact of the floods in November (debris flow and tsunami) was added to the difficulties caused by the ash fall from Tambora. All these hazards in the Buleleng region destroyed the rice paddies, fields, and farms of Singaraja, leading to very poor harvests, as mentioned in the *Babad Raja Anglurah Panji Sakti*: "The economic life of the people of Buleleng also seemed to stagnate: many of the population's rice fields were destroyed by the flood, and could not be planted immediately […], and the people suffered greatly" (Dwipayana 1954). The limited rice production was therefore insufficient for the stricken population of Buleleng, especially as the province's steep slopes were scarcely suitable for growing rice (van den Broek 1835). In Bali, the decrease in agricultural yields caused by the Tambora ash fall triggered a major famine after the 1815 disasters, leaving the people to eat their domestic animals, as van der Kemp mentions (1899): "However, the inhabitants ate horse and dog meat to satisfy their hunger. […] The number of the population, for whom the fields yielded barely half of the rice needed for consumption, and who had no means of supplying this need from elsewhere, was considered by the commissioner [van den Broek] to be the cause of the famine, in addition, however, to the repeated destruction of the crop by the incredible multitude of rats." Whereas before 1815, Lombok had been supplying Bali annually with rice, the populations of both islands were now suffering from hunger. In 1818, van den Broek traveled to Buleleng with a large but insufficient shipment of Javanese rice, equal to 30 *Kojang* of rice (since 1 K*ojang* equals ~1853 kg, the total shipment would be equivalent to 55.59 tons), to reach trade agreements with the Balinese kings (van Kemp 1899; Washburn 1926). Although Java was also hit by Tambora's ash, agricultural and textile exports remained stable between 1815 and 1820 and supplied the high demand from the Balinese kingdoms, in contrast to the Lesser Sunda Islands (Zanden 2012). The demand for rice was so strong in Bali that the Javanese rice price was rising, as Medhurst points out (1830): "The ground [in Bali] could not be tilled for a considerable time, and every kind of grain being kilIed by the ash fall, they were obliged to look elsewhere for their supplies of rice; it is reported that at that time rice imported from Java, fetched as much as 6 dollars the picul [equal to 60 kg]." Bali's famine offered frightening scenes for Western visitors. Food shortages in Bali drove the poorest populations to sell their children in exchange for food (van den Broek 1835; Vickers 1989). From 1816 onwards, starvation led to the proliferation of epidemics such as cholera (Medhurst 1830) and smallpox (Dubois Letters in Creese 2016), which hit hard: "Such is the extent of the horrible plague on Balie Island, that the survivors are too weak and too few in number to be able to give the daily dying victims the honor of burial." (Bataviasche Courant 1816). The poorest people from the lower castes died in greater numbers from hunger or disease. As custom dictated in Bali, lower-caste individuals who died in this manner had no right to a cremation or burial and were left by the roadside, as described by Dubois in 1830: "The corpses of people who die in epidemics and those of children before their second teeth appear are deposited on the sea shore or on the roadsides. They are covered with old matting and the place where they lie is encircled with a hedgerow of thorny branches to prevent carnivorous animals from approaching; they soon pollute the surroundings and engender another kind of epidemic" (Creese 2016). While the 1815 Tambora eruption plunged Bali into poverty and misery, Buleleng and especially Singaraja were doubly affected by the crop losses caused by the Gejer Bali cascade disaster in November.

4.3.2 Long-term recovery over decades

In the long term, the Tambora ash have made the rice paddies and fields very fertile once again (Melvill de Carnbee 1847). Fourteen years after the 1815 events, Dubois reported that the Balinese "harvested twice their needs" in rice. In the early 1830s, Bali and Lombok were the world's largest exporters of rice and other commodities, as noted by British navigator Earl (1837): "The natives of both islands devote their whole attention to agriculture, and large quantities of rice are exported to China and the Archipelago. Hides, tobacco, coconut oil, and coffee, are also exported; the cotton produced on the island [Bali] is of excellent quality, being considered the best in Eastern India. " The island became the "breadbasket of Singapore" in 1846 (Irwin 1944). The post-disaster recovery process in Bali was relatively fast for the time. None of these narrative sources mentions the duration of the recovery process at Buleleng. For around ten years, Bali was plunged into adversity, suffering from famine, disease, and economic hardship. However, based on the limited information available on the general situation in the province at the dawn of the 1830s, the recovery process including physical and economic development may have taken approximately fifteen years. Buleleng became an important rice exporter, at the center of trade routes between China, Singapore, and Australia (Nordholt 1996).

There is little information on long-term recovery in Buleleng, beyond Medhurst's (1830) descriptions of the province's prosperous trade and agriculture. Nevertheless, he mentions that water in Buleleng was abundant and "has been lately increased in Baliling, by the fall of a mountain, which opened a channel from one of the inland lakes, by which a stream of water was produced, that continually fertilizes the low country, […] the whole of their rice fields may be laid under water, while the superabundance may be carried off by the regular channel without fear of inundation." This description may have been exaggerated, as it is likely that the debris flow would only have eroded, cleared, and widened the Banyumala and Buleleng valleys, providing better access to water resources. However, the Banyumala and Buleleng rivers upstream rise on the northern slopes of the caldera and do not belong to the same watershed as the caldera lakes, so they could not supply these two rivers after the disaster.

After the November 1815 disaster, the inhabitants declared to Zollinger (1849) that the inner lands of Buleleng were cursed: "The natives told me that there was no way to get there [the waterfalls]; that the land around was cursed; that in days gone by a great flood had destroyed the woods adjoining it, and that since then no one had dared approach the falls. "Further downstream, in the Sukasada village area, the population resettled tardively, from around 1850 according to the 13th generation descendant of the Panji Sakti royal family, I Gusti Ngurah Agung Panji Anom, interviewed in February 2023. However, according to him, Singaraja-Buleleng and the villages along the coast were rebuilt and reinvested by the local population in the years that followed, thanks specifically to the Dutch presence near the trading areas. The *Babab Raja Anglurah Panji Sakti* recounts that Puri (Gede) Singaraja was rebuilt in 1818 by the leader I Gusti Agung Pahang (Dwipayana 1954). Other devastated areas were transformed into rice paddies or meadows in the disaster's aftermath, such as the original Sukasada palace site (Fig. 4), now buried and rebuilt in 1982 a few hundred meters further (Sastrodiwiryo 1994; Gorda 2004). The Banyumala village on the left bank of the eponymous river, which was also destroyed by the November 1815 debris flow, was transformed into a rice field. Following the event, the village was resettled on the right river bank (Figs. 3 and 4; Sastrodiwiryo 2007). In the early 20th century, the *Banyumala* village, changed its name to *Banyuasri*, meaning “clean or beautiful water” (Fig. 4; Sastrodiwiryo 2007). The recovery process in the highlands took longer than in the lowlands, as Panji Sakti’s descendant explained. The economic recovery process of the lowlands might have been quicker thanks to inter-island trade and the Dutch presence. The topographical bias may also have influenced the physical and societal recovery of Sukasada area (Fig. 1b), which was more isolated from the trade on the coast, as it was in Sembalun’s highlands recovery process after the 1257 Samalas eruption (Malawani et al. 2022).

5 Discussion

5.1 Weaknesses and validity of the sources

Written sources from Bali provide valuable data on the successive natural hazards, their effects on the community, and the post-disaster period. However, these historical documents have several limitations. The first limitation concerns the characteristics of the written sources (both Western and local accounts). These written archives are the corpus of oral traditions (*babad*) or interviews of local people with Westerners visiting a few years to decades after the events. Changes were likely made by errors of insertion, subtraction, or transcription between local and European in-place names and numbers, for example. In comparison, accounts written in the 20th century use the original colonial and Indonesian sources, enriched by unpublished elements from local oral transmissions. This is notably the case with several Balinese sources such as *Sejarah Buleleng* (Panji Sakti 1956) and others, which partly reproduce the writings of Bloemen Waanders (1868). We must be cautious in interpreting written sources and it is necessary to find scientific corroboration.

The second limitation is that no field evidence has been established about this cascading disaster. Currently, there are no archaeological finds in Buleleng to confirm the textual descriptions of the disaster. The suspected ruins of Puri Sukasada buried by the debris flow and now under a rice field, have never been excavated or subject to geophysical investigation. Apart from a seismic hazard assessment including the 1815 Bali earthquake on the Flores back-arc thrust (Nguyen et al. 2015; Griffin et al. 2019), no geomorphological or geological studies have yet corroborated the content of the texts with field evidence at Buleleng. However, the texts’ relevance is strengthened by the identification of place names mentioned in the written sources, some of which are still used today. Some of the names listed have been transformed, like *Ambangan* and *Banyuasri*. The spatial distribution of devastated villages and important places (palaces and temples) is consistent with each other, spreading from upstream to downstream along the debris flow path (except for three, as mentioned in the Results section). Furthermore, the detailed accounts of events provided in the various source accounts, especially European references, complement one another. The texts reviewed reveal the consistent and relevant nature of five of them: the Java Government Gazette (1815), Medhurst (1830), Broek (1835), Bloemen Waanders (1868), and Vriesman (1884).

The linguistics of written sources, such as indigenous vocabularies, is highly beneficial for a scientific comprehension of disasters, particularly in highlighting the natural hazards that have occurred and assessing the extent of the event. In Old Javanese or Balinese, for example, there is no specific term that distinguishes between flooding caused by a river's overflow and flooding caused by the sea. Two terms are used to designate the 1815 disaster in the local sources: *blabar agung* in Balinese, which means "big flood" or "a rushing stream of water", and *banjir bandang* in Indonesian, which translates as "debris flow" or "flash food". These expressions do not determine the flood's nature. The Balinese note handed down by Vriesman (1884) refers to the November 1815 disaster (Table S1 in Supplementary Material): "At first there was a great earthquake, floods [and] thunder. The mountain gaped open, then the earth collapsed. The city of Buleleng-Singaraja was destroyed. Inundated by the sea, the Bugis Quarter was destroyed" (*Mimitan linoeh mageng goentoer, kĕtoeg, sĕbak kang goenoeng, raris ébah kaprétiwi, rĕbah nagara Boelèlèng Singaradja, otjakang djaladi rĕbah Kampoeng Boegis).* In Old Javanese, the word *guntur* (transcribed as *goentoer* by Vriesman) has several meanings: "flood from a volcanic eruption" (i.e., lahar), "flood from the river mountain" or "thunder" (detonation) (Cahyono 2012). Thus, the term "flash flood" has different meanings in different languages, and the flood's nature may differ depending on the context. In this disaster, this term seems to have been used to describe the two flooding phenomena that occurred at the same time, i.e., the tsunami (a term not used at the time) and the debris flow entering the sea.

The death toll from the November 1815 disaster's direct consequences is inconsistent across written sources. The *Sejarah Buleleng* chronicle (Panji Sakti 1956) mentions 1,512 victims buried by the debris flow, which does not seem much considering the disaster time (at night), the extent of the 17 villages affected, the deposit thickness, and the devastation associated with it. This figure of buried victims increases with Bloemen Waanders' report, but especially with that of Vriesman, who mentions the precise number of 10,253 fatalities. Soloviev & Go (1984) and Nguyen et al. (2015) associate the 1,200 victims mentioned in the *Java Government Gazette* with the tsunami alone, but there is nothing in the description to allow such a conclusion about the hazard involved. These authors assess the total death toll at approximately 11,453. While ten thousand deaths seem plausible, we remain cautious about the respective numbers attributable to the debris flow or the tsunami. This figure would appear to be closer to reality, judging by the scale and sequence of the hazards, which, moreover, took place between 10 PM and 11 PM. Earthquakes and associated hazards that occur at night tend to be more deadly than those that occur during the day (Alexander 1996; Srivastava and Gupta 2004). The 1815 Gejer Bali disaster is the deadliest in Bali's history so far. By comparison, the 1963 Agung eruption killed 1,138 people (volcanic fallout, PDCs, lahars all combined; Tanguy et al. 1998) and the 1917, 1976, and 1979 Bali earthquakes killed 1,500, 573, and 27 people respectively (Soloviev and Go 1974; Leimena 1979; Felix et al. 2021).

While characterizing the social and economic circumstances of the province pre- and post-event poses difficulty due to limited accurate information, some data is available on the Gejer Bali context. It is a challenging task to determine the population size of the Buleleng kingdom before and after the disaster, especially given the more or less precise estimates provided in Western reports. In the early 19th century, the population data provided by the Balinese princes to Westerners were unreliable, since only men after puberty age were considered. The census excludes women, children, and the elderly, as Dubois explains in his letters (Creese 2016).

In Appendix K of *The History of Java* (vol. 2), Raffles mentions 806,250 inhabitants (Table 1) in Bali before the disaster of November 1815, including 30,000 men in Buleleng (most of Raffles' information on Bali in this book is based on details provided by J. Crawfurd, who visited Buleleng in 1814; Creese 2009). Van den Broek mentions 985,000, including 20,000 men out of 130,000 souls in Buleleng in 1818 (Table 1; Raffles 1817; Crawfurd 1820; van den Broek 1835). If we take these statistics literally, there would have been a one-third drop in the male population between 1815 and 1818 due to the two disasters and their environmental consequences. But this theoretical male loss, based on uncertain population figures (Table 1), seems unlikely, considering the attempts to flee to areas less affected by both disasters. It is hard to explain the population difference in just three years, considering that Bali also faced famine and epidemics. There is some doubt about the accuracy of these numbers, and pre- and post-1815 demographics in Bali seem to difficult to interpret from these inconsistent estimates. (Poffenberger 1983). In 1829, the island had a population of 700,000 (Table 3; Medhurst 1830). This estimated downward trend in the Balinese population of over 100,000 people over fifteen years seems unrealistic, even if this period is largely impacted by the aftermath of environmental disasters. Vickers (1989) estimates that the Balinese death toll from the Tambora eruption effects was higher than the 25,000 claimed by the Dutch authorities at the time (Table 2). According to these figures, in November 1815, the Gejer Bali disaster claimed at least 10,000 deaths in Buleleng, and at least another 25,000 victims should be added due to famine and epidemics, which brings the total to more than 35,000 deaths in Bali due to direct and indirect consequences 1815 disasters (Table 2). In Lombok and Sumbawa, by comparison, the number of victims of famine and disease due to the impacts of Tambora is estimated at approximately 49,000 (Tanguy et al. 1998).

5.2 Beliefs and myths about 1815 disasters

Natural disasters are considered a regular part of daily life in the Balinese Hindu belief system. They are necessary for maintaining a balance between man and nature (DeMuth 2018). These natural events are perceived as signs of power acting in the world (Sastrawan 2022). While these disasters are devastating at first, in the longer term, the Balinese see them as opportunities and a return to spiritual equilibrium. In Indonesia, such perceptions of risk are popular (Lavigne et al. 2008), as with the Tambora's eruption caused by God's wrath, described by the *Syair Kerajaan Bima* manuscript from Sumbawa (Sudibyo 2019; Malawani et al. 2022). Such beliefs persist even in the recovery process. After the November

Table 1 Population estimates for Bali and the Buleleng kingdom at the beginning of the 19th century

Years	Bali's population	Buleleng's population	Sources
1815	806,250	30,000 men	Raffles 1817; Crawfurd 1820
1818	985,000	130,000 including 20,000 men	van den Broek 1835
1829	700,000	No data	Medhurst 1830

Table 2 Estimated casualties of the cascading disasters of 1815

Causes of death tolls in Bali	Estimation	Sources
1815 "Gejer Bali" disaster	10,253	Vriesman 1884
Deaths caused by famine and epidemics due to the aftermath of Tambora's eruption in Bali	25,000	Vickers 1989
Direct or indirect fatalities caused by Tambora's eruption and the November disaster in Bali	35,253	This study

1815 disaster, areas devastated by the debris flow were not immediately reoccupied by local residents, particularly upstream in the watershed, in the grassy meadows, or cursed areas where wild animals such as tigers had regained their rights (Zollinger 1849). Similar practices can be found in Sumbawa, in the proximal and median zones of Tambora, which were considered cursed and inhabited by evil spirits after the eruption of April 1815 (Zollinger 1855; Mutaqin and Lavigne 2019). These beliefs affect disaster responses, as a strategy to avoid God's new wrath (Malawani et al. 2022). The highest zones are not rehabilitated, or only very rarely, after natural disasters, such as the November 1815 disaster or the Samalas and Tambora eruptions. The risk memory, especially through oral traditions that are very important culturally in Bali, contributes to indirect risk reduction strategies.

The oral traditions recorded in *Babad* and stories brought back to Europeans may have exaggerated some disaster elements due to the beliefs associated with them. One witness reported that thunder sounded seven times and that it was pitch-dark for a few days after the Gejer Bali disaster (Vriesman 1884). The oral traditions may have confused the muffled earthquake sounds with the mountainside collapse. Seven is also a mystical number regularly used in different cultures (Alavijeh 2013; Malawani et al. 2022). The seven thunder reference underscores the link between the mythical divine wrath and the natural disaster intensity. It is also worth noting that some descriptions from the November 1815 cross-reference elements from the Tambora's eruption seven months earlier. The two successive disasters with simultaneous consequences are recorded a few years after the events, and some descriptions and even beliefs could therefore have been mixed up. The darkness several days after Gejer Bali undoubtedly refers to the volcano ash cloud from Tambora, which spread across the Indonesian archipelago as far as Sulawesi (Ross 1816). Darkness can also be a metaphor for the chaos and desolation that followed the 1815 events. Some descriptions, such as Zollinger's (1849), wrongly associate the Buleleng disaster with Balinese volcanic activity, as indicated van Eck (1878) "It would not surprise us if the Batoer, which showed increased activity all that year and made itself heard during the flooding, is to blame for everything." These erroneous beliefs were widely disseminated in the early 20th century, and even more recently (Grader 1942; Nguyen et al. 2015).

Other disaster elements seem exaggerated, such as the overflow of water from the Tamblingan or Buyan crater lake through the wall opening set off by the tremors. Medhurst (1830), the *Babad Raja Anglurah Panji Sakti* (Dwipayana 1954), and local accounts two hundred years after the disaster mention that the lake's water overflowed the caldera rim. In texts (Tables S2 and S3 in Supplementary Material), several terms are used to describe the collapse of the northern outer wall through which the water had rushed. Some terms are related to explosive vocabulary: "burst with a tremendous explosion," and "the hills gave away"; other terms refer to a breach or fissure in the caldera wall allowing water to flood the lowlands. The oral tradition might have exaggerated this and the detonation may refer to the dull sound of the collapse of such a mass.

5.3 Useful information about multi-cascading disasters for human response

A detailed examination of past disasters in Bali provides crucial information for natural hazards and risk assessment at different time scales. It improves the management of prediction warning information for this densely populated island (4.2 million), which attracted over 16 million foreign and domestic tourists in 2019 (Pickel-Chevalier and Violier 2017).

The 1815 Gejer Bali disaster involved a complex scenario in which an earthquake (M 7.3) destabilized a rocky slope, triggering a massive, wide-ranging debris flow due to the large water content with large megaclasts and sediments swept along its path. The mechanism of these events seems comparable to other disasters due to complex cascading hazards, such as those of Nevado Huascaran in Peru in 1962 and 1970 (Evans et al. 2009a) or the landslides triggered by the 1979 Khait earthquake in Tajikistan (Evans et al. 2009b). Eruption-debris-avalanche-tsunami successions are more frequent, such as the Krakatoa volcano in Indonesia in 2018 (e.g., Grilli et al. 2019), the Kolumbo volcano in the Aegean Sea in 1650 (Karstens et al. 2023) or the Hokkaido Komagatake volcano in Japan in 1640 (Yoshimoto 1998). However, the earthquake-landslide-debris flow-tsunami sequence is less recurrent. As mentioned in the historical accounts presented in the Results section, the debris flow cascaded down and reached the sea. The volume of sediment would have pushed the water to either side, generating a local tsunami wave. The waves crashed onto the Buleleng coast and hit the villages north of Singaraja (Fig. 4). This scenario is very similar to an event observed on the slopes of Montagne Pelée in the French West Indies on May 5, 1902. Three days before Sant-Pierre was destroyed by pyroclastic flows on May 8, a voluminous lahar entering the sea had already generated a local tsunami, flooding the lower quarters of the city and sinking a ship. The waves reached 3 to 4 m a few kilometers south of the White River, where the lahars reached the sea. The flooded area extended up to 30 m inland (Chrétien and Brousse 1989).

Figure 5 depicts the schematic sequential geological hazards and cascading impacts of the Tambora eruption and subsequent Bali disaster in November 1815. This figure is based on the three components of cascading disasters: hazards, impacts, and escalation points (Alexander 2018; Alexander and Pescaroli 2019). Escalation points are critical points in the impact chain and which the effects, occurrence, or failure may be greater than the initial cause (Alexander 2018), e.g., the Tohoku disaster in 2011, where the tsunami's impact and the nuclear power plant's explosion were more deadly and significant than the original earthquake (Suppasri et al. 2021). In the case of the 1815 Gejer Bali disaster, the landslide evolved into a debris flow and a tsunami, generating several escalation points and secondary effects. The mudflow and tsunami, combined with the Tambora ash fallout, caused considerable damage to the agricultural and transport systems of the time (e.g. roads, and harbors). In an economic context that depended at the time on subsistence agriculture and regional trade, the interruption of agricultural production in Bali mainly due to Tambora, along with logistical and transport facility disruptions in Singaraja, represent major escalation points (Fig. 5). These consequences led to further cascade effects such as food shortages, famines, epidemics and, ultimately, the intensification of conflicts between the Balinese kingdoms. Escalation points in 21st-century disasters are hardly comparable, and the issues at stake focus more on infrastructure failures, networks, and warning systems that did not exist at that time (Alexander 2018; Suppasri et al. 2021). However, the escalation points are accentuated by the 1810s archipelago context. The post-1815 economic upheavals and their associated impacts (Fig. 5) are not exclusively caused by the 1815 environmental crises discussed in this study. Other factors can partly explain the island's economic slowdown. Policies to prohibit slavery in the archipelago led by the British (from 1811) and continued by the Dutch provoked indignation from the Balinese kings, and might have reduced exports and the resources derived from this trade on which the Balinese lords depended (Nordholt 1996; Farram 1997). During the 1820s, the export of enslaved people from Bali continued despite the formal ban, with the sugar plantations of Bourbon (present-day Réunion) and

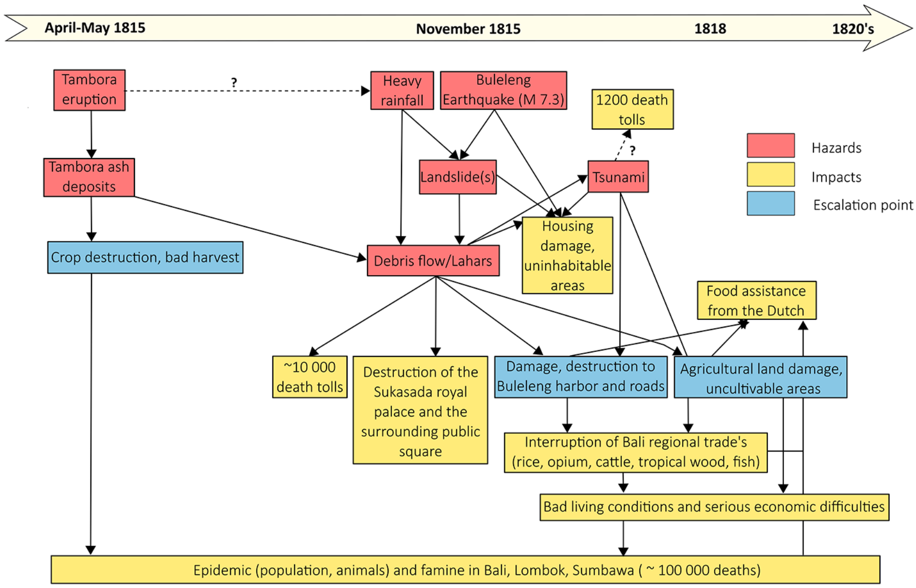

Fig. 5 Schematic sequential geological hazards and cascading impacts of the Tambora eruption and Bali disaster in November 1815 (based on cascading magnitude scale—Alexander 2018 and Suppasri et al. 2021)

the Dutch East Indies' efforts in the Java War (1825–1830) providing ongoing demand for Balinese enslaved people (van der Kraan 1983). An Arab trader, Pangeran Hasan Sayyid (Said) al-Habashi, who visited Bali in 1824, estimated the slave trade in Bali at four hundred people a year, adding that between 1819 and 1824 two thousand enslaved people (men and women) had been taken to Sumatra, not counting those taken from Buleleng, Karangasem Lombok (Creese 2016). After 1830, however, the Balinese slave trade went into abrupt decline with the closure of these two colonial markets. Then, slavery became a minor industry carried on by Bugis, Chinese, and French merchants (Creese 2016). The effects of these policies are, meanwhile, limited to the scale of Balinese society, as compared to the environmental and socio-economic impact of the two 1815 natural disasters, which led to a serious social crisis in the years that followed, especially for the Buleleng kingdom.

Based on the identification of the three components present in a cascading disaster system, a magnitude scale for cascading disasters was conceptualized by Alexander (2018). Its objective is to assess the complexity of an incident, a crisis, or a cascading disaster. This qualitative scale, comprising 5 levels (Table 3), aims to characterize the hazard sequence, the geographic extent of damage, the chain impacts, and the social and environmental consequences. This magnitude scale attempts to provide a more holistic measure of disasters, taking into account not only the initial event but also its aftermath and subsequent impact on society. This scale facilitates comparative analysis of events based on attributes such as cause, impacts, and escalation points (Alexander 2018). It prompts reflection on the extent of cascading effects, highlighting potential interactions and failure points for improved anticipation and preparedness. This classification serves as a dynamic tool, as the level assigned to an event may evolve as the scale and extent of the possible chain effect increase.

Table 3 Cascading disaster magnitude scale, from Alexander (2019)

	Classification (Alexander 2018; Suppasri et al. 2021)	Example
0	One simple cause and effect, without a significant chain of effects	A landslide cuts a rural road.
1	One simple cause and one chain of effects.	Aquila earthquake and snow avalanche in 2017 in Italy
2	One simple cause with two or multiple chains of effects.	Tokashi earthquake and tsunami in 2003 in Japan
3	Two causes, two or more chains of effects, and one escalation point.	Sulawesi earthquake and tsunami in 2018, Anak Krakatau volcanic eruption and tsunami 2018 in Indonesia
4	Two causes, two or more chains of effects, and two or more escalation points.	Indian Ocean disaster in 2004
5	Multiple causes, multiple chains of effects, and multiple escalation points.	Tohoku disaster in 2011 in Japan

According to the magnitude scale for cascading disasters (Table 3; Alexander 2018), the November 1815 disaster is a candidate for level 4. As explained above and illustrated in Fig. 5, we can identify the presence of multiple initiating causes, at least two or more causal chains, and at least two escalation points in the Gejer Bali disaster (Table 3). In comparison, Suppasri et al. (2021) assign level 3 (Table 3) on the magnitude scale of cascading disasters for the Palu earthquake (M7.4), tsunami, and ground liquefaction in 2018, emphasizing that the escalation point was caused by the tsunami warning failure which did not allow evacuation on time and increased the number of victims. The Sulawesi disaster caused the death of around 4,340 people and injured around 10,000. Severe damage was reported in coastal areas around Palu Bay, as well as to road infrastructure, airports, and harbors. However, if the Gejer Bali and Palu disasters are comparable regarding natural hazards, it is difficult to compare the two disaster sequences, for which the available data and precise observations vary significantly. While the magnitude scale of cascading disasters provides a comparative framework to understand the interactions between components of cascading systems, it seems challenging to compare events when variables such as space-time, socio-economic systems, networks, and knowledge related to disasters are different.

The Tambora eruption and the Gejer Bali disaster can be considered as interconnected events. These two complex events may be linked by a longer impact chain of climatic phenomena triggered by the Tambora eruption. While the global climatic impacts of this eruption are more thoroughly known in the northern hemisphere than in the southern, understanding of the regional impacts within the Indonesian archipelago remains limited. General circulation models show that large volcanic eruptions could induce wetter conditions in the year of the eruption in Southeast Asia (Anchukaitis et al. 2010). Tambora's eruption may therefore have had an impact on the monsoon regime (November-March), intensifying precipitation from November onwards (as mentioned in written sources, see Sect. 4.2), favoring the triggering of landslides evolving into debris flows (Fig. 5). This sequence of natural disasters possibly linked by a chain of climatic impacts could be considered an example of level 5 (Table 3), the highest magnitude of the Alexander et al. scale (2018). This qualitative approach allows us to characterize the extent of cascading disasters, understand the cause-effect chains, and better understand the escalation points to anticipate, target, and mitigate the impacts of future cascading disasters (Alexander 2018; Suppasri et al. 2021).

6 Conclusion

The Western and Indonesian written sources from Bali provide important new details on the impact of the Tambora eruption on Bali. We present and analyze unpublished descriptions of the November 1815 disaster at Buleleng, including information before, during, and after the event. Active tectonics combined with unstable and water-saturated rocky slopes created favorable conditions for a huge landslide evolving into a massive debris flow spanning some twenty kilometers. The debris flow entrance into the sea has triggered a local tsunami along the Buleleng coast. Based on the exegesis of Western and Indonesian written sources, our estimates indicate that the Tambora disaster in Bali and the November 1815 event would have killed 35,000 people and that the physical and economic recovery process would have lasted about fifteen years. Regarding human losses, the 1815 Gejer Bali was the deadliest natural disaster in Balinese history, far ahead of the Agung eruption in 1963, 1917, 1976, and 1979 Bali earthquakes.

This complex cascading disaster, in which the impact of a physical event generates a succession of secondary hazards and consequences, reveals the fragile interdependence between human societies and their environments. The survivors, their descendants, and the Europeans relate a story lost in the general history of Bali, eclipsed by the regional and global trauma left by the Tambora eruption. However, the 1815 Gejer Bali is very well preserved in the individual and collective memory of Singaraja's inhabitants, transmitted through written sources and oral traditions. By comparing descriptions, chronology, and details of the threads of testimonies that complement each other, we believe that the sources mentioned in this study are reliable and relevant for reporting the forgotten history of 22 November 1815, despite certain overstatements or transformations. Bali has many *babad* manuscripts from different periods containing potentially invaluable information about ancient disasters. Understanding the orally transmitted experiences of previous generations would improve our management and assessment of future cascading disaster telluric hazards.

The Balinese disaster assessment of level 4 on the cascading magnitude scale makes it possible to compare and cross-check events by identifying impact chains to create better planning scenarios for future cascading disasters. This systemic approach to disasters aims to help local planners and decision-makers appreciate the scale of such an event and reflect on the scope of impact chains in a modern, networked, and interdependent society.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11069-024-06671-5.

Acknowledgements This research is a part of collaborative research between Université Paris 1 Pantheon-Sorbonne, Universitas Gadjah Mada, and Universitas Pendidikan Ganesha. The first author would like to thank the Directorate General of Higher Education. Fieldwork in Bali and the Netherlands is also supported by the Aide à la Mobilité International program from the Université Paris 1, the Science and Impacts program from the French Embassy, and the field research grant of the Research Institute on Contemporary Southeast Asia (IRASEC). Thanks to colleagues and students from Universitas Pendidikan Ganesha who helped during the fieldwork. The authors would like to thank I Gusti Ngurah Panji Anom for his warm welcome and for sharing his family's history. We deeply appreciate the valuable exchange of information that has been preserved and passed down through the generations. The authors also thank the reviewers and the editor for their constructive comments, which improved the manuscript.

Authors contribution AF and FL designed the study and AF wrote the paper in collaboration with WJS and AS. Material preparation, data collection, and analysis were performed by AF. AF, FL, IGPES, MP, ADM, MWAK, MNM, and DSH conducted fieldwork in Bali and the Netherlands. AF, FL, WJS, IGPES, and AS

participated in toponymic, translation, and historical analysis. AF wrote the first draft of the paper and prepared the figures. All authors contributed to the discussion and final version of the manuscript.

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