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Cascading disasters triggered by tsunami hazards: A perspective for critical infrastructure resilience and disaster risk reduction

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ABSTRACT

Although many studies have investigated relationships between tsunami characteristics and the impact on physical property and infrastructure, such information cannot explain how the damage to each object or type of infrastructure can trigger failures of other facilities. To understand these connections and the cascading impacts, this article reviewed several recent damaging tsunami events in Japan and Indonesia, including the 2004 Indian Ocean tsunami and the 2011 Great East Japan Earthquake and tsunami. A proposed cascading magnitude scale was applied to each tsunami event to determine and categorize causes, effects, and escalation points. Large tsunamis tend to be associated with earthquakes, liquefaction, and landslides that multiply the scale of impact. The main escalation points for tsunami related disasters were found to be failures of tsunami warnings, power plants, medical facilities, educational facilities, and infrastructure. From the perspectives of critical infrastructure resilience and disaster risk reduction, analysis of cascading impacts of multiple recent tsunami events could contribute to greater understanding of economic, political, and social impacts that stem from technical decisions regarding infrastructure management. Detailed examples of tsunami cases demonstrate the potential scale and extent of damage from cascading events, and by identifying the roles and examples of escalation points, disaster managers and decision-makers can better mitigate cascading impacts by targeting and preventing escalation points. However, more detailed investigation on tsunami characteristics and their impact on failures of each type of facility is still needed to develop tools to support decision-making for better emergency management to address short- and long-term social impacts.

1. Introduction

1.1. Background

Throughout the world, systemic risks challenge the capacity of emergency relief to contain and mitigate the spread and scale of disaster impacts on communities. International guidelines such as the United Nations' Sendai Framework for Disaster Risk Reduction reflect the increasing complexity of crisis scenarios. Investigation and applied research on how to reduce exposure and vulnerability while simultaneously tackling underlying risk drivers is needed [1]. One particular challenge for understanding new forms of disaster risk pertains to critical infrastructure (CI), those assets and networks that are essential for the functioning of society such as electric power plants and roads. As noted by Pescaroli and Alexander [2,3], critical infrastructure disruptions can escalate crises triggered by natural hazard events, creating cascading effects by which emergency relief is challenged by non-linear and exponential multiplication of secondary crises. For example, the impact of the 2011 Great East Japan Earthquake (GEJE) and tsunami on the Fukushima Daiichi Nuclear Power Plant demonstrates how natural hazards induce technological (so-called 'natech') disasters and how combined impacts of infrastructure failures and environmental degradation can affect communities for years. Damage from the 2018 tsunami in Palu, Indonesia was complicated by soil liquefaction and other earthquake impacts, which each required different but simultaneous emergency responses, posing a challenge to disaster practitioners and

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scientists for how to address cascading effects. In the last two years, cascading impacts of the coronavirus pandemic (Covid19) spread across medical, logistical, social, psychological, and economic fields at a global scale, with multiple complexities and additional challenges for responding to natural hazard events. Earthquakes in Croatia in March 2020 and Greece and Turkey in October 2020 illustrated the difficulty of coping with events that require very different responses from those needed for a pandemic; the need for physical isolation to prevent the spread of disease is just one example of public health measures that complicate community-based disaster responses and local resilience. Challenges of simultaneously applying contrasting remedies extend across many fields, from healthcare to logistics, communication, and infrastructure management.

The complexity and interdependency of impacts triggered by tsunamis makes it is vital to adopt a systematic approach to disaster mitigation for tsunami events. As disaster risk is dependent on context and latent local vulnerability [4], addressing cascading disasters requires the consideration of root causes as well as primary impacts [3]. Understanding how impacts of disasters spread and multiply can mitigate the extent of disaster damage and disruption [5], and constructing scenarios to model interdependencies can aid this process and support the development of training and exercises for disaster mitigation and response [6]. Although structural measures such as seawalls and the relocation of urbanized areas to higher ground can reduce risks of tsunami casualties, the study of cascading disasters suggests other measures will also be needed. Critical infrastructure requires some built-in redundancy, and coastal livelihoods need to be protected. Disaster awareness must be developed in advance, through events such as evacuation drills with special consideration of local residents' characteristics, including their age and gender and other factors of social vulnerability [7].

Along with the integration of multiple dimensions of practical mitigation measures, there is a parallel need to integrate scientific investigations and knowledge from different perspectives. After a tsunami event, field survey reports tend to focus on one specific aspect, such as reports from science and engineering perspectives that focus on measurements of tsunami flow depths, tsunami arrival times based on eyewitness accounts, and damages to buildings, infrastructure, and critical facilities. Survey data is used to estimate tsunami sources, generation mechanisms, propagation, and inundation characteristics as well as the development of vulnerability functions. On the other hand, economic damages and impacts on society and communities, and peoples' physical and mental health, are summarized separately. Recognizing that linkages between these different approaches to the study of tsunami hazards that cause significant disasters is rare, this research examines how tsunami hazards can trigger cascading disasters from a more holistic and multi-disciplinary perspective. Based on analysis of disaster mechanisms, causes, and effects and related escalation points, this paper reviews impacts of eight major tsunamis over the period from 1983 to 2018. Through the application of this conceptual framework of cascading disasters, greater understanding of causes, escalation points, and disaster impacts, can be adapted for trainings for disasters managers and responders to anticipate and mitigate cascading effects and impacts on critical infrastructure and other aspects. Along with a deeper understanding of the potential scale and extent of damage caused by cascading events, knowledge of escalation points and resulting impacts can help disaster managers mitigate cascading impacts by targeting and preventing escalation points. A broader view of the scale of cascading impacts across various aspects of society could also help decision-makers have a better understanding of economic, political, and social impacts that stem from technical decisions regarding infrastructure management [16].

1.2. Interacting and concurrent tsunami hazard drivers and triggers of cascading disasters

Papadopoulos and Imamura proposed a tsunami intensity scale [8] based on relationships between tsunami height and damage conditions and effects on humans, objects (vessels and environment), and buildings. This tsunami intensity scale has 12 levels in total; from levels I–V (no damage/tsunami <1 m) to level XII (completely devastating/tsunami >32 m). Since the 2004 Indian Ocean tsunami, tsunami fragility functions have been another method to correlate tsunami characteristics such as flow depth, flow velocity and hydrodynamic forces with the probability of physical damage to buildings [9], bridges [10], marine vessels [11,12], fishing ports [13], aquaculture rafts and eelgrasses [14]. However, these types of relationships cannot explain the cascading effects on damaged components. As shown by the 2019 Global Risk Assessment Report, triggering events need to be understood not on their own, but within their broader context of natural and anthropic interactions [15]. As explained in Refs. [2,6], complex events have to be conceived in their multi-dimensional scales, including the possibility of:

a) compounding with other events happening in concurrence at spatial and temporal scales, such as a tsunami happening during a cold wave;
b) being part of a wider chain of interacting physical and environmental phenomena, such as a tsunami generated by earthquakes and causing landslides afterwards;
c) impacting vulnerabilities in the built environment, disrupting interdependencies and generating cascading disasters, such as a tsunami compromising a nuclear power plant [6].

These three aspects share some common elements, such as the possibility to develop cross-disciplinary mitigation measures for early warning systems and scenario building [6].

Alexander [16] proposed a magnitude scale for cascading disasters from the perspective of disaster management, not to be confused with tsunami magnitude scale [17] widely used by tsunami experts for measuring scales of tsunamis based on maximum height. Alexander's cascading magnitude scale proposes six magnitudes (from magnitude 0 M0 to magnitude 5 M5) based on cascading complexity of the crisis or disaster; as more escalation points create longer chains of effects and increase the magnitude of the impact and damage. Recognizing the challenges of definitive classification of events, Alexander's multiple scales consider the complexity of the disaster consequences resulting from events ranging from multiple levels of 'incidents' and 'disasters' and 'catastrophes.' [16] With a strong focus on the catastrophic scales of damage in space and time, and the attention to impacts on the international or global scale, Alexander [16] considers the 2004 Indian Ocean Tsunami and 2011 Great East Japan Earthquake and Tsunami (GEJE) as "candidates" to be considered as examples of disasters of the largest catastrophic magnitude–M5.

The 2004 tsunami included massive and cascading impacts throughout the disaster-affected areas and communities in multiple countries, and led to the development of international systems such as international tsunami warning services, as well as significant revisions in structures and methods for coordination of humanitarian relief and recovery support. Considering the international scale of both vast tsunami damage and impacts on organizational structures, the Indian Ocean Tsunami is certainly a disaster event of the largest magnitude. However, for the purpose of this paper, which focuses on the detailed analysis of components (causes, effects, and escalation points) of disaster cascades, from the perspective of critical infrastructure resilience with less of a focus on international impacts, we consider the case of the 2004 Indian Ocean Tsunami in Indonesia as an M4 scale disaster, as explained in subsequent sections.

In Japan the 2011 tsunami or so called "triple disaster" is the most prominent example of a cascading tsunami disaster, as in addition to massive and varied tsunami damage within Japan, major contamination resulting from the Fukushima Daiichi Nuclear Power Plant meltdown caused not only widespread and long-term displacement, but also significant international impacts for Japanese marine products and tourism, as well as related environmental issues. Similarly, the 2011 Great East Japan Earthquake and Tsunami also caused significant shifts in many aspects of thinking about disaster prevention and response; at the same time, there remain still many active and unresolved issues related to the complex nuclear disaster. While the 2011 triple disaster is a widely cited example of a cascading disaster, until now there has been no systematic definition and categorization of tsunami events based on a detailed analysis of the cascading components (causes, effects, and escalation points) across the cascading magnitude scales. Through the application and categorization of tsunami events across the range of these tsunami magnitude scales, the paper develops a more fine-grained analysis of the cascading disasters framework and the interactions of its components.

2. Cascading dynamics triggered by tsunami hazards

According to Alexander [16] (Fig. 1), there are three main components of cascading disasters, namely 1) cause (primary, secondary, etc.), 2) effect, and 3) escalation point (a critical juncture whose occurrence/failure will cause much a larger impact than the primary cause would suggest). The main criteria for each magnitude scale based on the combination of these three components are as follows:

Magnitude 0 (M0): One simple cause and effect.

Magnitude 1 (M1): Only one simple cause and one chain of effects.

Magnitude 2 (M2): Only one cause but two or more chains of effects.

Magnitude 3 (M3): Two causes, two or multiple chains of effects and one escalation point.

Magnitude 4 (M4): Two causes, two or multiple chains of effects and two or more escalation points.

Magnitude 5 (M5): Multiple causes, multiple chains of effects and multiple escalation points.

Based on these definitions, escalation points are particularly important for designating increasing magnitude scales of cascading disasters. The following sections explain each component in detail in the context of tsunami hazard events that trigger cascading disasters.

2.1. Tsunami causes

Although large earthquakes (i.e. seismic magnitude larger than 7.0 [18]) are known to be main cause of most earthquake-generated tsunamis, fault mechanisms are also an important factor. Large tsunamis are generated by dip-slip types of earthquakes (like the 2004 and 2011 tsunamis), in which the plates move vertically as opposed to strike-slip types of earthquakes where the plates move horizontally, generating much smaller tsunamis. Landslides and volcanic eruptions are also other possible causes of tsunami. Two unusual tsunamis that occurred in Indonesia in 2018 are good examples revealing the complexity of the cascading phenomena of tsunami hazards as unlike most tsunamis, they were not directly generated by earthquakes. The 2018 Sulawesi (Palu) tsunami was generated by several (aerial and submarine) landslides caused by a strike-slip earthquake with moderate earthquake magnitude [19,20]. In addition, the 2018 Sunda Strait (Krakatau) tsunami was generated by a flank collapse of the Anak Krakataa mountain due to a volcanic eruption [21].

2.2. Effects

Direct tsunami damages which vary based on factors such as flow depth, flow velocity and hydrodynamic force include human casualties, damage to physical property such as aquacultural facilities, infrastructure, and other buildings as well as environmental impacts. While not a cause of tsunami, liquefaction caused by earthquakes is another event that impacts performance of buildings and infrastructure. Although the tsunami event itself is a movement of seawater, it generates floating debris that can cause fires; both floating debris and fires can be considered secondary effects. Considerable tsunami fires in residential areas happened after historical tsunamis in Japan (e.g. 1896 Meiji Sanriku Tsunami, 1933 Showa Sanriku Tsunami or 1960 Chile Tsunami); much attention has also been paid to fires that erupted after the 1993 Okushiri tsunami as well as the 2011 Great East Japan tsunami due to conflagrations of large amounts of flammable fuel from vehicles as well as the wide use of gas canisters and oil stoves in homes [22]. Floating debris from damaged buildings, uprooted trees, floating marine vessels, and other vehicles may not only increase physical damage and human casualties, increase the chances of fire generation and spread, and delay rescue, recovery and reconstruction activities.

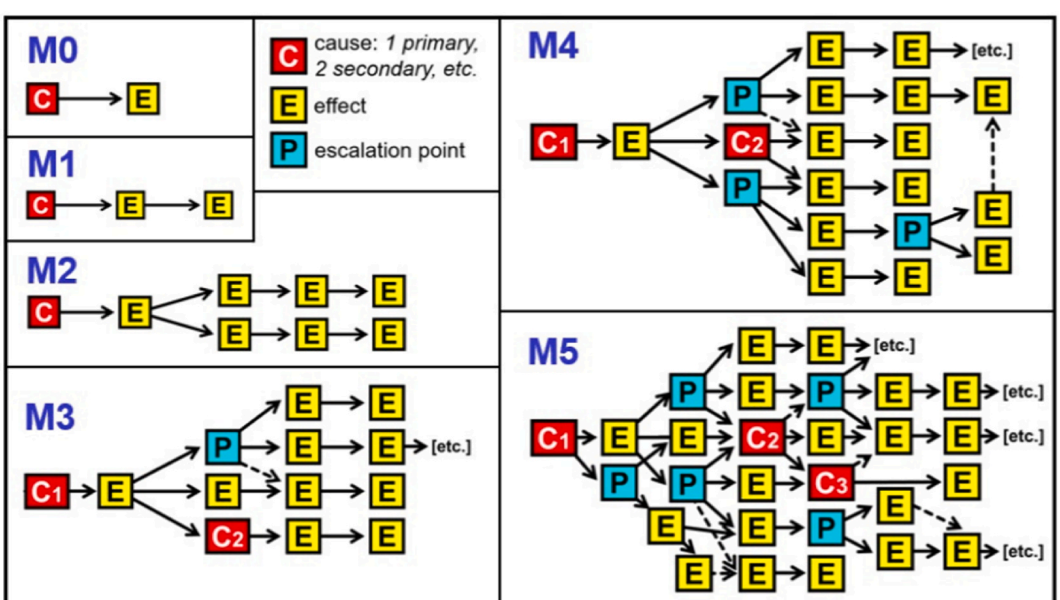

Fig. 1. Cascading disaster magnitude scales, from Alexander [16].

2.3. Escalation points

Escalation points are critical components for inducing multiple effects with disaster cascades, or even clarifying new causes of disaster damage. The following major items can be considered as significant escalation points [2,3,6,8and16] from the specific cases discussed in the following examples (section 3) but can also be applied to tsunami disasters in general.

2.3.1. Failures of tsunami warnings

This includes failures of warning systems that result in casualties at both local and regional levels. In some cases, distant (or far-field) tsunamis can also cause damage in areas far from the tsunami source. Casualties or damage from distant tsunamis may cause international issues because of factors related to early warning or other new causes, effects, and escalation points from distant tsunami-affected countries.

2.3.2. Failures of power plants

The failure of a nuclear power plant will not only cause radiation around the plant but also contamination of the sea. The various impacts and resultant issues include large numbers of long-term evacuees, delays of recovery and reconstruction activities, impacts on agriculture, marine products, and tourism, as well as various environmental issues. Failures of other critical electrical power plants or petrochemical plants might also cause serious chain impacts as they are important for daily life.

2.3.3. Failures of infrastructure

Ports, airports, seawalls, highways are some examples of important infrastructure. Damaged ports or airports interrupt networks of domestic and international shipping and any business related to the movement of passengers. Damaged seawalls, highways or other important roads will delay recovery and reconstruction activities, which in turn also affects medical and educational facilities.

2.3.4. Failures of medical facilities

Hospitals, medical centers, or other related facilities are important for the health of a community. Failure of these facilities results in decreased survival rates as well as impacted quality of health in the short- and long-term.

2.3.5. Failures of educational facilities

Schools or other educational facilities are often designated as evacuation shelters. Having these facilities inundated or damaged by tsunami means a high possibility of increasing casualties as well as the loss of evacuation capacity. Transferring teachers and students to other areas is another long-term issue.

2.3.6. Long-lasting psychological distress that goes beyond the impacts of primary hazards

Indeed, the traumatic nature of tsunamis is associated with the consequences of destruction, including damage and aftershocks, but also to criticalities in the satisfaction of basic needs [23]. Secondary events such as service disruptions or displacement can heavily influence the behavior of society, individuals, and communities, while multiple infrastructure disruptions can affect the availability of emergency personnel and recovery support, reshape the routines of citizens, and in some cases their trust in long-term recovery measures [24].

3. Applying a cascading disaster magnitude scale to tsunamis events

This section analyzes examples of tsunamis that have occurred in Japan and Indonesia in the last four decades according to the framework of the cascading disaster magnitude scale. Fig. 2 shows the locations of the considered tsunamis, including five damaging tsunamis generated by earthquakes in Japan, namely the 1983 Japan Sea earthquake and tsunami, 1993 Okushiri earthquake and tsunami, 2003 Tokachi earthquake and tsunami, 2011 Great East Japan earthquake and tsunami, and 2016 Fukushima earthquake and tsunami. The significant major tsunamis in Indonesia considered within this time period are the 2004 Indian Ocean Tsunami generated by an earthquake, as well as tsunamis generated by other mechanisms, including the 2018 Sulawesi tsunami and the 2018 Sunda Straits tsunami (Fig. 2). In the analysis of each of these cases, the relationships of components that make up the cascading framework (causes, escalation points, and effects) are represented by schematic diagrams. Due to the complexity of the components and their relationships, these schematic diagrams cannot show precise timelines of how events unfolded. However, with the progression of time on the X-axis, the diagrams show the causes and effects of cascading components over time for each case.

3.1. 1983 Japan sea earthquake and tsunami

An earthquake with magnitude of Mw7.8 occurred exactly at noon on May 26 off the coast of Akita Prefecture in Japan. There were few deaths from damages caused by ground shaking. Liquefaction caused damage to dikes, ports, roads, and railways; later this was noted as an important issue for earthquake countermeasures. The long period seismic wave caused damage to petroleum tanks and fires at crude oil tanks at a thermal power plant [25]. The earthquake interrupted various

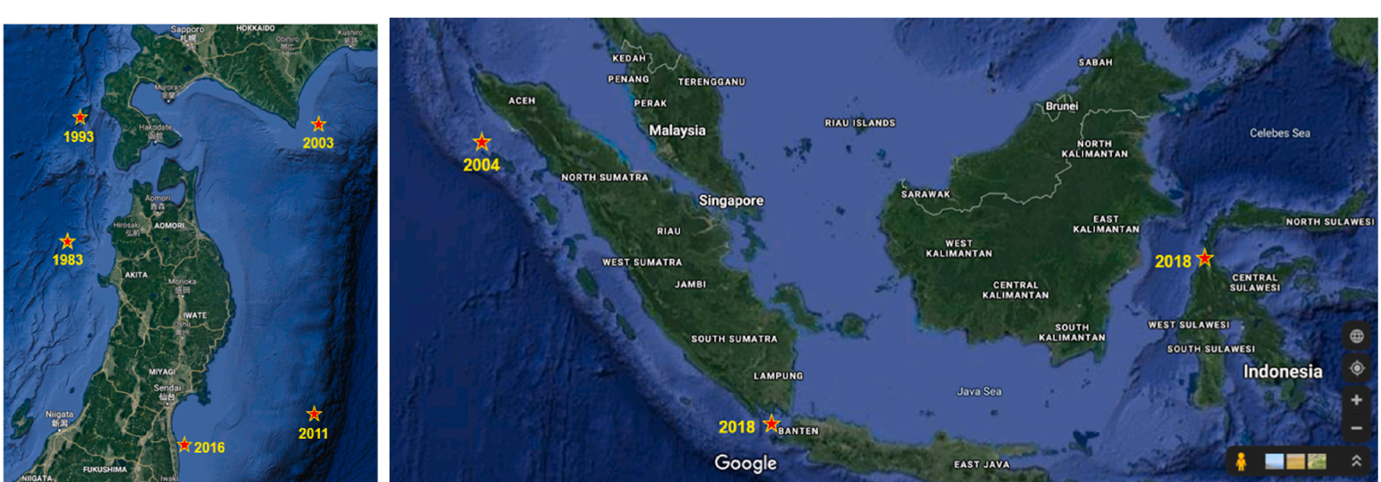

Fig. 2. Earthquake epicenters of the selected damaging tsunamis in Japan and Indonesia since the 1980s.

infrastructure lifelines of electricity, gas, water supply, and communications, which affected residents' daily life over the long term. The tsunami caused hundreds of deaths and damaged more than 5000 buildings [26]. Tsunami warning was one main issue for this disaster as the tsunami arrived about 7 min after the earthquake although the first warning was only issued 10 min after the earthquake [27]. In addition, two deaths in South Korea demonstrated the importance of tsunami warnings in the larger region [28]. The tsunami caused large damage in major ports, including to seawalls and related facilities in coastal areas [29]. There was no noticeable damage to educational and medical facilities. The failure of the tsunami warning system is considered to be an escalation point and this event is classified as cascading magnitude scale 3 (M3) (Fig. 3). Due to the failure of tsunami warnings, whose delays led to a large number of casualties in the local as well as distant areas, significant improvements were made to Japan's tsunami warning system.

3.2. 1993 Okushiri earthquake and tsunami

An Mw7.7 earthquake occurred on the night of July 12, 1993, with the epicenter located very close to the small island of Okushiri off of Hokkaido, where the first tsunami wave arrived after only 2–3 min. The tsunami caused almost 200 deaths in Japan and some missing people in Russia [27,28]. The tsunami caused damage to a ferry port, but no major cascading effects were observed from the loss of this service. The ground shaking itself caused landslides that killed about 30 persons. It was a difficult situation as residents living in mountain areas were aware of landslide risk, so they evacuated by car toward the sea, while an opposite situation happened for residents living along the coast who were aware of tsunami risk and tried to evacuate by car toward the mountains. The resulting heavy traffic was one major cause of many deaths [30]. There were also large numbers of fires reported, and this was the first tsunami event when fires were caused by gas canisters and oil-type stoves in homes. The fire generation mechanism for this event was studied in detail [31], but no deaths were related to the fires and no cascading affects were observed. There was no noticeable damage to educational and medical facilities. Based on the tsunami warning and issues that caused casualties in both local and distant areas, leading to a large number of deaths as well as improvements of the tsunami warning system, the failure of tsunami warning system is considered as the only escalation point, and this event is also classified as cascading magnitude scale 3 (Fig. 4). This tsunami demonstrated the limitations of the Japanese tsunami warning system from both the technical perspective (the first tsunami arrived faster than the warning message) [27] and social aspects (misinterpretation of warning messages and serious traffic jams caused by evacuation using cars) [30], and led to major improvements.

3.3. 2003 Tokachi earthquake and tsunami

A large earthquake with Mw8.3 occurred off Hokkaido in the Tokachi Sea on Sept. 26, 2003. There were only two deaths caused by building damage in this event [28]. The ground shaking caused damage to roads, bridges, and railways, which interrupted traffic for several days. Reconstruction took months, and up to several years in rural areas [32]. Damage from liquefaction and the tsunami was also observed in ports [32]. An electricity blackout happened due to an automatic system that stopped operation of a thermal power plant, which affected more than 20,000 households but did not cause long-term disruption [32]. Fires erupted after the long period seismic wave caused heavy oil to slosh out of a petroleum tank, similar to the case of 1983 event. There was no noticeable damage to educational and medical facilities. Although there were chains of disaster damage effects, as there were no noticeable escalation points, this event is classified as cascading magnitude scale 2 (Fig. 5).

3.4. 2004 Indian Ocean Tsunami

The 2004 Indian Ocean tsunami occurred on December 26, 2004, triggered by a 9.15 Mw earthquake off the west coast of northern Sumatra, in Indonesia. On that day, the major earthquake destroyed a large number of buildings, infrastructure, and changed the coastal area morphology around the northern part of Sumatra island [33–35]. A number of buildings also collapsed due to a combination of ground shaking and liquefaction. Around 35 min after the earthquake, a tsunami wave hit coastal areas of northern Sumatra [36], including major cities in Aceh, such as Banda Aceh and Meulaboh. The impacts of the earthquake and tsunami caused the death of around 230,000 people in 21 countries around the Indian Ocean [36]. In Aceh, the source of the tsunami, casualties were estimated at around 135,000 people.

The interruption of transportation logistics due to damage to roads and other transportation facilities also caused food scarcity in the first two weeks after the disaster in most of the affected cities in Aceh and Nias. In some areas, lack of drinking water led people to queue for drinking water distributed by emergency responders for several days after the tsunami. Public services such as education and citizen-related document services ceased for about one month after the disaster, and schools and campuses in the affected areas were closed for one to two months after the tsunami [37]. Telecommunication lines were disconnected for one month and people relied on satellite phones provided by district emergency responder units; the number of available phones was also limited. Electricity was off for about one week in some affected cities along the south-western coast of Aceh, and in some other cities it took even longer that one week to restore electricity.

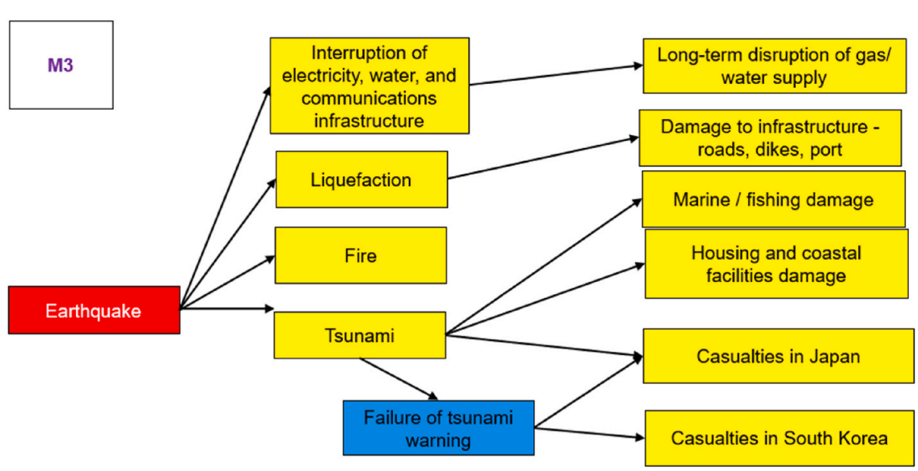

Fig. 3. Schematic process and cascading impacts of the 1983 Japan Sea earthquake and tsunami.

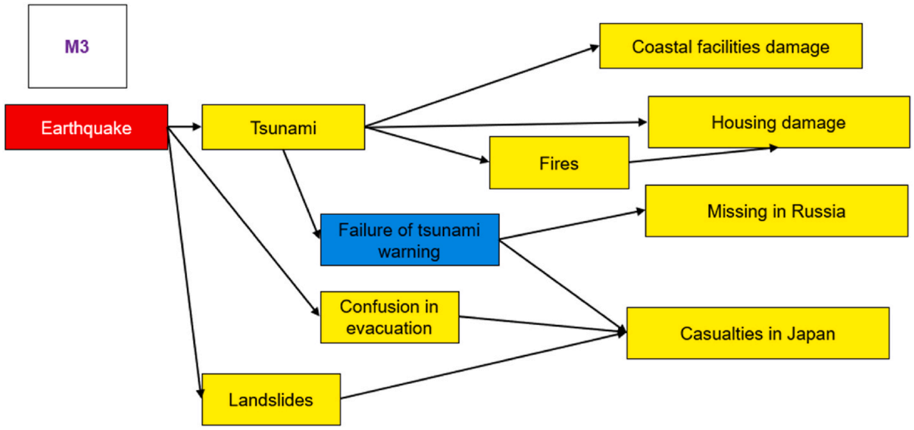

Fig. 4. Schematic process and cascading impacts of the 1993 Okushiri earthquake and tsunami.

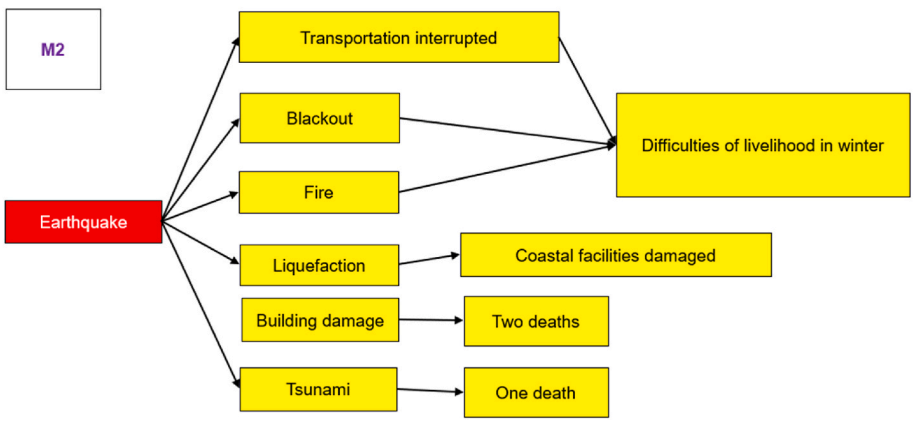

Fig. 5. Schematic process and cascading impacts of the 2003 Tokachi earthquake and tsunami.

As well as the ongoing conflict in Aceh with the separatist movement, the tsunami also affected an area distinguished at the time by a scarcity of resources and a period of limited ceasefire in the long-lasting civil war conflict between the Sinhalese and the Tamil in Sri Lanka. Together with the ongoing civil war, the tsunami created new psychological trauma because "it come from the sea, that was the source of economic livelihood for so many, whereas beaches were a place of recreation and relaxation" [38]. Increased stress was associated with sanitation problems that increased pollution and damaged medical facilities, while displacement camps lacked essential services such as adequate water, sanitation, and privacy [38]. As mentioned in a previous section, Alexander [16] has suggested that this disaster as a candidate to be

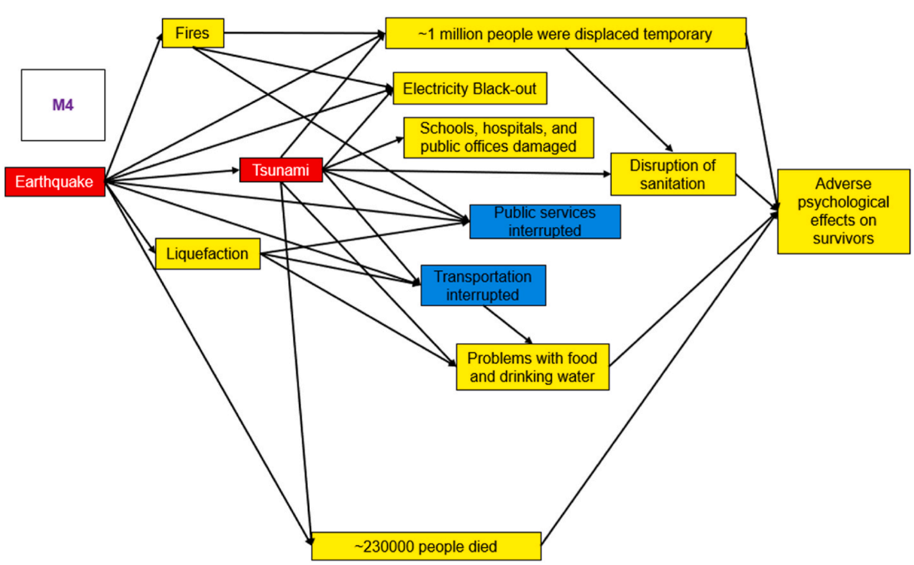

Fig. 6. Schematic process and cascading impacts of the 2004 Indian Ocean tsunami.

considered as an example of M5, the largest magnitude scale, in light of impacts on international systems as well as damage of a catastrophic scale across multiple countries. However, based on the cascading components of the disaster and factors and multiple escalation points explained above, and the focus of this research on infrastructure resilience, for the purposes of this paper the 2004 Indian Ocean tsunami is classified as M4, cascading magnitude scale 4, and the schematic process and impacts of the 2004 Indian Ocean tsunami are shown in Fig. 6.

3.5. 2011 great east Japan earthquake and tsunami

The largest earthquake (Mw9.0) ever recorded in Japan occurred at 14:46 on Friday, March 11, 2011 and generated a massive tsunami that caused devastation along the whole east coast of Japan. As mentioned earlier, the Great East Japan earthquake, tsunami and nuclear meltdown triple disaster event of 2011 is a cascading magnitude scale 5 disaster (Fig. 7). The earthquake caused a tsunami which in turn caused failures at the nuclear power plant that led to a meltdown. These three causes generated multiple escalation points as well as several effects. Because of limitations of the tsunami warning system at that time, failures of tsunami warning in the form of underestimating tsunami heights can be considered as an escalation point that led to a large numbers of deaths [39]. The ground shaking, tsunami, liquefaction, fire and nuclear accident caused significant damage to various kinds of infrastructure (waste water treatment plants, waste pipes, electricity stations and gas stations) and transportation systems (seawalls, ports, airports, roads, bridges and railways) [40–42]. Such interruptions can be considered as escalation points that caused several further effects such as delays of rescue and recovery related activities [43], decreases in tourism-related business [44,45] and regional economic impact on the distribution of goods and production of farming and fishery products [46,47]. Liquefaction also caused damage to agricultural areas as did salination of farmland [56]. School relocation and children's transportation was another escalation point that caused several effects such as compromised safety of routes to schools and disruptions of mental stability that reduced educational achievement [48,49]. Significant damage to hospitals and other medical facilities was another escalation point that impacted the quality of physical and mental health of the victims in the short- and long-term [50–55].

On March 11, 2011, the Onagawa Nuclear Power Plant was also hit by the same tsunami height of 13 m, but unlike the Fukushima Daiichi Nuclear Power Plant, it was built at elevation of 14.8 m above sea level, after considering historic tsunamis (i.e. 869 Jogan tsunami and 1611 Keicho Sanriku tsunami) as well as more recent tsunami experience in the Sanriku area (1896 Meiji Sanriku Tsunami and 1933 Showa Sanriku Tsunami) in the last century. Therefore, damage at the Onagawa NPP was limited, affecting only the underwater pump and related facilities. On the other hand, at the Fukushima NPP, which had been built at the height of 10 m above sea level not taking into account historical tsunamis, the 13 m tsunami in 2011 caused damage to the emergency electric generation system on the ground floor, an infrastructure failure whose cascading chain of effects resulted in an unprecedented catastrophe. The meltdown at the Fukushima Daiichi Nuclear Power Plant and related failures of preparation, evacuation, and risk communication can be understood as a chain of impacts from the tsunami event. At the same time, the nuclear disaster caused radioactive contamination, an escalation point, and related fears and uncertainties which have had long-term and ongoing impacts on people's lives and livelihoods. Initial confusion over evacuation was compounded by a lack of accurate information about the dispersal of radioactive particles. Scattered and disorganized evacuation processes meant that some communities evacuated together while others were on their own; in general, nuclear evacuees moved multiple times during the evacuation process. The loss of farmland, former jobs, and school environments, not to mention the loss of hometowns have all had multiple and heavy impacts on the nuclear evacuees, including economic as well as social and psychological.

3.6. 2016 Fukushima earthquake and tsunami

The 2016 Fukushima earthquake occurred with magnitude of 6.9 in the early morning of 22 November 2016. Nevertheless, as this was the first tsunami warning issued after the 2011 tsunami, some issues emerged. Initially, the tsunami warning was only issued for Fukushima Prefecture, the location of epicenter, but after 2 h, a tsunami warning was also issued for neighboring Miyagi Prefecture. This was due to technical issues in the tsunami warning database at that time, which

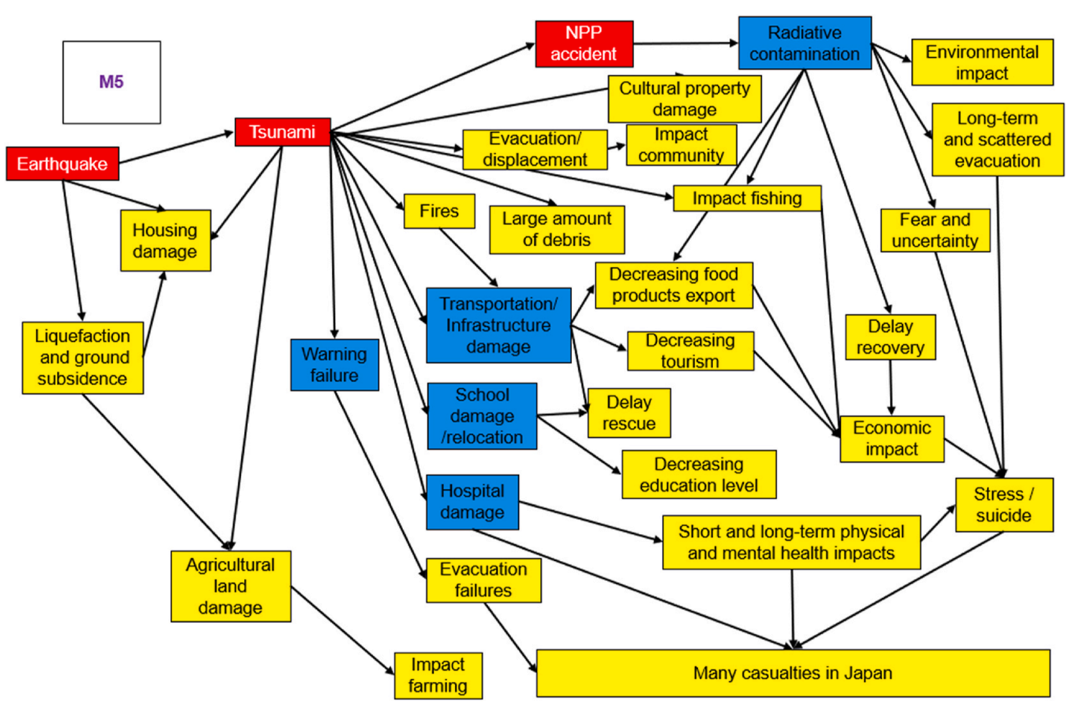

Fig. 7. A schematic process and cascading impacts of the 2011 Great East Japan Earthquake and Tsunami.

caused the system to underestimate the amplitude of the tsunami until it was observed [58]. The sudden upgraded tsunami threat level caused significant confusion for many stakeholders in different cities and towns in Miyagi Prefecture, as they had no idea if they should remain as they were or promptly evacuate [59]. Unlike the tsunamis previously discussed in the section, there were no deaths or significant damage caused by this earthquake and tsunami in 2016, and damage was limited to fishing boats and aquaculture facilities. As this event is considered as having no escalation points, it is classified as cascading magnitude scale 2 (Fig. 8). Although there were no casualties related to this tsunami, problems and impacts related to tsunami warnings later led to improvements from both scientific and social perspectives, including the subsequent revisions of the Prefecture's evacuation master plan.

3.7. The 2018 Sulawesi earthquake and tsunami

The 2018 Sulawesi earthquake and tsunami in Indonesia was triggered by a strike slip earthquake with magnitude of 7.4 Mw on September 28, 2018. On the Palu-Koro fault that transects the Indonesian island of Sulawesi in the south-east to north-west direction crossing Palu City and Palu Bay, the epicenter of the earthquake was on land, about 300 km north of Palu Bay in Central Sulawesi Province [60]. Although it was an inland earthquake, the earthquake caused sub-aerial and sub-marine landslides around Palu Bay, which has a significant depth, and is about 8 km in width and 15 km in length [61]. About 3.5 min after the earthquake, the first tsunami wave was recorded in an area of the port at the northern edge of the bay [19,20,62]. The tsunami waves later travelled to hit Palu City. Several minutes after the earthquake, large scale liquefaction occurred at three locations: Petobo, Bolaroa and Sidera villages [63]. The triple disasters, earthquake, tsunami, and soil liquefaction, caused the death of about 4340 people and injury to around 10,000 people. Severe damages were reported in the coastal areas around Palu Bay, in two villages that experienced liquefaction, and to infrastructure including roads, airports, and harbors. Palu and Pantoloan harbors were severely damaged [64]. An iconic yellow bridge that connects the northern and southern parts of the city also collapsed. Based on the cause of the disaster and their impacts, the 2018 Palu Bay Tsunami is classified as a disaster of M3, cascading magnitude scale 3, and Fig. 9 shows the schematic diagram of the causes and their impacts.

3.8. The 2018 Mount Anak Krakatau volcanic eruption and tsunami

Around 10pm on December 22, 2018, a series of tsunami waves hit the western coast of Java island and southern coast of Sumatra island, triggered by the southwestern flank collapse of the crater of Mount Anak Krakatau in the Sunda Straits of Indonesia [65–67]. The volcano had been active since July 2018. An accumulation of lava that had erupted from the volcano created a steep flank, that later caused sub-aerial and sub-marine landslides that created 45 m waves, that hit some small islands near the volcano only about 10–15 min later on the coasts of Banten and Lampung [21,68]. The tsunami waves caused the death of 418 people and temporarily displaced more than one thousand people. Tourism areas were significantly affected, causing severe economic losses in the region. Some areas were far from ready to face such a disaster. People evacuated by themselves to some unprepared areas without sufficient facilities, and some were attacked by venomous snakes. Fisheries were also severely affected by the disaster, with some fishing boats damaged and some aquaculture facilities made non-functional. Unlike other tsunami events discussed in this paper, impacts of the 2018 Mount Anak Krakatau tsunami were purely due to the hydrodynamic forces [21]. Caused by the volcanic eruption, the tsunami did not cause any major effects to the community around the area or to other public facilities. Therefore, this tsunami is classified as M3 on the cascading disaster scale. Fig. 10 shows the schematized impacts of the tsunami.

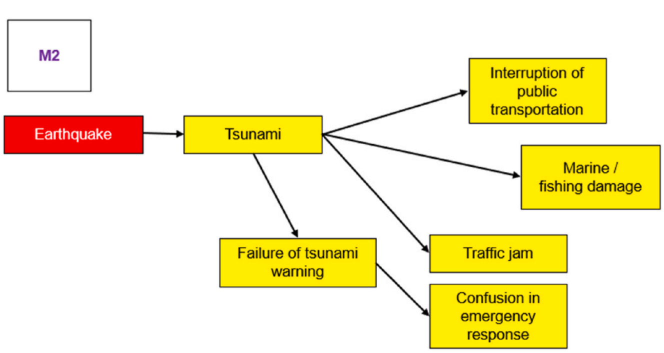

Fig. 8. A schematic process and cascading impacts of the 2016 Fukushima earthquake and tsunami.

4. Discussion and analysis of these tsunami events

Applying the cascading magnitude scale to these eight tsunami events in Japan and Indonesia, which range from M2-M5 on this scale, clarifies the interaction and impacts of components of cascading disasters, including causes, effects, and escalation points. Understanding cascading effects can give a better idea of how different types of failures amplified various impacts and damages. By categorizing various types of escalation points, some of the most critical factors in cascading disaster analysis, commonalities show which areas may be effective to target, to avoid escalation for future disaster mitigation. Table 1 presents the eight tsunami events, tsunami causes and heights [69], cascading magnitude scales, main effects and escalation points, categorized by failures of: 1) tsunami warning; 2) power plants; 3) infrastructure; 4) medical facilities; 5) education facilities; and 6) long term psychological stress.

Even among events of different cascading magnitudes, shared commonalities include failures of tsunami warning systems that became escalation points. For tsunamis that are not that large (i.e. tsunami warning level or lower), the effect of failures of tsunami warning alone could be limited to cascading magnitude scale M2, but for larger tsunamis, a similar escalation point could lead to M3 or higher. In all the tsunami events, failures of costal infrastructure occurred, as they were the front line before damage to other facilities. In cases where large scale failures of infrastructure became escalation points, cascading magnitude scales were amplified up to M4 and M5. Large scale failures of the nuclear power plant clearly generated an M5 cascading magnitude scale. Most failures of medical and educational facilities were limited to the function of an effect, but could become an escalation point depending on the size of the tsunami itself and affected areas. Currently, widespread long-term psychological distress was only found for tsunami disasters larger than M4. In general, it can be summarized that cascading magnitude scales can be limited to M2 if the maximum tsunami is less than a major tsunami warning level (<3 m) or if there is no failure of tsunami warning. However, classifying maximum tsunami height for cascading magnitude scales of M3 or larger needs more detailed analysis and discussion of earthquake intensity and tsunami flow depth at the location of each component. An analysis from the point of view of cascading disasters suggests that disaster mitigation should target measures to avoid escalation points, which cause exponential magnification of disaster damage and impacts.

5. Conclusions

The framework of cascading disasters first suggested by Ref. [16] offers a way to better understand large and complex disasters and their varied impacts. For the first time, this paper used the idea of cascading disasters, their components and magnitude scale, to analyze several key major damaging tsunamis that occurred in Japan and Indonesia in the last few decades, including two events in Indonesia with unique tsunami

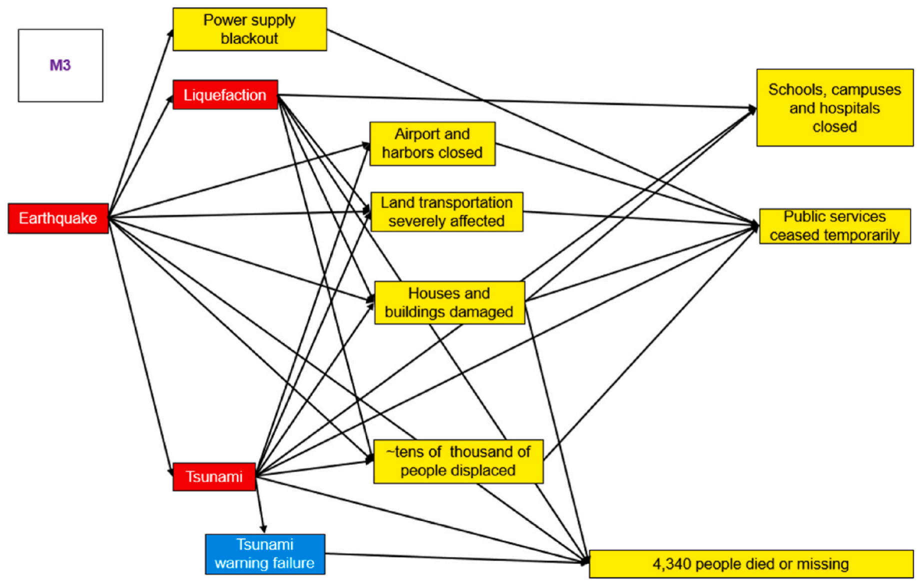

Fig. 9. Schematic process and cascading impacts of the 2018 Sulawesi earthquake and tsunami.

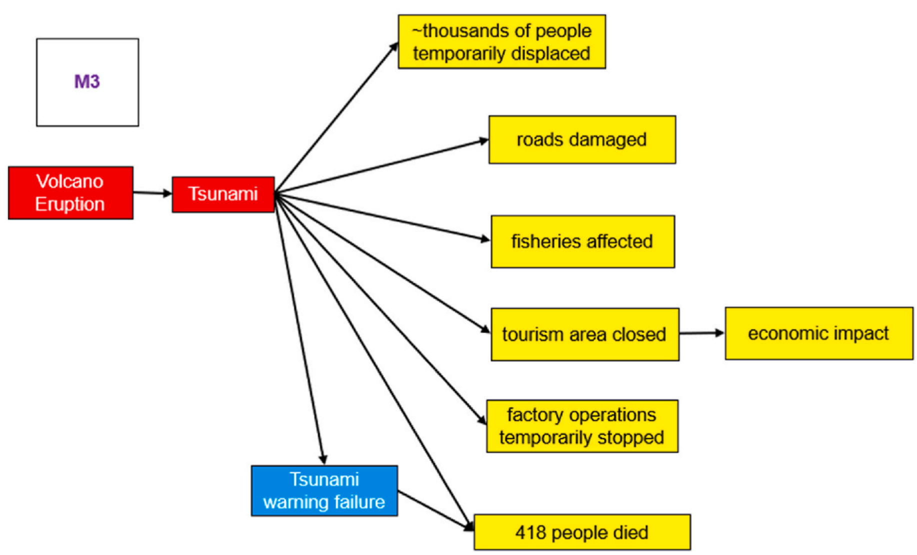

Fig. 10. The schematic process and cascading impacts of the 2018 Mount Anak Krakatau Tsunami.

generation mechanisms. Though the analysis of cascading components across the multiple cases, this research developed a greater understanding of the mechanisms by which tsunami hazards trigger interacting and cascading dynamics. Causes and effects were introduced along with an elaboration of the relationships of escalation points, categorized into failures of tsunami warnings, power plants, medical facilities, educational facilities, and infrastructure, that magnify disaster impacts and the magnitude of cascading disasters. From the perspective of critical infrastructure resilience, analysis of cascading effects show what damage was amplified and why, and the relationship of different failures and impacts. The paper illustrated also some other elements of complexity explained by Ref. [6], in particular in terms of interacting hazards and their implication for vulnerability scenarios [3]. The case studies reported physical dynamics between different hazards, such as volcanic eruptions triggering tsunamis, or earthquakes triggering both liquefaction and earthquakes. These are primary or secondary causes of cascading effects in the scale by Ref. [16], and they have to be considered as for understanding common points of failures in scenario stress testing for critical infrastructure resilience.

At a regional level, the maximum tsunami height of each event is not significantly related to the cascading disaster magnitude scale, as the effects and escalations points vary depending on tsunami impacts at the local level, compounded by local physical and social vulnerabilities. Most recent tsunamis show that failures of tsunami warning (including non-seismic sources) served as the most significant escalation points, causing the deaths of many victims. Failures of power plants seems to be the largest cascading impact, as they can also further generate interruptions of other critical infrastructure, and significantly affect the speed of recovery. Nevertheless, failures of other infrastructure, such as schools and hospitals, cause other significant social impacts as well. Although earthquake magnitudes and maximum tsunami heights were also considered, no clear trend was found that larger hazards will necessarily generate larger scales of cascading magnitudes. As failures of these escalation points are more local, future research could investigate details of earthquake intensity, flow depth and vulnerabilities, along with more detailed investigations of maximum tsunami flow depths at each critical facility or infrastructure that were considered as escalation points.

Table 1
Comparison of tsunami events and cascading components.

Disaster event	Cause (C)*	Main Effects (E) and Escalation points (P) **						Earthquake magnitude	Maximum tsunami height (m)	Cascading magnitude
		Failure of tsunami warning	Failures of power plants	Failures of infrastructure	Failures of medical facilities	Failures of educational facilities	Long-term psychological distress			
1983 Japan Sea	EQ	P		E	E	E		7.8	14.93	M3
1993 Okushiri	EQ	P		E		E		7.7	32	M3
2003 Tokachi	EQ		E	E				8.3	4.4	M2
2004 Indian Ocean	EQ, T	P		P	E	E	P	9.1	50.9	M4
2011 Great East Japan	EQ, T	P	P	P	P	P	P	9.1	39.26	M5
2016 Fukushima	EQ, T	E		E				6.9	1.44	M2
2018 Sulawesi	EQ, L, T	P		E	E	E		7.5	10.73	M3
2018 Anak Krakatau	V, T	P		E	E	E		–	85	M3

*EQ = earthquake, T = tsunami, L = landslide, V = volcanic eruption.

Further detailed interviews with disaster managers may also provide a clearer analysis of relationships between tsunami characteristics and cascading impacts from past experiences, towards their incorporation within future development of decision-making support models. Understanding relationships and cascading impacts of escalation points for disaster cascades based on past tsunamis has implications for future failure prevention, as well as imagining cascading scenarios for emergency management measures against future tsunami damage. By learning from the detailed examples of tsunami cases, it is possible to grasp the potential scale and extent of damage from cascading events, and by identifying the roles and examples of escalation points, disaster managers and decision-makers can better mitigate cascading impacts by targeting and preventing escalation points. This information could be incorporated disaster management training and exercises for critical infrastructure providers and emergency planners, giving a detailed vision of what could be expected and the basis for addressing the progress of events and mitigating impacts of chain reactions. A broader view of the scale of cascading impacts across various aspects of society could also help decision-makers have a better understanding of economic, political, and social impacts that stem from technical decisions regarding infrastructure management. As the first detailed analysis of multiple recent tsunamis in Japan and Indonesia, this research confirmed the applicability of the cascading magnitude scale from the perspectives of critical infrastructure resilience and disaster risk reduction. At the same time, as one specific application, it also suggests that the cascading magnitude scale may have the potential for other applications, including different interpretations, as a tool to build understanding of disasters that can lead to improved contingency planning for future mitigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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