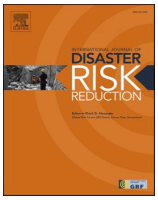
International Journal of Disaster Risk Reduction 70 (2022) 102771

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr



Tsunami risk communication and management: Contemporary gaps and challenges

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ARTICLE INFO

Keywords:
Tsunami risk
Preparedness
Preventive measures
Perception
Uncertainties
NEAM Region

ABSTRACT

Very large tsunamis are associated with low probabilities of occurrence. In many parts of the world, these events have usually occurred in a distant time in the past. As a result, there is low risk perception and a lack of collective memories, making tsunami risk communication both challenging and complex. Furthermore, immense challenges lie ahead as population and risk exposure continue to increase in coastal areas.

Through the last decades, tsunamis have caught coastal populations off-guard, providing evidence of lack of preparedness. Recent tsunamis, such as the Indian Ocean Tsunami in 2004, 2011 Tohoku and 2018 Palu, have shaped the way tsunami risk is perceived and acted upon.

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https://doi.org/10.1016/j.ijdrr.2021.102771
Received 2 August 2021; Received in revised form 23 December 2021; Accepted 28 December 2021

Based on lessons learned from a selection of past tsunami events, this paper aims to review the existing body of knowledge and the current challenges in tsunami risk communication, and to identify the gaps in the tsunami risk management methodologies. The important lessons provided by the past events call for strengthening community resilience and improvement in risk-informed actions and policy measures.

This paper shows that research efforts related to tsunami risk communication remain fragmented. The analysis of tsunami risk together with a thorough understanding of risk communication gaps and challenges is indispensable towards developing and deploying comprehensive disaster risk reduction measures. Moving from a broad and interdisciplinary perspective, the paper suggests that probabilistic hazard and risk assessments could potentially contribute towards better science communication and improved planning and implementation of risk mitigation measures.

1. Introduction

Tsunamis pose increasingly complex challenges to modern societies. Triggered by other hazards (e.g., earthquakes, landslides, volcanoes), they are part of a cascading event chain that may propagate beyond direct physical wave impact, causing damages to coastal infrastructures (e.g., serious damage to the Fukushima power plant in 2011), as well as direct and indirect societal losses, especially when coupled with pre-existing anthropogenic risks (e.g., infectious diseases, break of supply chains, crime, increased unemployment, mental health issues, etc.; [1–7]). While hazard and risk assessments in general have recently made significant advancements, gaining a better understanding of tsunami risk and its various related types of vulnerabilities is imperative. Despite the progress, commonly accepted and streamlined procedures for managing complex and potentially systemic risks, such as those of tsunamis and their consequences, are still missing.

Several alternative approaches aiming to gain a better understanding of vulnerabilities and risks have been developed by different schools of thought and with specific purposes. An example is the consequence-based approach in assessing vulnerabilities and risk (e.g., PEER's framework for risk assessment [8], which has its roots in engineering), often dealing with a need of decision-makers in addressing a specific regulatory concern. This approach follows a logical flow from causes of a disruptive event towards quantifying its direct and indirect socio-economic consequences. Another example is the context-based approach, which has its roots in the humanities and social sciences. This school of thought is interested in the social context and the interactions between all different actors (e.g., social, political, economic) and different drivers (e.g., climate, societal changes), and how different decisions can affect the overall context and the complex interplay in between them. It is imperative that the two approaches complement each other and that they are considered in policy making for disaster risk reduction in an integrated manner [9,10]. The Global Risk Assessment Framework (GRAF) aiming at encompassing all hazards, the tsunami-specific Global Tsunami Model (GTM), and Accelerating Global Science in Tsunami Hazard and Risk Analysis (AGITHAR, COST Action[2]), are among the several internationally adopted frameworks and international networks that are advocating for the incorporation of the complexities and uncertainties inherent to multi-hazard and multi-risk scenarios in the computations of risk. These initiatives are currently discussing the existing good practices, identifying gaps in knowledge, and are aiming at harmonizing and setting standardized approaches.

Scenario-based tsunami impact assessments (e.g., "worst-case" scenarios) are currently used as the basis for several risk management decisions (see e.g., Ref. [11]). On the other hand, Probabilistic Tsunami Hazard Analysis (PTHA, e.g. Ref. [12], and Probabilistic Tsunami Risk Analysis (PTRA, e.g. Ref. [13], are quite useful in taking into account various sources of uncertainty (e.g., consider a comprehensive set of plausible scenarios as described below) in the assessments. However, communication of probabilistic concepts and the uncertainties might encounter barriers to understanding and addressing these barriers is a gap. In fact, communicating the outcome of PTHA and PTRA (hence overcoming the barriers to their understanding) can shed light on why a (typically big) design-tsunami has been chosen, or raise awareness to the impact of smaller intensity tsunamis, which in fact are significantly more frequent and still can lead to loss of life, significant damage, and disruption [14].

The state-of-the-art in tsunami hazard analysis has shifted from treating a specific tsunami event based on a single source, to approaches that address the likelihood of occurrence and uncertainties through PTHA and PTRA. These frameworks provide "structured and rigorous procedures that allow for tracing and weighting the key elements in understanding the potential tsunami hazard and risk in globally distributed applications" [13,15]. Such methods face the challenge of quantifying uncertainty, which is a key factor for enhancing the public credibility of scientific advisory and for improving consequent decision making [16–22], but at the same time they challenge communicators with more elaborated products and methods to communicate. Since probabilistic methods account for different types of uncertainties, explore the range of plausible events over long timescales for low-frequency hazards, and are tailored to produce metrics comparable across multiple hazards (as in e.g. the UN's Global Risk Model [23]), they are relevant as input for assessing tsunami risk [12,13,24–26]. PTHA provides the mean annual frequency of exceeding a prescribed threshold for a tsunami intensity measure (IM) (e.g., flow depth, maximum tsunami inundation depth, etc.), whereas PTRA provides the mean annual frequency of exceeding a given threshold of a "decision variable" (e.g., number of casualties, economic loss, etc.). Tsunami risk could even be further assessed as part of an elaborate systemic and multi-risk approach which explains the complex and interconnected risk

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[2] https://www.agithar.uni-hamburg.de/about.html

landscape across the multiplicity of hazards and vulnerabilities (see e.g., [7,27]).

This paper includes a brief overview of current gaps and challenges in tsunami risk communication and management, visualized through a schematic figure (see Fig. 1 and Table 1). Fig. 1 illustrates an integrated risk governance process [28,29] adopted in this paper and described in detail in the following. Table 1 provides a summary of different stages of "understanding risk" and "risk management" as the two spheres of an integrated risk governance process shown schematically in Fig. 1 and discussed in the paper. Table 1 shows ***what*** are the different communication messages related to these stages, ***how*** these messages are going to be communicated, ***who/whom*** are the main actors involved in the communication process, ***which*** examples of methods are currently being practiced ***where***, and the tsunami events (among those discussed in the paper) that have taught relevant lessons.

An integrated risk governance process (Fig. 1) comprises all involved actors such as the affected communities, public and private sectors, scientists, experts, and governments in producing and circulating knowledge and understanding risk. Understanding risk arguably covers the first initial phases of a risk governance process [11,27,28,30]: the *risk drivers* (i.e. physical, environmental, social, economic); *hazard* assessment (scenario-based or through PTHA); considering possible *multi-hazard* interactions (cascading, simultaneous, or consecutive events); *exposure* to risk (human exposure, assets exposed to risk, and the dynamic aspects of tsunami risk exposure); *vulnerability* (integrating multiple dimensions of vulnerability, e.g., physical, social, institutional); and *socio-economic impacts* assessed through scenario-based methods, or through a full PTRA, and/or considering multi-risk consequences. As shown in Fig. 1, risk drivers can affect both hazard (e.g., climate change affecting the meteorological extremes, change in land cover), and societal impacts (e.g., increased vulnerabilities due to changing climate, environmental degradations, demographic changes, or pre-existing social conflicts). Risk management, constructs the "other sphere" of an integrated risk governance process (discussed below briefly). In such a process, the role of risk communication is central; it provides a shared and common understanding of tsunami risk among all the actors within an integrated risk governance framework as shown in the diagram.

Risk perception is socially constructed through many ways; by media exposures, collective memories, knowledge, and experiences gained from past events (e.g., selected events discussed in Section 2), scientific knowledge, and other related social processes. As shown in Fig. 1, risk perceptions and risk communication bind themselves through reciprocal relations. Based on pre-existing definitions (e.g. [31–36];), we hold that tsunami risk communication (discussed in Section 3) refers to any meaningful exchanges of information about tsunamis, i.e. tsunami dynamics, probability and related uncertainty, severity and possible consequences, whatever the source of messages, the direction of flow and the channels.

Tsunami risk communication is a two-way process that takes place before and after an event and it includes messages being delivered and conveyed by scientists, authorities, broadcast, and social media as well as common people. Tsunami risk communication aims to provide people with information to ground decisions, to affect the way tsunami risk and related information are perceived and understood. It can also affect and modify pre-existing systems of beliefs and prescribed behaviors. Such a definition does not have a normative content and is not intended as a means to distinguish between good communication and miscommunication. Tsunami risk communication can improve risk management effectiveness to the extent it would improve collective mitigation to such events. Its effectiveness and its actual capacity to mitigate tsunami risk may also be flawed by both misinformation (unintentional) and disinformation (intentional and strategically pursued).

To understand these dilemmas, Section 3 of this paper provides a discussion that reflects on the: 1) lack of reviews on current

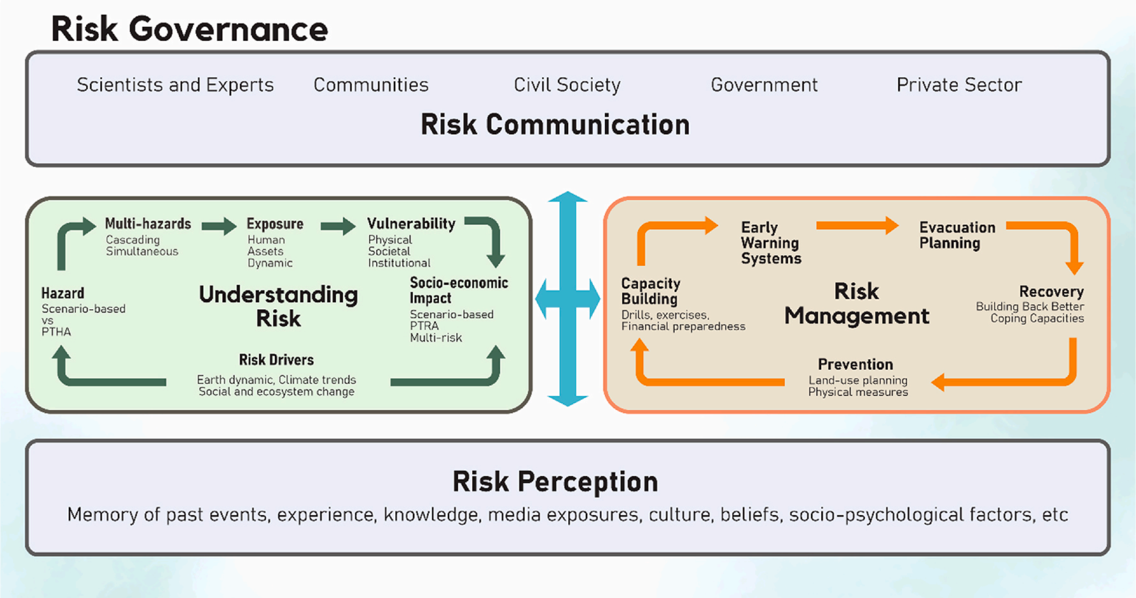

Fig. 1. An integrated risk governance cycle for dealing with tsunami risk. It is important to acknowledge here that addressing complex and systemic risks is usually a (highly) non-linear process and cannot be properly captured by simple schematization with circular relations.

Table 1

Risk communication and the different stages of an integrated risk governance process as depicted in Fig. 1.

Risk Governance	Communication message	Methods for Communication	Actors Involved	Good Examples	Relevance with some Lessons from past tsunami
Understanding risks	***What***	***How***	***Who/whom***	***Which/where***	***Example***
Hazard	Probability of exceeding tsunami intensities, Map of tsunami intesities for various return periods, Map of various percentiles of tsunami intensity measures reflecting epistemic uncertainties, Scenario-based or hazard-based tsunami arrival time	Hazard intensity footprints, Hazard zonation maps, Social media and "traditional" media (e.g., news papers, magazines, printed publications and reports, electronic media, TV, talk shows, radio), Public events, Seminars, Community-based hazard mapping, Arts and expositions, Story telling	Tsunami scientists, Journalists, Science communication practioners, Local government, Social groups, Communities at risk	GAR15, GAR19, New Zealand national PTHA maps, (MCDEM) and Italy (DPC) based on inundation maps for a design return period (e.g., 2500 years) and prescribed level of epistemic uncertainty (e.g., 84th percentile)	Maule, Tohoku
Multi-hazard	Interacting hazards, Cascading hazards, Uncertainties	Lessons from past events, Story telling, Social media, Printed publications, Electornic media, Eye witness documentary	Tsunami & social scientists, Journalists, Science communication practioners, Local governments, NGOs', CSO's, Social groups, Communities at risk	Limited integration in formal risk governance processes, IOTIC-UNESCO compilation documentary on eye-witnesses	Maule, Palu
exposure	Designating zones and assets prone to tsunami risk, Designating safe zones, Scenario-based or hazard-based tsunami arrival time	Exposure maps, Agent-based simulations, Land cover maps, Urban Morphology Maps, Public education, Citizen Science	Scientists and engineers, Science communication practitioners, Journalists, Local government, Community at risk	Evacuation planning or simulation in the USA based on information about the number of people exposed to tsunami risk and identifying demographic sensitivity	All events
Vulnerabilities	Physical vulnerabilities, Uncertainties, Social vulnerabilities, Level of awareness, Inequalities	Vulnerability curves, Vulnerability maps, Public education, Capacity building, Citizen science, Focus groups	Scientists and engineers, Science communication practitioners, Journalists, Local government, Relevant development sectors, Social groups incl. schools, Community at risk	InaRISK Indonesia Apps, STEP-A Apps to measure school preparedness, Community understanding of tsunami risk and warnings in Australia	Indian Ocean, Maule
Socio-Economic Impacts	Scenarios and previsions of tsunami impact, Uncertainties, Likelihood of tsunami consequences, Uncertainties, Multi-risk, Unkown unknowns	Portfolios of scenarios, Maps, Social media and traditional media, Story telling, Loss curves and maps, Social media, Traditional media, Seminars, Workshops	Tsunami scientists, Journalists, Science communication practioners, National & local government, Social groups, Communities at risk, Private sector, Civil society organizations (CSO's), Relevant development sectors	50-year resilience master plans for Seaside Oregon, Maximum Considered Tsunami, GAR15, Science for disaster risk management guidelines (European Commission)	Tohoku, Palu
Risk management	***What***	***How***	***Who/Whom***	***Which/Where***	***Example***
Prevention	No-build zones, Tsunami Design Zones, Pros and cons of physical measures	Advocacy, Social media, Traditional media, Public education, Building Codes	All possible actors (scientists & experts, communities at risk, CSOs, private sectors and government at national and local level)	Multi-layer planning of physical countermeasures in Japan, USAID/ASIA Guidelines, MCDEM NZ, DPC Italy, California Geological Survey, Tsunami building codes (e.g., ASCE)	1960 Chile, Tohoku
Capacity building	Evacuation routes, Position of vertical shelters, Warning messages, Natural signs, Self evacuation, Assets protection	Education programs, Drills, Exercises, Focus groups, Training, Long Strong Gone, Tsunami ten-den-ko, Citizen Science, Tourist training programs, Public education on insurance	All possible actors (scientists & experts, communities at risk, CSO's, private sector, government at national and local level)	Tsunami Ready Program (US NWS, UNESCO), TSUNAMI*Kit* , Citizen Science initiatives NZ, ShakeOut US, Tsunami Ready Hotels Bali, trainings and workshops organized by UNESCO IOC/TIC (Tsunami Information Centers), Community understanding of tsunami risk and warnings in Australia, Limited integration so far of disaster funds, catastrophe bonds, (Re)-Insurance policies	Bodrum-Kos, Samos-Izmir, Palu
Early warning systems	Warning system services and its limitations, Warning messages, Natural signs, Evacuate or not, False alarm, Withdrawn alarm	Public education, Citizen Science, Official warning via multiple channels, Siren networks, Mobile phone alerts, Local legends	National tsunami warning centers (NWTCs), Offline and online media, Local government, Private sector, Communities at risk	Development of TEWS and UNESCO IOC, GNSS Chile, Ruaumoko's Walk children book, Knowledge of "Smong", TSUNAMI*Kit*	Lisbon, Aleutian, Aceh, Maule, Mentawai, Bodrum-Kos, Samos-Izmir, Palu
Evacuation planning	Where to evacuate, How to evacuate, Scenario-based or hazard-based tsunami arrival time	Reaction scheme, Get tsunami ready, Tourist training programs, Town watching	Tsunami scientists, Journalists, Science communication practioners, Local government, Private sector, Communities at risk	TSUNAMI*Kit* , CDEM New Zealand, Tsunami Ready Hotels Bali, Washington State pedestrian walk-time maps	Lisbon, Aceh, Mentawai, Samos-Izmir, Palu, Tohoku
Recovery	How to survive after tsunami (short and long term)	Trainings on contingency plans, Consultive groups	Tsunami scientists, Journalists, Science communication practioners, Local government, Social groups, Communities at risk	Guidelines on contingency planning, & Building Back Better, "Build Back Greener" in Japan, Moken communities in Thailand	Lisbon, Indian Ocean, Mentawai & Palu, Tohoku, Maule

methods and practices; 2) lack of recognition on the indispensable relations between risk communication and risk perceptions; 3) the currently limited scientific body of knowledge on tsunami risk communication comparing to other types of hazards; and 4) lack of integration of risk communication within the risk governance framework.

In the context of this paper, risk communication is intended as a comprehensive means to inform decisional processes at both individual and societal level as well to build an improved understanding of risk features, impacts, consequences, and measures to be put in place to face tsunami risk within different stakeholders. Risk communication herein is viewed as something that may enable the necessary conditions to involve people in the decisional process [2,3,28]. To this end, risk communication and perceptions "bridge" lay people's understanding of risk within *risk management* methods and techniques (Fig. 1, discussed in Section 4).

Risk management (the right-hand side of Fig. 1) is discussed herein as long-term planning for different phases: *prevention* (discussed in Subsection 4.1, e.g., land-use planning, planning for physical measures), *capacity building* (discussed in Subsection 4.2, e.g., planning drills, exercises, education, enhancing financial preparedness), the *Early Warning Systems* (EWS, discussed in Subsection 4.3), the *evacuation planning* (discussed in Subsection 4.4), and planning for *recovery* (discussed in Subsection 4.5 through building back better strategies, enhancing coping capacities, and efficient use of funds from financial protection instruments).

Table 1 serves to emphasize the central role of risk communication in all stages of an integrated risk governance process. It provides tangible examples of communication messages for each of the stages of "understanding risk" (color green) and "risk management" (color beige) as depicted in the diagram in Fig. 1. It also describes the methods currently used for communicating each of these messages, the actors involved in communication of these messages, examples of good practices around the world and some selected past tsunami events that have provided relevant lessons and have thus helped in reflecting the use and challenges of the current approaches. Furthermore, this table is meant to guide the reader through the paper where the different elements of Fig. 1 are discussed

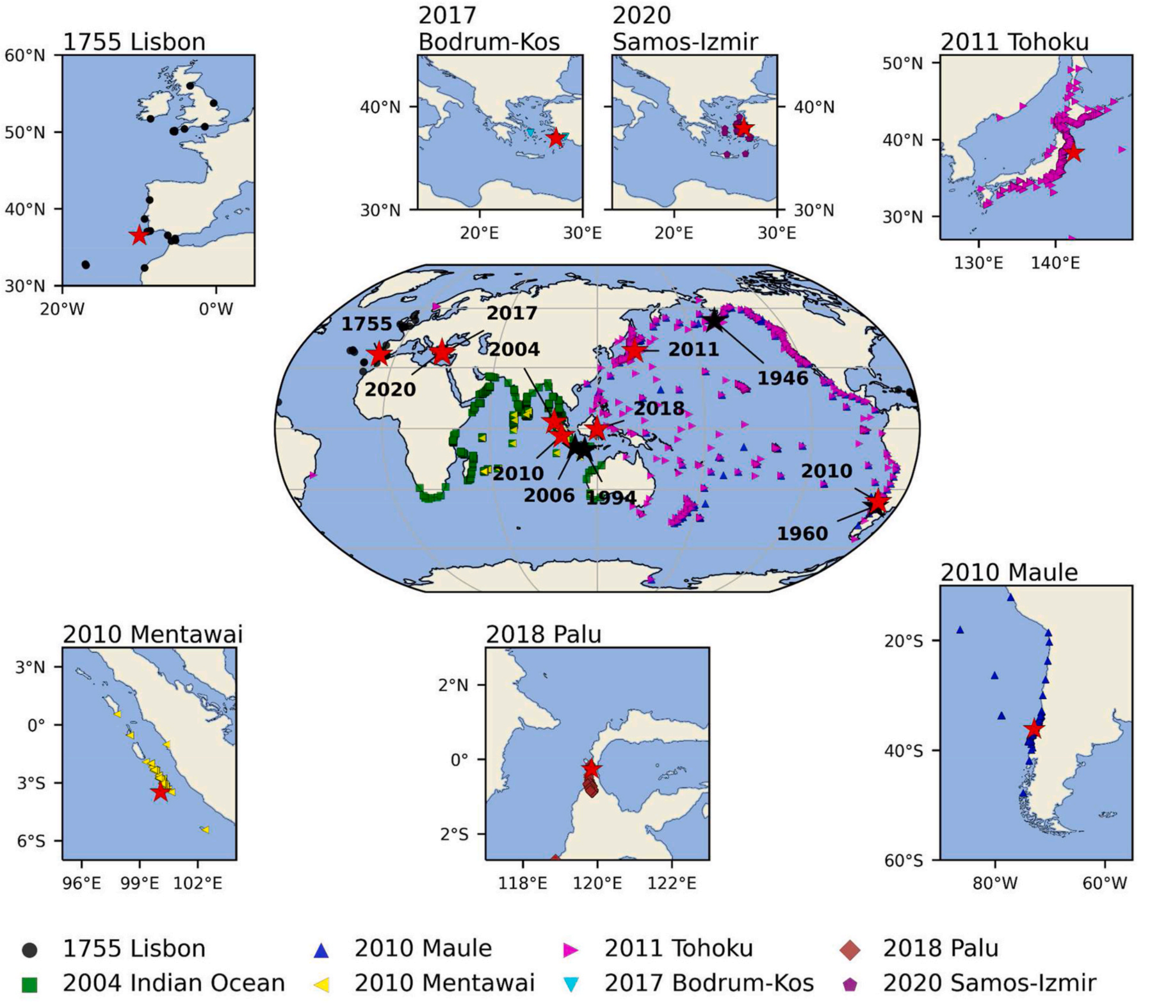

Fig. 2. A qualitative sketch of the affected regions for the events discussed in section 2. Coloured symbols represent the affected areas from a single event with red and black stars indicating the earthquake epicentre discussed in detail and briefly mentioned in section 2, respectively. The symbols off-shores indicate tsunamis observed in small islands that are not seen due to the scale. The affected areas are summarized from the National Geophysical Data Center/World Data Service: NCEI/WDS Global Historical Tsunami Database. NOAA National Centers for Environmental Information. Compiled from various sources by the authors for IJDRR.

in more detail.

How could we effectively communicate the complexity of risk and the related uncertainties and manage their multifaceted nature? How should lessons from contemporary tsunami events be utilized to improve risk communication and better manage the systemic risks? How could regions with arguably moderate to high tsunami risk but a rather low perception of tsunami risk learn from these contemporary events, for example the NEAM (North Eastern Atlantic, and the Mediterranean and connected seas)? The very recent Samos and Izmir earthquake and tsunami on October 30th, 2020 had claimed at least 115 lives, one fatality reported due to the tsunami that hit Seferihisar district of Izmir, 1035 injured, and substantial damages because of the earthquake impact (see Section 2 for more details). This is quite a typical event with a driver of low-risk perceptions of tsunami in Sumatra, Greece, and Turkey. The lack of understanding of the natural signs preceding the tsunami and the failure to implement appropriate mitigation actions have certainly contributed to increased risk exposure and might possibly result in loss of lives in future events.

To better address the possibility of a larger and catastrophic tsunami in a region with low perception of tsunami risk such as the NEAM, it is worth to mention the past events such as the earthquake (estimated magnitude 7.1) and tsunami (up to 13 m observed run-up) that hit the coasts of Calabria and Sicily on December 28th, 1908 [37], causing about 2000 or more fatalities, which added up to the approximately 80,000 caused by the earthquake [38,39]. A similar event today would cause more serious consequences and inestimable damage due to the increase in population living on the Calabrian and Sicilian coasts, the expansion of tourism infrastructures, the built industrial complexes, etc. It is important to note the impending risk of rockslide triggered tsunamis in Tafjorden, a fjord in western Norway, where a tsunami took place in 1934, resulting in the loss of 40 lives in the villages of Tafjord and Fjørå [40,41]. These events speak even more about the challenges faced by the region.

Motivated by the questions above, this paper aims to provide: 1) a review from the existing body of knowledge and literature and state of the art of existing methods, methodological gaps, and challenges in tsunami risk communication (Section 3) and management (Section 4), and lessons of selected past and contemporary tsunami events (Section 2), 2) examples of implementation of PTHA and PTRA in the risk governance and management processes, and 3) reflections of different risk communication and management approaches (including deterministic, probabilistic, or systemic) as key references to improve the current practices. This review is provided through intensive dialogue across disciplines, given that the authors are part of a group of natural and social scientists, engineers, and catastrophe risk analysts who were brought together under the AGITHAR COST Action.

2. Lessons learnt from selected past and contemporary tsunami events

A thorough understanding of risks is built upon data coming from past events. Moreover, the lessons learnt from past events and their collective memory affect all the main elements of an integrated risk governance cycle as shown in Fig. 1. In the current section, we provide retrospective analysis of selected historical events with the goal to learn how historical experience can help us to understand gaps in risk perception and communication. Of course, the selected set of events is only a small subset of previous significant events which, unfortunately, could not be addressed in this paper due to the obvious reasons.

2.1. The Great Lisbon tsunami 1755

The 1755 Lisbon tsunami, referred to as “the first modern disaster” [42], is amongst the few well-documented historical tsunami disasters in South-West Europe with regional impact from Southern Portugal to Iberia and Northwest Africa, the Caribbean, and the British Isles [43–45] (see Fig. 2 for areas affected by the Lisbon tsunami). It occurred on November 1st, 1755 from a ca. 8.5 magnitude earthquake [46] as a collateral disaster, like fires, liquefaction, and landslides that followed the earthquake. The approximate number of fatalities caused by the earthquake and the tsunami was estimated to be at least 14,000, with around 10,000 in Lisbon alone [43]. The number of casualties due exclusively to the tsunami is estimated to be 1000 victims [46]. The tsunami in the city of Lisbon is estimated to have reached maximum run-up heights of ca. 5 m and an inundation distance of ca. 250 m [46].

People were unaware of the imminent tsunami risk. They watched the sea receding before the tsunami wave crest inundated the city causing major destruction. Many people escaped the damaged areas from the town towards coastlines assuming it was a safer place. It is not known if there were previous events inspiring any preparedness for tsunamis before 1755 in the affected area. However, people were generally aware of the possibility of large earthquakes. The Lisbon Earthquake and Tsunami is recognized as one of the first disasters receiving governmental emergency response and reconstruction [42]; in the aftermath of this event, the primary resilience-enhancing response was to improve the earthquake resistance of structures.

2.2. The 2004 Indian Ocean Tsunami

The 2004 Indian Ocean tsunami during Boxing Day (Fig. 2), triggered by a Mw 9.1 earthquake, is acknowledged as the most devastating tsunami in modern history [47]. The total number of dead and missing people in a matter of hours mounted to about 230,000 across the Indian Ocean countries [48]. Although well known in academia, the term tsunami became widely known to the public and used more frequently by the media only after 2004 [49]. Unfortunately, the existing local knowledge was insufficient to respond to the tsunami, and there were no tsunami early warning systems in place. Prior knowledge was preserved in scriptures, oral stories, and eye-witness account of events for example the Makran 1945 tsunami that affected Mumbai India,[3] [50]. Many survivors reported the absence of collective knowledge and risk information, although some good examples of self-evacuations were demonstrated. Communities in Simeulue Island in Aceh, Indonesia, recollected a past tsunami event (1907), with the local knowledge of “*Smong*”, (which

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[3] https://iotic.ioc-unesco.org/1945-makran-tsunami/.

means huge wave). They effectively conducted self-evacuation without official warning. This saved at least 10,000 lives [51,52]. Nevertheless, this event was so devastating that it fostered radical changes, which in some cases resolved existing social problem, and in other cases created new problems. For example, it influenced: political conflicts (e.g. [53]), social changes and increase of vulnerabilities due to the rise of post-disaster capitalism [54], the way tsunami science is understood, the tsunami warning systems improvements [48,49,55,56], and the way rehabilitation and reconstructions are reinterpreted through the "Build Back Better" concept [48,54,57].

Before 2004, none of the earthquake and tsunami affected countries in the Indian Ocean had tsunami warning systems in place; hence, the tsunami caused victims on distant coasts even many hours after the earthquake. This event kicked off the development of several national and regional tsunami early warning systems (TEWS) under the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWMS) and later with support from the Indian Ocean Tsunami Information Center [58]. The 2004 Indian Ocean Tsunami raised awareness, beyond the affected region, that there was a broader tsunami risk than had previously been considered and it eventually led to the inauguration of the North-Eastern Atlantic and Mediterranean Tsunami Warning System (NEAMTWS) in 2005.

2.3. *Maule (Chile) tsunami 2010*

The Mw 8.8 Chilean Maule 2010 earthquake and tsunami occurred on February 27th, 2010, at 03:34 a.m. local time (Fig. 2). The earthquake induced collateral damages; building collapses, failure of engineering infrastructure, liquefaction, fire, massive landslides, followed immediately by a power outage in most of the affected areas. The earthquake and tsunami killed 521 persons, with at least 200 loss of lives occurring in coastal areas directly exposed to the tsunami. The earthquake and related cascading events directly affected over 800,000 individuals through death, injuries, and displacement [59]. The government suffered from the lack of ability to immediately respond [60]. Self-evacuation decisions were the highlighted success in the event, made due to previous collective memories of past events (particularly when tsunamis take place relatively more frequent), and strengthened by preparedness trainings, likely saving hundreds if not thousands of lives [49,59]. Social cohesiveness among communities enabled improvised temporary shelters housed by the displaced people for a couple of weeks. Communication disruptions affected the control over looting [59]. The Maule tsunami triggered persistent actions to improve the tsunami early warning in the country. In a very short time, Chile upgraded its national TEWS with additional sensor systems and new approaches in decision support. More specifically, a real-time Global Navigation Satellite System (GNSS) network was installed along the whole Chilean coast with the goal of accelerating the determination of rupture parameters in real-time [61,62]. Noteworthy is also the April 1, 1946 Aleutian Tsunami. The tsunami waves traveled across the ocean and reached Kauai and Hilo, Hawaii around five hours later, causing about 200 fatalities and extensive damage in Hilo. Many people were warned about the coming waves. But some people thought it was a joke (April Fool's day) so they did not take the warning seriously (see [63] for more information about Tsunamis in this region). Historically, the Aleutian Tsunami motivated the US tsunami warning center establishment in 1949. Later, the Chilean May 22, 1960 triggered the establishment of a Pacific-wide tsunami warning system in 1965 [48,63,64]. The Maule 2010 event triggered improvements to science and technologies in the warning system in Chile and in the Pacific, 45 years after its development.

2.4. *Mentawai (Indonesia) tsunami 2010*

The Mentawai October 25th, 2010 tsunami was classified as a tsunami earthquake (Fig. 2). Tsunami earthquakes [65] can roughly be defined as earthquakes that generate tsunamis larger than expected based on their moment magnitude. Tsunami earthquakes normally tend to cause less intense shaking than "conventional" earthquakes [66], but the duration can be longer. The Mentawai 2010 tsunami, triggered by a Mw 7.8 earthquake, caused 530 fatalities [67]. Official warning reached very few communities with access to television. The tsunami happened in the evening and reached the coasts in less than 10 min, affecting rural and remote island areas with very limited electricity, communication infrastructure, and no adequate providence of evacuation infrastructures, including sirens [66]. Similar tsunami earthquake phenomena happened before in Indonesia. The Banyuwangi 1994, and Pangandaran 2006 tsunamis resulted in casualties [68–70].

The indigenous communities of Mentawai originally resided in the hinterland and were forcibly relocated to coastlines to access development services in the 1980s. Hence, they did not bring along the knowledge of past tsunami events [57], which would have been crucial for reacting to the long lasting –yet relatively weak– shaking. Migrations to coastal areas from hinterland and vice versa does not necessarily bring past knowledge with them that could otherwise save lives.

Several NGOs intervened with risk communication activities but referred to the lessons from the 2004 Aceh with 30 min lead time, strong ground-shaking, and water receding phenomena. Some villages had moved to higher ground after the 2007 earthquake. Another village succeeded in saving the entire population due to preparedness training, by quickly running to higher ground. Official warning reached few communities with access to television. The islands have limited access to electricity and internet connections. It was only the following day that the public learned that Mentawai islands had been devastated by a tsunami with run-ups up to 14 m. Communities exposed to the tsunami disaster continued to suffer problems with resettlements due to the pre-existing social conditions (before 2010), such as marginalization and land tenure conflicts. They were once again pushed back to the hinterland for the sake of "avoiding future tsunami risks" and were distanced from their sea as sources of livelihood, coupled with reemergence of the tenurial conflicts and dispute land ownerships. For most of the communities, these new realities were even more devastating than the tsunami itself [57].

2.5. *Tohoku Tsunami 2011*

The March 11th, 2011 Tohoku tsunami (Fig. 2) took death tolls up to 15.880 [71], and further 2.813 missing or assumed dead [72].

It was triggered by a Mw 9.1 earthquake and the maximum run-up reached about 40 m in Miyako in Tohoku. The number of dead and missing could have been larger if the people in Tohoku region were not well trained to self-evacuate according to the code "*tsunami ten-den-ko*" –meaning that each person should evacuate individually after an earthquake. However, this disaster also highlights the importance of designating "safe" evacuation areas as many people lost their lives in the evacuation sites [73]. The economic loss and damages reached more than US $200 billion, and restorations will cost another US $300 billion and will take place 10–20 years [74]. The event also vividly showed challenges of disaster response during wintertime. This tsunami triggered a so-called NATECH event (a technological disaster induced by natural hazards). The automatic shutdown procedure triggered by the earthquake and the physical damage caused by the tsunami (thus leading to station black out [75]), led to nuclear plant leaks and contamination, power supply failure, and disruption to supply chains [76]. The event also led to environmental contaminations and extensive damages to the coastal ecosystems, that can be observed as an example of cascading events, as referred in Fig. 1 and Table 1. The post-tsunami disaster situation was equally alarming: around 1500 people died with causes of post-disaster suffering and health problems [74]. The tsunami had a huge global impact. For instance, as an indirect effect associated to nuclear safety, it led to the shutdown of 8 nuclear power reactors[4] and triggered the decision to shut down nuclear power in Germany by the year 2022 [77]; UNDRR, 2013[5] .

Before March 11, 2011, a magnitude 7.5–8.0 was deemed likely to happen in a time interval of 30 years with 99% probability (considering a 33 years lag with the previous magnitude 7.4 event in the Miyagi Sea, [78]. As the event exceeded the expected magnitude, it was realised that the risks were under-estimated and the countermeasures were under-designed, being based on the impacts of the distant 1960 Chile tsunami [79,80], while events like the Jogan earthquake (869 AD with 8.6 magnitude) were closer to what happened in 2011 [78,81,82]. However, the design regulations at the time were not based on the Jogan event. Learning from the 2011 event, authorities have opted for multi-layer planning based on two levels of tsunamis which considers both the large events (level 2, for evacuation planning) and the more frequent (Level 1, for the cost-benefit design of coastal protection infrastructures) events [83]. It is worth to note however, that the advancements of the tsunami warning system in Japan, and how it played an important role in saving lives, were contributed by lessons learnt from the 1946 Aleutian and 1960 Chilean Pacific-wide tsunami disaster. It can be argued that more devastating losses could have happened, but were avoided, due to the already matured disaster risk governance and management practices in Japan.

2.6. *Bodrum-Kos (Turkey and Greece) tsunami 2017 and samos izmir tsunami 2020*

The July 20th, 2017 Bodrum-Kos tsunami event was a typical example of a relatively frequent hazard with moderate impacts, with 1–2 m inundation height (Fig. 2). The Mw 6.6 earthquake itself resulted in two lives lost [84]. Social media posts and electronic media coverages observed how people were running towards the coast after the ground shaking, a sign of low awareness on tsunami risks. In the NEAMTWS, there are at least three Tsunami Service Providers (TSPs) with the capacities to provide official warning information, namely; INGV of Italy, KOERI of Turkey [85] and NOA of Greece. All are operating under the coordination of UNESCO-Intergovernmental Oceanographic Commission. As part of the upstream component of the NEAMTWS, the three TSPs issued alert messages at 10 min by the CAT-INGV, at 18 min by the NOA/HL-NTWC, and at 19 min by the KOERI-RETMC.[6] However, these messages failed to reach communities in a timely manner, before the first wave crest arrival (at 12–13 min after the earthquake, [86]). With the absence of effective integration infrastructures, awareness, coastal planning and preparation, including strengthened tsunami education programs, the "last mile" of tsunami early warning did not work [83,87]. This event emphasized the need for strengthening local tsunami warning systems [88]. Three years afterwards, the region was challenged by another nearshore event.

The tsunami generated on October 30, 2020 by the offshore Samos Island earthquake of Mw 7.0 is the largest in the Aegean Sea since 1956 Amorgos and the third largest in the NEAM region since the 1908 Messina Strait earthquake [89]. The tsunami arrived within 10 min to the north-west coast of Samos Island and within 20 min to the coast of Turkey, where one person died due to the tsunami. The tsunami caused significant damage to the coastal infrastructure [90]. Two hundred boats were sunk and destroyed at the heavily damaged Teos Marina in Sığacık. In Samos, wave runup reached 1.8 m in the harbor of Karlovasi and the most impacted area was the island's most populated town, Vathy, where a series of waves flooded the waterfront buildings, and a maximum inundation distance of 102 m was reported.

The coastal population, with relatively low perceptions of seismic and tsunami risks [91], had a very short time to evacuate and move to higher ground. The official warning through NEAMTWS TSPs messages could not reach the people in time and be acted upon by local authorities [92], mainly due to the failing in the dissemination of the official warning system as part of the classical downstream[7] component issues. Field survey measurements showed the largest tsunami runup (3.8 m) in Akarca, Turkey, 91 m from the shoreline (even a run-up height of 5.3 ± 0.3 m is reported at north of Sığacık, Turkey, according to [93] owing in part to local

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[4] https://pris.iaea.org/pris/#

[5] https://www.preventionweb.net/english/hyogo/gar/2013/en/home/download.html.

[6] CAT-INGV: Centro Allerta Tsunami dell'Istituto Nazionale di Geofisica e Vulcanologia (Italy); KOERI-RETMC: Kandilli Observatory and Earthquake Research Institute-Regional Earthquake and Tsunami Monitoring Center (Turkey); NOA/HL-NTWC: The Hellenic National Tsunami Warning Center of the National Observatory of Athens (Greece) [145],

[7] Downstream component is the part where the tsunami warning information is already generated, and further issued to different users particularly communities at risks in coastal areas. These components consist of, for example, means of disseminations through various media (e.g., sirens, loudspeakers, TV, radio,TV, Radio, Emergency Operation Center/local government, SMS, etc). It could also go through Apps or social media. Local officials play an important role to disseminate the warning to the community. The warning could fail to reach the downstream components, for example if there are failures in the warning chain (electricity short circuit/blackout, delay of dissemination, etc.). Tsunami warning could also fail to reach communities in cases of very short lead time, where the tsunami waves arrive earlier. See also Palu case in section 2.7.

morphology), and approximately 3 m runup in Samos, Greece. The maximum tsunami height of 2.3 m and a maximum inundation distance of 410 m were observed at Kaleici region in Sigacik, Turkey [94]. The NEAMTWS TSPs disseminated their warnings to their respective countries and neighbors as well, these information went out within 8–11 min after the earthquake (Amato et al., 2021). This was the first case where a national Civil Protection Authority disseminated tsunami alert messages to all cell phones in the geographical area between the islands of Kos, Ikaria and Chios, Greece [92], which was useful in triggering tsunami evacuation even if the broadcasting to the mobile phones took place 24 min after the earthquake origin time. The current set-up is better suited for distant tsunamis. Classical tsunami warning methodology depends on the reliable identification of the location, depth and magnitude of an earthquake, which dictates >7 min for the issuance of the initial tsunami warning with acceptable reliability, which may be still late for some coastal locations in the Eastern Mediterranean, at risk of nearshore tsunamigenic earthquakes. Various studies aimed to address this design-deficiency through demonstrating the possible use of local tsunami warning systems. Another approach, based on utilizing multiple sensor systems to reduce forecast uncertainty, was proposed in Behrens et al. [95].

In the case of the Bodrum-Kos 2017 earthquake, the low level of the tsunami inundation and the fact that the earthquake occurred in the middle of the night (meaning that the family nucleus stayed together at the time of the event) were most likely the main reasons for not having any fatalities due to the tsunami. The Samos 2020 event occurred during COVID times when most people stayed at home. Normally, the tourist area is highly populated. The gradual increase of the flow depth permitted some kind of self-organized evacuation, which should however not be seen as a sign of adequate level of tsunami risk perception and preparedness. Furthermore, recalling the near-field and multi-hazard characteristics of the 1908 Messina and 1999 Izmit earthquakes, where tsunami impacted areas already damaged by the earthquakes, these events highlighted once more the importance of integrated disaster risk mitigation strategies in coastal areas subject to be impacted both by earthquake and tsunami. In 1908, people escaped the damaged town center to find refuge near the coast, thus exposing themselves to the incoming tsunami waves.

2.7. Palu-Donggala (Indonesia) earthquake, liquefaction and tsunami 2018

The tsunami in Palu, Central Sulawesi Indonesia occurred on September 28th, 2018, when a Mw 7.5 earthquake followed by submarine landslides, a tsunami, and massive liquefaction caused substantial damages (Fig. 2). Due to the extreme proximity of the source to the most affected areas of Palu Bay, the lead time of the tsunami was less than 5 min after the earthquake. An official warning was issued in accordance with the national requirements –within 5 min. However, the warning message failed to reach local authorities and most of the population. In most places, the waves came earlier than the warning. The one and only tsunami siren malfunctioned, and communication channels were disrupted, this impeded the delivery of text messages to cell phones. The total number of dead and missing people due to the earthquake, tsunami, giant liquefaction, coastal slumps, and landslides was estimated at around 4340 [67], with approximately 1000 lives lost for the tsunami alone [96]. The Palu-Donggala catastrophic event is an example of a complex cascading event including multiple natural perils interacting with infrastructural damages and societal factors. For example, one of the reasons for the severity of the disaster could have been the overconfidence in the Tsunami Warning System (TWS). This highlights the importance to consider local, geographical, infrastructural, and cultural aspects when downscaling risk mitigation and governance systems to a local community level. In particular, the Palu-Donggala case demonstrated the importance to educate coastal populations living in areas close to tsunamigenic sources to interpret the natural signs of tsunamis and to start self-evacuation when ground shaking is felt, instead of relying solely on the tsunami warning system. Indeed, the very short lead time highlights the importance of capacity building activities aiming at training the population to recognize the natural signs (earthquake) and to perform self-evacuation. The case highlighted again the ultimate role of risk perception and crisis communication.

The selected events discussed in this section (summarized in Table 2), which represent a limited part of deadly and devastating tsunamis worldwide, demonstrate the knowledge gaps, complex social situatedness [97] and lack of preparedness as part of the challenges in tsunami risk management and communication. They highlight a need for changes in technologies, policies, and science, with the aim to lead to new approaches in understanding, communicating, and managing risks [7]. Nevertheless, authors also acknowledge for example success stories of self-evacuation, which evidently is among the most important capacities for communities at tsunami risk characterized by short warning time. The widespread disaster of historical tsunami events have conditioned global conventions such as the Yokohama Strategy (1994–2005), the Hyogo Framework for Action (HFA, 2005–2015), and the Sendai Framework for Disaster Risk Reduction (SFDRR, 2015–2030). We note that the HFA was distinctively influenced by the lessons from the 2004 Indian Ocean Tsunami, while the SFDRR was informed by the lessons of the Great East Japan Tsunami 2011.

3. Existing methods and gaps in tsunami risk communication

Risk communication can refer to any public or private communication that informs individuals about the existence, nature, form, severity, or acceptability of risks. In this broad use of the term, risk communication may be directive and purposeful or non-directive and fortuitous. It may describe the controlled release of information towards certain well-defined ends, or it may represent the unintended consequences of informal messages about risks [31,98].

Risk communication relates to the interconnectedness of experiences, trust, perceptions, and preparedness towards taking correct actions [99]. Risk communication is a key factor to enable effective and sound decisions about individual and societal ability to survive, resist and live with risks. Hence, it should be considered central within the whole tsunami risk governance process (Fig. 1). Dominey-Howes and Goff [100] highlight how physical mitigation measures alone might not yield effective strategies of tsunami risk mitigation, as their precondition is community awareness about the hazard and a clear-cut understanding of risk coming both from science and traditional environmental knowledge (coupled human-environment systems framework).

Risk communication becomes the crucial resource for effective management of tsunami risk and a means to increase preparedness

Table 2
Summary of lessons from recent tsunami events, approaches to tsunami risks assessments, communication, and risk reduction measures prior to the respective events. Compiled from various sources by the authors for IJDRR.

No	Tsunami Event, Type, and Date	Casualties	Prior Risk Assessment	Approach to Tsunami Risk Assessment	Risk Communication Prior/ Reflected in the Event	Tsunami Risk Reduction Measures Prior/During the Event
1	Great Lisbon Tele-tsunami November 1, 1755	Ca. 14,000	None	Not available	Unknown People went to see the water receding.	Unknown
2	Indian Ocean/ Aceh Nias Tele-tsunami, 26 December2004	2,30,000	None	Not available	Some communities have local knowledge on Smong in Aceh from the 1907 event. Most of the communities were not aware of the word ‘tsunami’. People went to see the water receding. There was no time left to save lives when the waves came in. The April 1, 1946 Aleutian tsunami that hit Hawaii was also a reminder of similar notion of low-risk perception. Communities rushed to collect fishes and shells when the water receded, and suddenly the waves caught them by surprise. There were no warning systems in place during the time. Similar with the Aleutian tsunami 1946 and Chile tsunami 1960 that motivated warning system improvements in the Pacific, the grave experiences of the Indian Ocean tsunami 2004 encouraged the development of the region’s warning system.	No warning system and evacuation plans in place. Emergency response failure. 10,000 lives saved by self-evacuation through local knowledge. Recovery and reconstruction problems: communities returning to risk area
3	Maule (Chile) Local/regional tsunami, February 27, 2010	521	Available inundation map (tsunami flood charts)	Probable extreme event.	Lessons from 1730 to 1751 events were preserved. Almost half of the fatalities from the second or third wave. Effective preparedness and training saving many lives.	The warning system did not reach communities Disruption to communication networks Weak emergency response capacities Evidence of self-evacuation and social cohesiveness. The Pacific Warning System was established after the 1960 Chilean tsunami event. More Improvements were made after this 2010 event, for example the use of GNSS to determine more real time earthquake parameters for more effective responses.
4	Mentawai local tsunami, October 25, 2010	530	Evacuation plans developed from a simplified and pragmatic approach	None.	Risk perceptions and education interventions by NGO constructed by the 2004 Aceh Nias tsunami, (30 min lead-time). People went to see the water receding. “Mentawai Megathrust” narratives by scientists. No discussions on aftermath/ resettlement causing severe and long-term social problems	Very few evacuation plans at village level. The evacuation training, if any, was geared towards far-field tsunamis with strong shaking and around 30 min lead time. Warning system hardly reached rural and remote island areas with very limited electricity, communication infrastructure One entire hamlet conducted self-evacuation and saved all lives

(*continued on next page*)

Table 2 (*continued*)

No	Tsunami Event, Type, and Date	Casualties	Prior Risk Assessment	Approach to Tsunami Risk Assessment	Risk Communication Prior/ Reflected in the Event	Tsunami Risk Reduction Measures Prior/During the Event
5	Great East Japan Regional tsunami March 11, 2011	15,880	Yes	Scenario-based assessments. Referring mostly to the 1869 Sanriku and 1960 Chile and tsunami. The local government planned to accommodate the Jogan 869 AD scenario in 2015, but the tsunami disaster came earlier.	Rigorous and continuous public education.	Evacuation plans, routes, safe zones, and shelters were built, the tsunami warning system in place according to the risk assessment, but the event exceeded the expectations.
					Strong role of media	Communities preserved past knowledge and experience in their present daily life, and this helped to effectively save lives. Evidence on self-evacuation.
					Lack of discussions on aftermath resettlement and impacts of radiation, creating social problems. New vulnerabilities: 1500 people died due to post-disaster suffering.	Physical measures such as the breakwaters, seawalls, and control forests at times could also create a false sense of security.
6	Bodrum-Kos Local tsunami20 July 2017.	2	Yes	Deterministic	People went to see the water receding	Warning system in place, but could not respond to the short lead-time
	Samos-Izmir tsunami October 30, 2020	1	Yes	N/A	Low perception on risk suggests limited risk communication interventions	Evidence of self-evacuation. Lack of proper evacuation training. Tsunami warning system in place, unfortunately did not reached the communities.
7	Palu Local tsunami, September 28, 2018	Ca.1000 (from total 4340)	Yes	Deterministic. No analysis of collateral hazards.	Several interventions, including the national tsunami drill in 2012. Existing local knowledge from previous events.	Warning system in place but failed to reach local communities and most of the population.
					Issues on post-disaster resettlements unaccounted in the risk assessment/ contingency planning	Communities waited for sirens. Overconfidence in the TEWS. No dedicated evacuation infrastructure. Evidence of self-evacuation in rural areas.

and resilience. It is imperative to address needs for a broader understanding of risk communication; beyond the traditional one-way model of communication as a linear transfer of information from scientists and authorities to a passive and undifferentiated public [101]. This model has influenced the theoretical and practical development of risk communication and has been used in some cases to justify and legitimate reductionist stances within a technocratic approach [32,102–108]. Aiming for a better understanding of tsunami risk communication, this section provides an overview of identified gaps that could be further addressed.

3.1. *Existing methods in risk communication*

From lifesaving to strengthening resilience, the existing methods in risk communication aim at both conveying messages that urge immediate decisions and actions, and risk communication messages that implicate long-term interventions on a wide spectrum of risks. This shall include all relevant stakeholders engagements and support to deliberative and collaborative processes to address risk mitigation measures. Table 1 provides examples of the current methods and practices. The authors believe that risk communication, and its limitations, should be rooted in sound research and/or risk analysis, possibly incorporating the different degrees of uncertainties in the risk communication strategies. Some notable lessons learned from real events in section 2 suggested how such considerations failed to be achieved, or how some others were in fact successful. The underlying gaps are addressed in the following sub-section.

3.2. *Lack of recognition on the reciprocal relationship of risk perceptions and risk communication*

The well-documented tsunami events, from the 1755 tsunami in Lisbon to 2018 in Palu and the Samos event in 2020, clearly demonstrate how perceptions shape actions, and how appropriate actions can indeed save lives (see Table 2). Also, the behaviours and actions observed in the public videos[8] on the web as well as the descriptions of what happened during the Samos-Izmir tsunami (October 30, 2020), published in some newspapers, reflect the different perception of the tsunami risk and the lack of information on the phenomenon. Risk perception is about the way people judge and evaluate risks, and it is based on a combination of both individuals' psychological and socio-cultural factors shaping their behavioural responses to risk issues. Consequently, there is no one single way to process, understand, and react to risk information, as implied by one-way communication models. It follows that people's evaluation of risks, and their level of acceptance heavily depends on attitudes, affects and culture (including media discourse). These factors are influenced by an individual's affiliation to different relevant social groups within the same culture, thus resulting in different ways to understand and respond to risks [109]. It follows that effective risk communication strategies must rely on consistent and solid empirical research on the way risk is perceived and understood within different social contexts rather than on purported good intuitions [110] and these must also consider the role of social context in addressing the relevance and the meaning of information to be conveyed and its possible use to improve preparedness [111].

Tsunamis have typically low occurrence probabilities but can have devastating consequences. However, tsunami risk perception is deeply conditioned by the occurrence of large tsunami events and their traces in collective memory, along with media coverage of recent events that occurred abroad [14,112] . The role of local knowledge and collective memories in constructing risk perceptions and triggering effective response actions, such as evacuation, has been seen among the local communities of Simeulue Island in 2004 [51, 113], the actions of school children in Kamaishi, Japan in 2011 [78], and the rural communities in Donggala related to the Palu bay tsunami 2018 [96], to name a few. However, younger generations of villagers in Simeulue island have increasingly vague memories of "Smong" knowledge (see Section 2). This means that if the event had occurred a few decades later, the number of casualties on this island may have been higher [114]. On the other hand, lack of recognition of the subsequent tsunami hazards may hinder effective responses, for example the elders in Natori Japan demonstrated significant delay in evacuation during 2011, as they have never experienced tsunamis reaching their residential areas in the past [115]. This underlines the importance of understanding how risk perceptions shape responses to certain events and that those perceptions are dynamic. As a consequence (of risk perception and understanding), risk communication is not solely about the intents of the technical source (namely scientists and risk managers), but it concerns the ways intended recipients make sense of the whole set of available, relevant, and trusted information on it (scientists, authorities, media, etc.).

Tsunami risk perception influences society at risk differently, and this brings relevance to the importance of contextualized tsunami risk communication within a given society. The Mentawai case in Indonesia demonstrated good examples, where the communities in Tumalei hamlet, who possessed no ancestral knowledge on the destructive waves, accepted education interventions by NGOs prior to the tsunami in 2010. This contributed to building shared perceptions and understanding of tsunami risk, which in turn saved an entire community [116]. This was also true for several survivors of the Maule (Chile) tsunami in 2010. Another good example emerges from a survey conducted in Chile by Arias et al. [117]; which found a direct and positive correlation between citizens' high tsunami risk perception and hazard proximity. Recent experiences among the residents of Iquique city (Chile) with earthquakes and tsunamis, allow them to accept tsunamis as a present risk, which can occur always and unexpectedly. The survey also shows that the actions taken by local authorities and experts to keep the population aware and prepared have probably contributed to such understanding of the hazards and accepting its risks. The field survey results suggest that preparation actions should build on what individuals and communities have learned from past events and explicitly identify the hazard zone and its nature.

The absence of risk communication in times where communities were not shaped by any perceived tsunami risks, were exemplified in the Great Lisbon tsunami 1755, the 1908 Messina-Reggio Calabria tsunami, the Indian Ocean tsunami 2004, the Pangandaran tsunami 2006, which all ended up with the tragic loss of lives. A study on tsunami risk perception among Indian Ocean tsunami-affected communities shows that differences in risk perception due to lack of knowledge, lack of adequate information during emergencies and lack of tsunami drills, as well as different socio-cultural backgrounds, caused higher casualties in some regions [118]. The loss of past or intergenerational knowledge has direct relations with migration and urbanization, as this was found in the case of Palu 2018 tsunami, affecting memory preservations due to high mobility of population. However, the study by Kurita et al. [118] taking samples from several Indonesia, Sri Lanka and Maldives shows how communities tend to favour and request more information on tsunami risk from institutions and are supportive with the inclusion of risk education in school programs. The study further shows that in areas where tsunami risk is addressed, the community has better dealt with the emergency. A testament to the importance of tsunami risk education (as well as risk education in general) in education programs is an episode that happened in Phuket, Thailand during the 2004 Indian Ocean tsunami. A 10-year-old girl (Tilly Smith) saved over a hundred people on the beach thanks to a tsunami lesson she learned at school in U.K. before leaving for Christmas vacation. This was possible because the lesson she learned explained the signs of a tsunami's arrival [119].

Arguably, the current level of tsunami risk perception in the NEAM region is generally low [14,120,121], except in a few particular places, such as some North-Western Norway fjords, where rock-slide triggered tsunamis occurred in the 20th Century [40,122]. This is a logical consequence of the fact that, in the past decades, few strong tsunamis have hit the NEAM coasts. Even in the case of substantial impact, they have resulted in low fatalities (e.g. the 1956 tsunami in Greece, triggered by a Mw 7.7 earthquake that occurred in the sea close to the Cycladic island of Amorgos).

Some communities might rely more on traditional environmental knowledge, based on social memory and experiences of past events inherited from one generation to another; transcendental or religious values that also contribute to the way disasters are learned. Others might also rely on contemporary sources of knowledge such as the media, educational programs issued by schools,

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[8] https://www.youtube.com/watch?v=hnh-ncpoGBk&t=2s.

universities, civil protection, and scientific institutions. These are the social realities that risk communication research and practitioners should be able to understand. For example, the Italian National Tsunami Alert Center developed its communication strategy on the basis of the results of ongoing research on Tsunami Risk Perception [123]. Cerase et al. [14] have shown the importance of social memory of past events, comparing the level of risk perception in two regions with similar tsunami hazard (namely Calabria and Apulia in southern Italy), the former still influenced by the 1908 event memory, whereas the second was affected by tsunamis three-four centuries ago. It is worth mentioning that the lack of recent previous events in certain places does not mean that those places are to be intended as tsunami free areas. Also, small tsunamis are more likely to occur practically in any place along the coast and in particular conditions they can result in local yet relevant effects, as happened in the Samos - Izmir event where, an older person, lost her life for not being able to resist the strong current generated by the tsunami [94].

One of the most notable products is the Tsunami Alert Center Website[9] of NEAMTWS-TSP INGV that is designed and developed based on the most recent social research. It also incorporates the recent and past events in the NEAM region, to provide an accurate description of natural signs anticipating a tsunami and of its impact, and knowledge on expected behaviour to be adopted in case of an impending event. This information is made available in user-friendly texts and visuals that also serve the less-literate communities at risk. This knowledge and information tool aims to work with the various dissemination channels used by INGV including the historic "INGVterremoti'' platform [124,125] that, in addition to communicating essential information during emergencies, supports journalists and the public by communicating scientific data, current events, publication of new studies and insights. The disseminated information quickly reached over 500,000 accounts registered to the services (Twitter and Facebook), with peaks of more than 1 million views in a day in case of large earthquakes. Despite the progressive use of communication technologies to reach out to wider public, we still need to consider the considerable number of coastal communities lacking perception of tsunami risks as exemplified in the NEAM context.

Media play an instrumental role in constructing perceptions of risks. The extensive media coverage of the 2004 Indian Ocean tsunami and 2011 Tohoku Tsunami across the globe, for example, fostered misleading perceptions that all tsunamis are big, effectively underplaying the importance of smaller and more frequent tsunamis. The smaller tsunamis of Kos 2017 and Izmir 2020 showed how in small-moderate earthquakes (and recognition of ground-shaking as a natural warning of tsunami) people may not expect an impending tsunami. As observed in these and other similar events, some people do not evacuate and may even go towards the shore after the ground shaking (see section 2). In many events, although a moderate tsunami is considered likely to happen, people still tend not to evacuate due to several reasons, which can be directly influenced by effective education and awareness activities [126].

Given the above arguments, risk perception and risk communication do in fact have reciprocal relationships (Fig. 1). Communication shapes the way risks are perceived, and risk perceptions potentially construct how (and in some cases whether) risk is communicated to populations at risk. In short, the human response to tsunamis is clearly conditioned by risk perception and a reasonable level of awareness and understanding of such events along with their immediate and long-term consequences. These can be fostered through building clear and reliable communication strategies. These strategies should be able to shape effective messages, convey them through the most convenient and relevant channels, and reflexively re-adapt its course of action according to feedback and contexts.

3.3. Limited tsunami risk communication research to improve good practices

By investigating risk communication practices and learning from past lessons, we can improve the way we communicate and manage risks. The dramatic increase of relevant tsunami research following the 2004 Indian Ocean tsunami triggered well-deserved attention from governmental, international organizations, and scientific institutions, which was not the case in the previous years. This body of research included studies of how risks are perceived and communicated. A simple survey on Scopus showed that no article on "tsunami + risk communication" was published before 2007 and only 3 out of 211 articles on "tsunami + risk perception" were published prior to 2005. The Web of Science did not retrieve any paper on "tsunami + risk communication" prior to 2007. It found merely 1 paper for "tsunami + risk perception" in 2005, after the Sumatra event.

With few, yet remarkable exceptions, research on both tsunami risk communication and tsunami risk perception is still struggling to be sustained. It is much less developed and consistent, than other socio-natural risk research such as floods, earthquakes, volcanic eruptions, hurricanes, landslides, and wildfires. Fewer articles indexed on Scopus with the search keys "tsunami + risk communication" and "tsunami + risk perception" were compared to those retrieved by replacing the word "tsunami" with the words "earthquake" or "landslide". Despite obvious differences in categorization criteria and a partial overlapping of the records, queries on Web of Science (all databases) also display a similar situation with a slight difference for "landslide". Furthermore, among all the articles retrieved for "tsunami" + "risk communication" on Scopus, those that refer to social sciences are just over half the total. The variety of the points touched by these research efforts (among others) span from the relationship between risk perception and political orientation [127], to self-evacuation willingness [128], to levels of preparedness and knowledge about natural warning signs of tsunamis [129]. They span from the individuals' psychological characteristics to enhanced ability to cope with tsunamis [130], to the way tsunami risk is perceived by particular social groups such as international tourists [131]. The heterogeneity of issues, geographic and cultural contexts, interdisciplinary approaches, methodologies, and communication models being contextually used is at the same time a gap and a point of strength. This makes an in-depth meta-theoretical analysis immediately necessary and indispensable even though it is beyond the scope of this paper.

Tsunami risk communication remains a promising domain, but published research seems to have a substantial delay with respect to

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[9] Available at https://www.ingv.it/cat/en/.

the academic risk communication debate. More research is needed to foster sound risk communication tools and strategies. This involves assessing theoretical concepts, stressing empirical data and methodologies, and critical evaluation of practical development [32,102–108,132,133]. Further analysis might consider the role of both broadcast and digital media, and of cultural traditions (traditional environmental knowledge (TEK) native/emic knowledge), the importance of understanding tsunami risks, along with the difficulty to effectively manage concepts such as probability and uncertainty within the whole risk communication field. These were proposed for example by Juhri Selamet [134]; by extracting lessons from the Palu tsunami case. It is also worthwhile to critically reflect on how risk communication practices are traditionally being used to justify and legitimate technocratic approaches of propaganda-like science communication. This clearly signals the asymmetric relations among actors in risk communication, which could cause tensions and resistances. Equal and collaborative processes of risk communication require sufficient understanding of local hazards contexts, along with the social and cultural contexts. By doing so, these approaches could be more effective, and come with more sustainable impacts.

3.4. Challenges in communicating probabilities, uncertainties, and ambiguities

Basically, any PTHA/PTRA based risk communication approach relies on communicating the meaning of probability distribution functions and the meaning but also the need to represent the expectations and the uncertainties about the future tsunami events and their impacts. For instance, PTHA can provide, for a given stretch of coast, the different probabilities of exceedance of various tsunami intensity measures (e.g., flow depth, maximum tsunami inundation height) within a given time. In the context of PTHA, higher probabilities of occurrence are associated with small yet hazardous tsunamis, whereas, considerably lower probabilities of occurrence are associated with larger events. As it is inherent to a probabilistic methodology as an approach, the role of uncertainty in providing hazard/risk estimates is central.

This approach naturally demands to shift the focus of risk communication from the idea of the tsunami as a single, unpredictable, and catastrophic event to a wider understanding of phenomena as largely uncertain but yet predictable results of an ongoing geophysical process. The development of PTHA/PTRA approaches may potentially set the future rules of tsunami risk communication. Such a radical perspective change will inevitably lead to a review of basic assumptions that implicitly inform tsunami risk communication, challenging commonplaces and misassumptions, and also focusing on possible relevant impacts at a local level (such as of the Izmir/Samos 2020 event) rather than remaining anchored to media imagery of past big events (namely Sumatra 2004 and Japan 2011; [14]). While the media played an undeniably significant role in constructing the imaginations of tsunamis, the identification of tsunamis as "destructive" and "devastating" phenomena could foster the risk of rejection and also lead to fatalistic beliefs. On one hand, social constructions of tsunami imaginaries contributed to raising community awareness, but on the other hand, a message centred on the idea of the tsunami as a giant wave may lead to false expectations, and affect communities' ability to take relevant mitigation measures [135]. Such ambiguities are common challenges to many risk communication practitioners. In general terms, tsunami risk communication should cater to the local contexts and cultures. Therefore, risk and uncertainty associated with more frequent tsunami events with low impacts are similarly important to be communicated.

Effective communication on probabilistic concepts to the non-experts and the public is challenging, as these approaches are prone to ambiguous interpretations [136–138]. That is why the reciprocal relation between implementation of the output of PTHA/PTRA methodologies (as tools for reaching a better understanding of risk) and tsunami risk communication and management is key (Fig. 1 and Table 1). As recalled by Rød et al. [139]; probability-based assessments usually follow an analytic approach to risk evaluation adopting the scientific language of risk assessment; whereas lay people, policymakers, tourists, and other layers of societies are most likely to draw on an experiential understanding of risk, which includes images, numbers, graphics, metaphors, and narratives as well as their attached feelings.

Communicating probability information is particularly challenging, due to the inherent difficulty to turn statistical reasoning and abstract concepts into understandable and viable concepts, that are related to the recipient's experience [140] and the way risk statements are framed [141]. Further empirical discussions of risk ambiguities are given by research of communication on health, diseases, and other types of disasters which can be applied to tsunami cases. Depending on the individual, collective communities, and contexts, ambiguous information could lead to a negative affective response, for example, worry or distress or even less worry [142], and it can also potentially lead to resistances in many forms towards the notion of tsunami risk [116]. One should pay attention to how the notions of tsunami risks can also be contested by certain local or traditional values [143]. Therefore, discussions about probabilities need to be effectively built through eye-level dialogues between modern science and local, traditional, or religious values.

Several tools are used to facilitate the risk communication process. Each of them comes along with gaps and limitations depending on the context, the territory, the culture, and the local policies. Visual media on hazard maps, warning dissemination schemes, etc., could be a powerful and user-friendly means of communication if they are well structured and simple. They should avoid providing ambiguous information, and communicate the uncertainties related to local aspects of hazards and the multiple plausible risk possibilities they potentially induce [136–138]. Communicating risks to indigenous communities, people with special needs, children, and elders with less access to information and technology would require even more accessible, simplified, and user-friendly media. This is a huge challenge for communicating uncertainties.

Multiple options and proposals of hazard maps could confuse the policy-maker. The so-called "Padang Consensus Meeting" in 2010 is a good example of a multi-stakeholder mediation process in deciding multiple interpretations of hazard information proposed by different research groups, all aiming to build the city's preparedness and policy-making for tsunami risk reduction [55,144–146]. The effect of communicating ambiguities, i.e., worries, anxieties, or resistances can be moderated by numbers, maps, figures, and other options of formats ([142]; Table 1), but needs to be complemented by dialogue and participative engagements [147]. Further examples and lessons learned on early implementation of PTHA/PTRA-informed risk communication are exemplified by the USA, New Zealand, Indonesia, Australia, and Italy (see Section 4).

Communication through easily understood early warning system information (described in Subsections 4.2 and 4.3) is evidently effective in several cases. However, it is not part of latent communication "in peacetime" or prior to the occurrence of a disaster. Crisis communication, if not explained properly and made accessible to the public (including tourists) beforehand, can be misinterpreted, causing erratic, ineffective, and fatal response behaviour during the real event. Social media can be a good means of communication in crisis time as they may contribute to quickly spreading trustworthy messages through multiple digital channels by mean of "digital volunteers" [148], thus improving message redundancy and achieving complex social functions related to the ongoing emergency [149]. The Cry Wolf Effect triggered by false alarm, or termination of tsunami warning, within disaster risk communication is worth mentioning. Risk communication "in peacetime" should inform exposed people about the eventuality of false alarms as something that could occur and that an early warning could be withdrawn when there is little or no evidence of incoming tsunami. Evacuation during events in which tsunami did not occur despite the issuance of official tsunami warning is often perceived as a failure by the public, and effective communication to clarify on this issue is imperative. Digital media can also be used in the long term as a means of preparedness to share material and information useful to get a better understanding of hazards. Examples of communication through official and reliable channels are the Tsunami Wave Exercises (PacWave, IO Wave, etc.), coordinated by IOC UNESCO and National Tsunami Warning Centers. These exercises are held regularly at regional to local levels, to test communication and response on warning system products and to avoid misleading interpretations and false responses (See also Subsection 4.2). They engage media, local administrations, schools, communities, as well as national warning centers and regional tsunami service providers. The exercises also introduce multiple scenarios of drill responses to unconventional and imminent tsunami events.

It is always necessary to study the context in which communication is directed to avoid unnecessary and unintended consequences. For example, the risk communicated to Mentawai islands communities prior 2010 on the potential tsunami lead time should have not referred to the Indian Ocean 2004 event that suggested a 30 min lead time. This had in fact caused losses of lives due to the absence of understanding that tsunamis can locally arrive within 10 min or less. Acknowledging the objective uncertainties as well as limitations of contemporary knowledge, science and technology in dealing with complex risks would have more positive effects, e.g. allowing for better individual judgments and responsibility to self-evacuate [7]. Above all, investing in human resources in all relevant sectors with a sound academic background and multi-interdisciplinary views in risk communication is paramount.

3.5. The need of better integration of risk communication and risk management within risk governance framework

Risk governance (see Fig. 1), "includes the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analysed, and communicated and management decisions are taken" [28] that is intended as "[…] a common analytic structure for investigating and supporting the treatment of risk issues by the relevant actors in society. The focus is not restricted to how governmental or international authorities deal with risk, but equal importance is given to the roles of the corporate sector, science, other stakeholders as well as civil society –and their interplay" [106].

Within the risk governance framework, the risk communication role goes far beyond the traditional yet pragmatic function of mediating between expert judgments and the variable public perceptions of risks. Risk communication is not intended as a one-way transfer of information nor as a stand-alone activity and decision making merely by disaster risk managers. It is based on a two-way communication model and as an important element being embedded within the whole risk governance process, that involves all the relevant stakeholders in a mutual learning process, where all the participants share rights, duties, and responsibilities [3].

The risk governance framework appears as a promising way to deal with systemic risks, where the large scale increase of vulnerabilities is a consequence of the complexity of the social system, and where geographical factors and physical events are amplified (or mitigated) by functional dependencies between different sectors of society (sub-systems) as science, technology, economy, politics, culture and social structure itself [2–4]. As risk communication might enable both formal and informal institutions (e.g., communities, small groups, villagers) to reduce their inherent vulnerabilities [150], and at the same time play a bridging role among those involved in risk governance, it should be therefore intended as both a significant part of the tsunami risk governance processes and as a relevant resource to effectively manage the risks to which the coastal communities are exposed.

Risk governance is particularly challenging in the so-called "limited notice" to "no-notice" hazards or rapid-onset events with little to no warning lead time [151], which is often the case for atypical tsunamis (e.g., triggered by underwater landslides, submarine volcano eruptions or tsunami earthquakes; [152]). These types of hazards require more inclusive and all-actors participation in: early warning; reduction of physical and social vulnerabilities including poverty and inequality; facilitating evacuation including equal access to adequately designed and rehabilitated buildings; strengthening institutional settings and risk transfer mechanisms; and advanced planning recovery processes such as building back better livelihood and resilience (discussed in Subsection 4.5).

The following section will further discuss the challenges of incorporating risk communication in risk management efforts, for strengthening preparedness in the short- and mid-term, to enhance resilience in the long-term within the risk governance framework.

4. Existing methods and gaps in tsunami risk management

The socio-economic impact of tsunamis can be mitigated through *prevention*, community *preparedness*, timely warnings through *Early Warning Systems* (EWS), and effective *evacuation* and *recovery* (see Fig. 1), informed by risk analysis and thorough risk understanding. This section provides an overview of existing methods and identified gaps in long-term planning for *Preventive Strategies for Enhancing Coastal Community Resilience* (Subsection 4.1), *Capacity Building and Enhancing Community Preparedness* (Subsection 4.2), *Tsunami Early Warning Systems* (Subsection 4.3), *Evacuation Planning* (Subsection 4.4), and *Recovery* (Subsection 4.5). It should be emphasized that this section discusses the solutions and measures to be adopted and planning for risk management during the "peace time". Therefore, it does not discuss issues related to emergency actions and response coordination in the immediate aftermath of a tsunami.

4.1. *Preventive Strategies for Enhancing Coastal Community Resilience*

4.1.1. *Strategic land use planning*

Land use planning guides the location, type, and intensity of development and can be used to reduce the coastal community's exposure to coastal hazards. To this end, land-use planning is a very effective preventive measure which contributes in the first place to having fewer people in harm's way. For instance, the National Tsunami Hazard Mitigation Program and the Department of Land Conservation and Development, in Oregon, USA, have both released comprehensive guidelines for land use planning to mitigate the loss of life and infrastructure due to tsunami inundation ([153,154]; respectively). Strategic decision-making and land-use planning for coastal communities should be informed by risk and hazard data (e.g., PTHA and PTRA results), with tools to assist planners to consider the likelihood and consequences of hazards in their processes [155].

The USAID/ASIA USAID/ASIA [156,157] guidelines on the resilience of coastal communities were prepared in response to the 2004 Indian Ocean tsunami. It includes best practices in tsunami risk management, for example establishing coastal forests, moving existing shopping areas to the upper floors, relocating sewage treatment facilities outside of tsunami run-up areas, and creation of the Pacific Tsunami Museum (in order to keep the memory alive) in Hilo, Hawaii. The guideline cites examples of best-practices in land-use planning such as the delimitation of "buffer zones" and "no-build zones" in the coastal zones of Sri Lanka, and *Build Back Better* (see Subsection 4.5) initiatives [158] such as design of Tsunami Safe(r) Houses in Sri Lanka [159]. Even before the 2011 Tohoku event, tsunami risk management guidelines were available for Japan [160].

Gaps in risk-informed land-use planning: PTHA and PTRA studies have been performed for the UNDRR Global Assessment Reports - GAR15 [25] though the results are not intended to support a local decision-making purpose. More refined regional PTHA maps have been made available through the TSUMAPS-NEAM [161] Project, whose results (NEAMTHM18 [162,163], are used for national planning in Italy [164]. This was partly inspired by the example of New Zealand, where national PTHA have been applied in risk management ([165]; See also Subsection 4.4 for evacuation zones). It is however to note that PTHA for evacuation planning has not been applied everywhere in NZ, except at the wave height at coast level. Nevertheless, there are not many guidelines available about how PTHA/PTRA information can be translated into land-use planning. For example, the 50-year resilience master plans for Seaside Oregon which consider the new advancements in tsunami modelling for delineating the areas subjected to tsunami inundation seem to be based on various earthquake scenarios [166]. The California Geological Survey has provided PTHA maps to be used for land-use planning and evacuation planning purposes, with the support of a Tsunami Technical Advisory Panel [167,168]. However, it remains challenging to indicate appropriate hazard levels to be used for land-use planning and evacuation planning [168]. The general lack of risk-informed guidelines can be attributed to the low probability of occurrence of destructive tsunamis and low perception of tsunami risk in coastal areas that have not experienced it before [83] and the perceived difficulties in implementing tsunamis in risk management policies [169]. In addition, PTHA and PTRA studies mostly focus on earthquake-generated tsunamis and there is a need to incorporate other tsunami sources for a comprehensive inclusion of tsunami risk.

Need for multi-risk framework: Strategic decision-making for coastal communities needs to consider the possible interactions and cascading effects between different hazards (e.g., storm surges, tsunamis, coastal erosion, earthquakes, landslides, volcanoes, and even pandemic outbreaks) and their consequences [170–173]. Even the physical preventive solutions are often multi-purpose (e.g., delimiting "no-build zones" such as green belts could also decrease rainfall-runoff, see e.g., [174]. In some cases, the preventive solutions can be contradicting (e.g., designation of safe zones for earthquakes without taking account the possibility of ensuing tsunamis, [171]). Such interactions at the level of hazards, vulnerabilities, and mitigation need to be considered, as they may significantly increase the overall risk. Nevertheless, there is a general lack of broad-brush methodologies for multi-risk assessments and multi-risk strategic planning [175].

4.1.2. *Physical preventive measures*

Physical mitigation measures are essential to reduce the impact of tsunamis and enhance the resilience of coastal communities exposed to tsunami hazard. Physical measures can be classified as *nature-based* (e.g., tsunami control forests, actions for coastline ecosystem protection) and *engineering-based* (e.g., breakwaters, seawalls, design of tsunami-resistant vertical evacuation shelters).

Nature-based Solutions: Nature-based solutions (NBS) are generally quite effective in enhancing a community's resilience. This can be attributed to their multi-risk nature; that is, NBS's benefits can regard more than one hazard [176] and potentially bring social and environmental benefits beyond risk reduction. Coastal ecosystems (e.g., mangroves, coastal forests, fringing reefs) may act as a buffer against tsunami through a reduction of water flow velocity and inundation depth, debris blockage, saving people from being washed away, and formation of sand dunes [177,178] as shown in the 2004 Indian Ocean tsunami event (e.g. [179–181]). Coastal vegetation, especially the mangroves due to their large roots, but also the coral reefs and natural reefs, limited the number of casualties and preserved coastal villages from destruction [182]. Tsunami attenuation by mature mangroves examined under laboratory conditions indicated a decrease of tsunami transmission by 20% for both solitary waves and tsunami bores [183]. Nevertheless, a study by Suppasri et al. [78] on lessons learned after the Tohoku 2011, points out that the degree of effectiveness of tsunami control forests depends also on the height of the trees, compared to the tsunami height, and their diameter. In some situations, damage to a controlled forest contributed to floating debris and tree trunks damaged buildings (e.g., the control forest in Rikuzentakata city, [78]). NBS should be considered as complementary solutions.

Engineering-based Solutions: The most common engineering-based physical measures consist of protective structures such as breakwaters (offshore), seawalls (along the coast) and tsunami gates (inland, off-shore) constructed as reinforced concrete barriers with active or passive floodgates; and the design of tsunami resistant buildings (see Subsection 4.4 for vertical evacuation shelters). Breakwaters, even if insufficient to withstand the tsunami, led to an overall reduction in tsunami height and arrival time for the Tohoku 2011 Tsunami [78]. For example, one can mention the Kamaichi Bay Breakwater (destroyed by Tohoku 2011 event) which had a maximum depth below water of 63 m and 8 m height above mean sea level [184]. Seawalls (e.g. [185]), represent a complementary strategy to NBS for coastal defense, as they aim to dissipate tsunami energy and thus help to protect structures and infrastructures from major damage [186]. However, there is limited evidence for the overall effectiveness of seawalls. In the 2011 Japanese tsunami, after the seawalls at Sendai broke, a deluge of foamy water was released into the inundation zone, magnifying the destruction. Tsunami gates can be effective in stopping the tsunami, if the tsunami maximum height does not significantly exceed the gate height. However, according to Suppasri et al. [78]; some of them were under-designed for the Tohoku tsunami (e.g., designed for a 5-m tsunami where the wave height above sea level reached 15 m), thus creating a false sense of security. Moreover, these gates were manually activated, and many firemen lost their lives while activating them. Overall, the lessons learnt from the Tohoku 2011 Tsunami in Japan indicate that these physical measures may be partially effective in buying some time when the run-up exceeds their design height. Nevertheless, in some cases their presence can be a “moral hazard” and give a false sense of security to local people, leading to the perception that engineering countermeasures could provide sufficient protection [187].

Actions can be taken to reduce the damage to physical assets (e.g., buildings and critical infrastructure) and prevent their collapse during tsunami inundation. Damage inflicted by tsunami onshore flow on structures is caused by hydrodynamic forces, buoyancy, and floating debris. Several numerical studies indicate that a typical collapse mechanism for reinforced concrete frame structures under hydrodynamic tsunami loading is the occurrence of shear failure in the columns [188–190]. Actions aimed at strengthening the columns at ground floors can effectively increase the resistance of the structure against the hydrodynamic forces, debris damming, and debris impact. Moreover, the adoption of tsunami breakaway walls can reduce the overall lateral load demand acting on buildings [191]. Innovative materials can also be used for strengthening masonry buildings against tsunami loads [192,193]. The capacity of structures to withstand the hydrodynamic loading will likely decrease during inundation due to buoyancy forces [194]. Buoyancy can cause damage in the form of uplift failures of slabs and decks up to the overturning of the structure, as it was observed in Japan during the 2011 tsunami. Countermeasures to avoid damage due to buoyancy may consist in the adoption of breakaway slabs and of deep pile foundations to increase the overall stability of the structure against overturning. Finally, soil erosion (e.g., scour) during the inundation can cause the local loss of support below foundations, leading to partial structural collapse [195–197]. Solutions for reducing the effects of scour can be to strengthen the building foundations with additional plinth beams or to add a well-constructed apron around the building [198], a protective slab on grade, or the adoption of reinforced earth systems [197]. Empirical observations from past events indicate that deep pile foundations, if properly designed to withstand the strong ground shaking and eventual soil liquefaction (see the counterexample for Tohoku 2011 in Refs. [78,196], generally provide adequate tsunami resistance.

Tsunami building codes: Tsunami design provisions are now included in US design codes through the introduction of a new Chapter 6, Tsunami Loads and Effects, in ASCE 7–16 [197,199]. This design standard has been included by reference in the requirements of the 2018 International Building Code [200]. An extensive guide to the provisions with example applications is now available in Robertson [201]. The ASCE 7–16 tsunami design provisions apply to essential (risk category IV) and critical (risk category III) facilities, and designated tsunami vertical evacuation structures located within the mapped Tsunami Design Zone (TDZ). The TDZs are within the area vulnerable to being inundated by the Maximum Considered Tsunami, defined as having a 2% probability of being exceeded in a 50-year period, roughly equivalent to a 2500-year return period (same as in Italy and New Zealand for evacuation, see Subsection 4.4). Although not required by ASCE 7–16, local communities are strongly encouraged to require tsunami design for taller risk category II buildings (residential, commercial, etc.) in the TDZ to provide additional options of refuge-of-last-resort. This also improves community resilience by ensuring that important and substantial buildings survive the tsunami and can be re-occupied relatively soon after the event. For coastal areas subjected to seismic risk, the design provisions introduce an acceptance criterion based on a comparison between the tsunami lateral load applied and the structure’s seismic design capacity [202]. Specific guidelines for the design of vertical evacuation shelters exist in Japan [203]; summarized by Ref. [204], the United States [205], and Washington State [206]. European building codes, however, do not provide for the tsunami-resistant design of vertical evacuation shelters and coastal structures.

The need for multi-layered physical preventive strategies: Recent tsunamis, especially the Tohoku 2011, have stressed that there are no “one-size-fits-all” preventive strategies. In fact, engineering- and nature-based solutions resulted in certain cases partially/totally ineffective or even hazardous. Therefore, it is important to design multi-layered preventive measures. For example, the seawalls and the tsunami gates can be cost-effective for more frequent tsunamis, whereas, for very strong and infrequent tsunamis, the only effective measure seems to be evacuation. Nature-based solutions are almost always complimented with “grey” solutions such as engineering-based solutions. For instance, the green belts, the seawalls, and breakwaters have been envisioned in a multi-layer tsunami risk reduction planning in Japan [83]; Example 5).

The need for risk-informed (a.k.a. performance-based) design of physical measures: Viable tsunami risk reduction physical measures can be designed so that the structure in question withstands a tsunami event corresponding to prescribed return periods (known as multi-tier design) or alternatively to have an acceptable risk of failure (performance-based design). Both approaches have been included in US building code (ASCE 7–16) but their application has been very limited so far. The performance-based design, which has roots in earthquake engineering (e.g. [207]), relies on code-recommended, socially- or stakeholder-accepted risk thresholds.

The need for validating the effectiveness of physical measures: Despite a large amount of damage observations from recent events, the interaction between tsunami inundation and onshore physical obstacles needs to be much better understood [208]. The inherent complexity of reproducing tsunamis at a laboratory scale has limited the ability to test the performance of structures under realistic loading conditions. More research should be conducted to validate the response of different types of building systems, structural components, and seawalls, also accounting for sheltering and scour effects around buildings.

Enhancing the resilience of critical infrastructures: To enhance the resilience of coastal communities to tsunami, critical infrastructures such as hospitals and schools should be either located outside inundation zones (e.g., Ref. [166]; ideally delimited based on refined PTHA) or designed to resist tsunami loads (e.g., bridges). Hospitals and schools that can sustain tsunami actions can save lives, can be used as shelters in the aftermath of the disaster, and can help coastal communities to return to normalcy in a shorter time.

4.2. Capacity Building and Enhancing Community Preparedness

Preparedness to tsunami requires collective action of communities, school, government, academics, and private sectors through different means of public education; in school curricula, through exercises and drills, by organizing training and capacity-building workshops, or even in forms of inclusions in cultural and religious values [147,209]. Knowledge and skills, governance, evacuation planning, and resource mobilizations (funding, infrastructures, human resources, etc.) are empirical drivers of preparedness [210, 211].

4.2.1. Evacuation exercises and preparedness guidelines

While the success of evacuation depends on collaborative planning (see Subsection 4.4), communities should have adequate tsunami risk awareness, strong participation in planning, and commitment to evacuation plans [212]. Awareness-raising initiatives should emphasize recognizing natural warning signs (i.e. the earthquake shaking, sudden change in sea level, or unusual noise from the ocean) and evacuating when experiencing a 'long or strong' earthquake at the coast (e.g., advice issued by Ref. [213]), which is instrumental for local tsunami preparedness. Another example of local community engagement is the creation of *Te Hikoi a Ruaamoko - Ruaumoko's Walk* [214], which is a bilingual (English and Te Reo Māori) book, based on Ngāti Kahungunu legends, describing earthquake, tsunami and their natural signs to small children through storytelling [215].

Better preparation in this respect might have contributed to saving lives from the tsunami that occurred in 2018 in Palu Bay [96, 216,217]. UNESCO's Tsunami Ready[10] program (based on the US [218] [11]) provides guidelines for communities at tsunami risk to achieve the minimum requirements necessary to be prepared in responding to tsunami threats through preparedness and awareness strategies. UNESCO had facilitated training for facilitators to implement the program in the US, Pacific, and the Caribbean. Another example of a preparedness guideline is the TSUNAMI*Kit* [219] [12] project, which provides checklists and tools for improving community preparedness for tsunamis. Through regular evacuation exercises, one can test the efficacy of evacuation routes and train the population and officials (including first responders).

The need to involve local communities in the evacuation planning: Evacuation plans must be trusted, well-known to, and rehearsed by the local community; if they are to be effective during an emergency (e.g., testing of emergency mobile alert in New Zealand, [220]; citizen science initiative [221]). Rapid evacuation by some communities in the Tohoku 2011 tsunami was credited to high awareness and regular evacuation exercises. Local community involvement was applied successfully in Wellington, New Zealand, which yielded an innovative "blue lines" project in which the edge of a tsunami evacuation zone was indicated by painting a line on roads and generated much publicity about the tsunami risk (e.g., Ref. [165]). Tsunami evacuation exercises are crucial to maintain awareness and familiarize local people with the process and facilitate improvement over time. Tsunami evacuation has been incorporated into state-wide and national ShakeOut earthquake response exercises in coastal areas of the US Pacific Northwest and in New Zealand and could provide effective models for other tsunami-prone regions.

The need to raise awareness of tsunami in tourist spots: Coastal areas with high numbers of tourists face challenges of communicating evacuation information to visitors, who may not speak or read the local language and may not be aware of tsunami risk. The evacuation information should be easily identifiable and understood; by using internationally recognized tsunami hazard and directional signs. Disseminating information about tsunami risk and evacuation protocols is a challenge. Ensuring that the staff in the tourism industry are trained to assist in the evacuation of visitors can be one effective preparedness mechanism. However, this resource is not well-developed for assisting evacuation. For example, in the State of Washington in the USA, which has high seasonal tourist numbers, only 22% of interviewees in the tourist industry said they had been trained about how to respond to tsunami and had tsunami-related information available for guests [222]. More research should be done to understand the potential for the tourism sector to improve tsunami risk awareness and assist evacuation.

4.2.2. Community engagements in the development of early warning systems

Local communities and organizations can actively contribute to improving the tsunami early warning systems. One notable example is the project "Community understanding of the tsunami risk and warnings systems in Australian communities" which was aimed at exploring and addressing the factors that affect community resilience to tsunami in Australia. It was also meant to improve tsunami warning risk communication, thus enhancing the overall effectiveness of Australian Tsunami Early Warning System [135]. Such a project was based on in-depth qualitative interviews with volunteers and members of community, and maritime groups and organizations to support the development and implementation of a community engagement strategy to be used to develop community warning and response strategies. Interviewees strongly believed that no tsunami events would have occurred in Australia, as seismic or volcanic sources were absent. The lack of government discussion and media coverage of tsunami risk in Australia would have strengthened these beliefs, thus resulting in an overall tsunami risk downplaying. This initiative also considered as the opportunity to

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[10] http://itic.ioc-unesco.org/index.php?option=com_content&view=category&id=2234&Itemid=2758.

[11] https://www.weather.gov/tsunamiready/.

[12] https://www.gitews.org/tsunami-kit/index_en.html.

increase public visibility and awareness of tsunami risk issues, also involving volunteers in the development of local level strategy to improve the effectiveness of local warnings as well as community response capabilities.

4.2.3. Financial protection strategies

The relationship established over the years between natural hazards and (re-)insurance industry has become increasingly important for the public and private sectors. Tsunamis typically cause very large losses (e.g., $10 billion USD in the case of Sumatra in 2004, or $300 billion USD due to the 2011 Tohoku tsunami). The (re-)insurance industry has widely adopted probabilistic approaches for risk assessment and pricing activities. PTHA and PTRA can provide a bridge to expand coverage in most tsunami-prone areas by means of risk transfer products (e.g., catastrophe bonds, [223,224]). Disaster risk financing and insurance can alleviate the impact of large events by making funds available for emergency relief, recovery, and reconstruction activities in the aftermath of an event. It can encourage, through contingent funds, programs to undertake risk mitigation measures. Availability of better probabilistic models and data to the insurance industry, who can then more reliably assess the risk, can stimulate more affordable risk financing and insurance, resulting in greater financial resilience.

Limited integration of risk assessment in financial protection instruments: Although the (re-) insurance sector has played an important role in developing a culture of safety, efforts to integrate tsunami risk assessment with financial protection instruments are still limited; an aspect on which insurance practitioners can play a fundamental role.

4.3. Tsunami early warning systems (TEWS)

Under the coordination of UNESCO-IOC, TEWS now cover much of the world's tsunami-prone coastlines, divided into four regions: Caribbean, Pacific Ocean, Indian Ocean, Mediterranean and North Atlantic; all served by regional TSPs, information centers, and national tsunami warning centers.

A tsunami warning system comprises several stages: from event monitoring and detection, to tsunami forecasting and to generation and transmission of warning information, in a consistent and officially verifiable manner, to people who need to be informed [225]. These components are largely technical (decisions to communicate a message may be made by an official), but technical solutions alone cannot generate the desired and effective evacuation from places at risk. An effective response requires planning, discussion and communication, education and equal participation, and exercises –all underpinned by scientific research and advice, besides periodic evaluation of the warning effectiveness [225].

Tsunami warning systems should be tailored to the type(s) of tsunami threats faced by the coastlines in its jurisdiction (e.g., the prevalence of local or distant events, type of sources). A far-field tsunami can be detected and possibly characterized by sea-level data well in advance of tsunami arrival, providing opportunities for disseminating official warnings via multiple channels and executing planned evacuations. In contrast, near-field tsunamis may arrive at the shore only minutes after the triggering earthquake, leaving minimal time to process and disseminate official warnings, in a regime of higher uncertainty, with only the early estimate of magnitude and location of the earthquake source available. Besides improvements to technical components of warning systems, continued improvements to the effectiveness and sustainability of siren networks, mobile phone alerts, and other disruptive technologies, and related evacuation plans could help to maximize evacuation response to future events (see also Subsections 4.2 and 4.4). For scenarios characterized by extremely short lead-time, below 10 min, self-evacuation would be the most effective way in saving lives (see lessons from Table 2), while the official warning information can still be useful to confirm whether a tsunami had occurred, to activate the post-disaster responses.

4.3.1. TEWS for local seismic tsunamis and uncertainty

Progress in seismic and geodetic methods (e.g. Refs. [62,226–228]), enhanced tsunami monitoring (ideally as close as possible to the source to reduce uncertainty; thus, highlighting the importance of having a dense array of monitoring devices) [229,230], and data assimilation techniques without source reconstruction [231–233] all contribute to dealing with the challenge of EW for local tsunamis. Uncertainty treatment and involving decision-makers may allow gaining some lead time in a rational manner [22,95,152,234–239]. Apart from those related to the tsunami source, uncertainty sources affecting rapid inundation mapping stem from inaccuracy/unavailability of high-resolution topography and near-shore bathymetry, numerical model limitations, and their computational cost. The inherently transnational character of TEWS demands enhanced data exchange mechanisms, procedural harmonization, and local high-resolution data and model availability as a complex task; sometimes dealing with political barriers and decentralized decision-making.

4.3.2. TEWS for atypical sources

Tsunamis originating from non-seismic sources (e.g., submarine or subaerial landslide, or volcanic) or non-typical seismic events (e.g., slow tsunami earthquakes or crustal faults, including strike-slip faults) may not be easily detected and even if detected it may be difficult to constrain them. They can have a localized but significant run-up, with very little time for warning or evacuation, like for tsunami earthquakes which have weak seismic precursors [65] or difficult-to-predict faulting mechanisms [152], like the above-mentioned 2018 Palu-Donggala tsunami triggered by strike-slip faulting close to the affected area (see Subsection 2.7). In areas susceptible to slope failure, local tsunami warning systems could be designed; for example, by integration with local slope stability monitoring at collapse-prone slopes such as volcanoes or moving rock slopes (e.g, Anak Krakatau 2018, [240]; Stromboli 2002 & 2019, [241]; Aaknes and Lyngen Norway, [152,242,243]). In areas prone to atypical seismic events, specific seismic characterization tools should be fully integrated (e.g., Refs. [22,240,244,245]). In such a context, enhanced synergy and coordination between local and regional authorities is mandatory. A general approach to early warning for tsunamis generated by submarine landslides is probably still out of reach. Self-evacuation capacity, without waiting for an official tsunami warning is paramount in such cases [96]. This requires extensive capacity building campaigns (see Section 4.2) aiming at increasing situational awareness and preparedness among the local population to tsunami from atypical sources. These campaigns should aim to prepare the population in the coastal areas to recognize the natural signs of an imminent tsunami (e.g., a strong or a very long earthquake, a moderately strong earthquake).

4.3.3. *Real-time impact forecasting*

Contemporary tsunami early warning systems provide forecasting conveyed in the form of graded warning levels (e.g., *advisory*, *watch*, *warning*); which, in turn, are based on *physical* impact at the coast, such as offshore tsunami surface elevation and run-up. More detailed estimates with direct on-the-fly inundation modelling may also become an option with emerging HPC-workflows and/or exploiting machine learning (e.g., Refs. [246–249]). Information of modern TWS does not encompass *economic and societal* impacts such as the expected amount and distribution of damage to buildings and critical infrastructures, human loss, disruption of services, or financial loss, preventing quantitative risk assessments. Merz et al. [250] review for various natural hazards concluded that complementing early warning systems with impact forecasts would bring a twofold advantage: (1) provide richer information to make decisions about emergency measures and (2) boost the development of multi-hazard early warning systems since extreme events usually involve multiple hazards, and their consequences need to be considered in a multi-hazard framework. Steps in the direction of impact forecasting are exemplified by Oishi et al. [246] and Koshimura et al. [251].

4.4. *Evacuation planning*

Evacuation planning is one of the most important measures to increase the tsunami preparedness of coastal communities. Evacuation plans and maps (e.g., Tsunami Ready Hotels in Bali, TSUNAMI*Kit* [219]; CDEM evacuation zones New Zealand; Italian evacuation maps, [164,241]; see also Subsection 4.1) should clearly identify the evacuation zone(s), inform coastal residents and visitors of safe evacuation routes (via maps and street signage) and recommended mode of travel (generally on foot, since vehicle evacuation has been shown to cause congestion). They should clearly identify “safe” zones depending on the severity of the expected threat(s) (e.g., Ref. [165]); possibly including walking times and arrival times (e.g., Washington State pedestrian walk-time maps). “Safe” zones are generally located on high ground, above the maximum expected tsunami run-up height in that area. If the natural high ground is not close enough to be reached, vertical evacuation may be included in plans. This requires the definition of suitably tall, earthquake- and tsunami-resistant buildings or purpose-built towers, which can withstand the forces of the tsunami and have the capacity to host evacuated people at a height above the tsunami inundation range.

Vertical evacuation buildings may be buildings with another regular use, but should be clearly signposted, assessed by engineers through formal design procedures (see the paragraph in Section 4.1 on Tsunami Building codes) to be of sufficient height and strength, be always accessible in an emergency, and have welfare provisions for evacuees ([252,253]; see also Subsection 4.1.2). Planning vertical evacuation is essential for low-lying areas subject at risk of the local tsunami (e.g., Cascadia, US; Tohoku, Japan; or Hikurangi, New Zealand to name a few, and virtually all the coastlines of the NEAM region) and should involve designating buildings based on simulated evacuation times and clearly communicating to the community which buildings can be used for vertical evacuation. A plan must also communicate the need to remain in the safe locations until given the “all clear” (i.e., it is not safe to return to the hazard zone after the first wave because tsunami comprises multiple waves and it is possible that the first wave is not the largest).

Evacuation drills (Subsection 4.2), simulation, and mapping are key elements of evacuation planning. Once the potentially inundated area is identified and designated as an evacuation zone(s), the time required for the population to evacuate the zone(s) can be either simulated or tested in practice based on the definition of evacuation procedures (e.g., routes, safe locations, shelters). The information coming from detailed PTHA such as tsunami inundation depths and tsunami arrival times can be quite useful for evacuation planning (e.g., Ref. [254]). In fact, the scenarios used for evacuation planning are usually hazard-informed. The need for use of evidence provided by PTRA in scenario-based evacuation planning is a recognized gap [168]. Different approaches can be used to simulate evacuation. The most common tools are agent-based models (ABM) (e.g. Refs. [255–258]), and least-cost distance (LCD) models. Anisotropic (accounting for the impact of slope on travel speed) LCD models were developed by Wood and Schmidtlein [259] to understand the potential for pedestrian evacuation in US Pacific Northwest, applied to understand the need for vertical evacuation in Napier, New Zealand [260], and developed and applied in the Balearic Islands and the Caribbean ([212] and [261]). It should be mentioned that application of such methods requires detailed exposure data, which is not available in many situations. It is nevertheless important to also observe and compare the different evacuation behaviours during tsunami drills, and that of real events [96]. The citizen science initiative documented in Blake et al. [221]; studies (through a post-event survey) the different evacuation behaviours in response to the local-source 2016 Kaikōura Tsunami amongst two coastal communities affected by the tsunami.

4.4.1. *Dynamic exposure and vulnerability mapping*

In many coastal locations, the population can be extremely variable from day to night, or between seasons if the economy relies on tourism. Coastal locations may also be heavily populated with visitors unfamiliar with local risks or evacuation routes. Evacuation planning should ensure that routes and shelters are able to serve the maximum potential population at any given time, and that information is accessible to and understandable by visitors (Subsection 4.2). Some examples of evacuation planning or simulation in the USA are based on information about the number of people exposed to tsunami risk and identification of demographic sensitivity to evacuation including variable walking speeds and requirements for assisted evacuation [83,260].

4.4.2. *Tailoring evacuation strategies to local conditions*

All stakeholders need to collectively consider how local services (e.g., public transport, schools, etc.), businesses, and public administration may be affected by an earthquake preceding a tsunami evacuation and develop plans to manage the response of a combined event. Physical obstacles, network, and systemic disruptions (e.g., collapsed buildings, roads closed by first tsunami arrival, traffic jams), potentially secondary hazards in the case of local earthquakes (e.g., liquefaction, landslides) need to be considered. It is important to involve in planning local scientific agencies and the immediate local community, who can recognize locations that may be potentially hazardous or cause bottlenecks in evacuation or recognize local routes that could improve evacuation.

4.4.3. *Considering the human response*

Evacuation planning should incorporate the range in the behaviour of the population following a warning or local earthquake [262]. It is crucial to consider the speed at which various groups (e.g., elderly, disabled, those with children) can evacuate relative to unaccompanied and healthy adults, the time required to begin evacuation, preferred or default mode of transport, and whether people decide to or are able to evacuate. Human response delays evacuation through information seeking or attempting to unite family groups [263–265]. In areas at risk of earthquake-induced tsunami, plans should consider that people may not be able to move until the shaking ends. These significant reductions in evacuation time should be considered when planning how far people can travel on foot in a limited time. Gender, age, income levels, and ethnicity may act as significant factors in the response capability of a population with respect to awareness levels and access to facilities as a case study in Padang city, Indonesia revealed [146].

4.4.4. *Considering appropriate scenarios/hazard information*

In Japan, before 2011, evacuation plans had been drawn up on a worst-case scenario basis (see Subsection 2.5), envisioning evacuation zones and shelters to protect the population, based on the (distant) 1960 tsunami. In fact, in 2011 a larger-than-expected (local) tsunami occurred and several shelters were inundated. Where numerical tsunami hazard modelling is incorporated, deterministic scenario-based assessments are more commonly applied and operational (mostly worst-case scenarios). Nevertheless, there are examples of evacuation maps based on PTHA (i.e. for a uniform hazard level); New Zealand based on the national PTHA [165] and Italy [164] based on inundation maps for a design mean return period (e.g., 2500 years) and prescribed level of epistemic uncertainty (e.g., 84th percentile). Deterministic worst-case tsunami scenarios, especially when based on the largest past event, may lead to underestimation, and correspond to an unknown return period (hazard/risk level). Rigorous PTHA allows planning for a prescribed hazard/risk level and can be integrated with a cost-benefit analysis by decision-makers.

4.5. *Recovery planning*

4.5.1. *Building back better strategies*

The concept of *Build Back Better* (BBB) was introduced during the 2 nd year commemoration of the 2004 catastrophic tsunami and was later adopted by the Sendai Framework for Disaster Risk Reduction. BBB was predominantly interpreted as building back better infrastructure. Recently, the concept of “build back greener” has been used for post-disaster recovery in Japan to improve resilience by adopting nature-based solutions [266].

The vulnerable communities could be even more susceptible or become further marginalized in post-disaster situations. The problems related to returning to “normal” life are often accumulated with social, economic, and political vulnerabilities. If not carefully considered in long-term risk assessments, the process to build back better would potentially fail. Building back better implies also improving human wellbeing, a notion often taken for granted. For example, building superior housing units in indigenous communities could compromise local needs and desired functionalities, as exemplified by Moken communities in Thailand. Forced relocation to areas with lower tsunami risk could threaten livelihoods and potentially lead to land tenure conflicts [57,267,268]. These considerations need to be carefully tailored in strategic decision-making.

4.5.2. *Efficient use of funds from financial protection instruments*

The recovery process and the overall impact on the development of the affected area after a disaster are heavily dependent on the existence of ex-ante mechanisms to cope with the economic losses. Incorporating PTRA components in catastrophe modelling (e.g. Ref. [269]), will facilitate impact assessments of future household welfare. Specific financial protection instruments (e.g., disaster funds, catastrophe bonds, (re) insurance policies) should enable public and private sectors to minimize the costs, without the need for budgetary reallocations, the introduction of new taxes, or relying on external aid. The use of these resources needs to be planned; making clear distinctions between the amounts to be used in the emergency and reconstruction phases, as different phases of good disaster governance. During the reconstruction stage, the main requirement should be avoiding “reconstructing vulnerability”; meaning that all repaired/reconstructed assets should include the minimum characteristics to guarantee a good performance in future events.

5. Discussions and conclusions

Despite a progressively better understanding of tsunami hazard and risk, in the last few decades, tsunamigenic episodes continued to be a stress test of the existing countermeasures with often grave consequences. Coastal development and tourism, in recent decades, have increased the exposure to tsunami hazards in several areas. A significant tsunami, for example in the NEAM region which is characterized by a generally low level of tsunami risk perception, may have complex consequences to global security due to the humanitarian crisis and political instability that may be triggered as a result of the catastrophe generated by the earthquake and tsunami. Even moderate tsunamis may have severe consequences at the local and regional levels. Nevertheless, risk awareness is limited, particularly in places where a major catastrophic event has not occurred over a significant period. Moreover, and specifically for Europe, coastal populations have inadequate risk perception and do not consider that similar or larger tsunami disasters that occurred in the past could happen again in the future. This inadequate level of perception is also due to the relatively lower occurrence rate of tsunami with respect to other natural hazards. This is one of the reasons why the tsunami risk has never reached a high priority in the eyes of policy makers.

Risk perception is directly related to the way risk is communicated (Fig. 1). Furthermore, the lack or an insufficient level of risk perception generally maps into an inadequate level of disaster preparedness. This is especially true for preparedness to tsunami risk and underlines the central role of risk communication in increasing resilience to tsunami. In fact, risk communication needs to move on from traditional one-way communication models (e.g., scientists communicate the scientific results to the society) to models that envision constant dialogue and active participation of all the societal actors (as shown in Fig. 1). Moreover, understanding of tsunami risk, risk communication and management should interact as parts of an integrated and circular risk governance framework (Fig. 1). In this integrated governance framework, communication which is tightly related to risk perception, is relevant to all of the different stages encompassing the understanding of tsunami risk and the measures adopted in a "risk-informed" management frame (Table 1). This is a very relevant issue within the risk management field, as decisional processes rely on different understandings and perceptions of tsunami risk. Scientists, decision makers, stakeholders and people who live in coastal areas need to refer to the same concepts: *risk communication should ensure a common and shared understanding of tsunami physics, of type of effects and of inherent probability and uncertainty as a pre-condition to enable informed and aware choices.*

In concrete terms, this review highlights an imperative need for implementing further research on tsunami risk perception and awareness, as an indispensable base to ground any sound risk communication strategy. Secondly, it suggests that risk communication methods based on PTHA/PTRA could be effective means of improving people's perception of tsunami risk. This would entail communicating the probabilities associated with specific tsunami intensity levels being exceeded, and communication of anticipatory natural signs of an incoming event and its possible impacts for both large and moderate events. Thus, it challenges misleading yet widely shared commonplaces on tsunami as a destructive and devastating event that leaves very little space for individual and societal response. Third, this paper advocates improved awareness and understanding of tsunami as a logical pre-condition to establish and operate more effective mitigation measures (evacuation plans, drills, community planning and so on).

An alternative, broader approach to risk communication should be considered as potentially relevant to all risk-related messages that flow through different communication networks as evidenced in Table 1 (e.g., mainstream media, interpersonal communication, public events, social network platforms), regardless of the source and the recipient. Such a broad approach should accommodate multi-hazard and risk assessments (understanding of risk) to achieve higher degree of risk perception among the target audience, also improving familiarity, confidence, and trust towards scientific sources. This broader understanding of risk communication includes mainstream media contents (including news, documentaries, movies, arts and music, and other fictional products), school and educational booklets, advertising, press releases, technical documents, including social media platforms and, discussions between and amidst scientists, decision-makers, lawmakers, media, civil society, local groups of interest, private sectors, and relevant industries such as tourism and fisheries. Whereas some of these communication tools are similar across various hazard settings, the need for targeted tsunami risk communication remains pivotal, as the context differs significantly. For example, distinct differences between earthquake (e.g. building codes, duck-hold-cover, earthquake early warning system) and tsunami (e.g. safe ground, vertical evacuation, tsunami early warning system) risk mitigation plans should be also reflected in the respective communication plans, preferably in a holistic manner.

Some of the challenges that need to be addressed, related to *understanding tsunami risk* and risk-informed *tsunami risk management* (the two spheres depicted in Fig. 1) are listed below.

- It is important to reflect on the trade-offs of risk governance based on scenario-based versus PTHA/PTRA approaches. As far as it regards understanding of tsunami risk, scenario-based approaches provide efficient and pragmatic means of assessing socio-economic impact of tsunami and it might be more straightforward to communicate the results to the population. On the other hand, approaches based on PTHA/PTRA consider the full range of plausible events and their likelihood (hence, provide more information about the uncertainties) and involve very heavy computational efforts. Nevertheless, communication of probabilistic concepts to the population is challenging and needs further attention and research. As far as it regards risk management, the scenario-based approaches are currently the basis for tsunami risk management decision making. However, the scenario definition is becoming increasingly hazard-informed. Further transition towards risk-informed scenario definition is a subject for further research.
- PTHA/PTRA naturally challenge people's understanding of tsunami risk, making it necessary to rewrite tsunami risk communication rules. First, experience from 2004 Indian Ocean and 2011 Tohoku tsunamis, along with a few smaller events like those occurred in Greece and Turkey in 2017 and 2020 make clear that it is unrealistic to expect that people would properly react and evacuate to tsunami natural signs or to unexpected tsunami alert if not prepared long before. Second, people's understanding of tsunamis appears to be biased by images of a big, catastrophic stand-alone event rather than the more realistic idea of events that have different characteristics and have various ranges of intensity. In such cases, PTHA/PTRA bring such issues to the table and offer potential opportunities for the public to understand tsunami risk better.
- There is a general lack of coordination and reference guidelines on how the information from hazard and risk analysis (e.g., PTHA, PTRA) can be translated into policies and operational practice. When available, most PTHA and PTRA studies focus on earthquake-generated tsunamis. Moreover, there is a lack of established methodologies for strategic planning in a multi-hazard and multi-risk context, in which tsunami is one of the potential contributors. Furthermore, research is needed related to establishing acceptable risk levels for land-use planning purposes. The acceptable risk levels are in general defined based on safety considerations for buildings, which have a central relevance in seismic risk management and decision-making. Hence, risk-informed land-use planning for tsunami needs to establish its own tailor-made risk acceptability criteria, to be translated into return periods and design scenarios.

- Risk-informed design of physical countermeasures poses several challenges and questions about their overall effectiveness in protecting the population. There is no one-size-fits-all physical countermeasure for tsunamis. It is desirable to design multi-layered physical protection measures to consider various plausible tsunami scenarios for different return periods. This is perfectly in line with the risk-informed "multi-tier" buildings design adopted in the American building code (ASCE 7–16). Yet, there is a need for the provision of harmonized tsunami-resistant design of coastal protection infrastructure and vertical evacuation shelters in the European codes, which are also integrated harmoniously into daily social functions. The design of physical measures needs to consider the local context and the social aspects. For example, the very presence of the physical countermeasure (e.g., a breakwater or a tsunami gate) can provide a false sense of security to the population or in some cases may obstruct the view of the imminent tsunami waves. These aspects need to be considered in both the design of the physical countermeasures and capacity building activities aiming at raising awareness. It is important to convey the message that, despite the presence of physical countermeasures, evacuation (horizontal and vertical) remains the most effective means of reducing casualties due to a very strong tsunami.
- Evacuation plans need to be co-designed with local officials and communities to ensure that the information communicated about routes, shelter locations is accurate, relevant, and trusted. Community preparedness including evacuation exercises should be periodically undertaken as local government policies and be periodically assessed and improved. To boost financial preparedness for tsunamis, there is a need to streamline and homogenize the implementation of PTRA and multi-hazard risk assessment in the (re-)insurance industry. As mentioned before, evacuation remains the most effective means of saving lives for very big tsunamis. This gives special relevance to capacity building activities aiming at raising awareness and increasing preparedness of the population to tsunami.
- For local tsunamis with lead time in the order of minutes, self-evacuation capacity is a requirement. There is very limited time to process and disseminate official warnings in a regime of high uncertainties which is not always explicitly dealt with. Moreover, tsunamis originating from non-seismic sources or non-typical seismic events may not be easily detected for a timely warning. There is an urgent need to improve awareness of the natural signs preceding tsunamis, enabling people to recognize the danger and take proper actions (e.g. avoid lingering on sea shore when sea is withdrawing). In general, the closer the tsunami sources are, the more important it will be for the communities to have self-evacuation capacities. For such cases, official tsunami warning can serve as a confirmation on whether a tsunami had occurred, and to also inform at which point the communities exposed can return home after the tsunami threats are all cleared/terminated. In general, interoperability between local and regional, and inter-regional warning systems is imperative. The next generation of TEWS may consider moving towards systems that integrate hazard forecasts with information about vulnerability and exposure. Extension of TEWS products for communicating potential impacts has also been identified as a future direction.
- There is a need to develop standards for evacuation planning approaches, which incorporate: PTHA to define as robustly as possible the range of potential inundation from local, regional, and distant sources; selection of multiple scenarios from which to compute arrival times and onshore flow depths; and application of these in risk assessment for multiple plausible exposure scenarios. Testing the sensitivity of evacuation dynamics such as response to local earthquake versus response to official warnings, and the impact of vulnerability related to evacuation potential and the required time (due to gender, age, disability, visitors, presence of cars), and at the same time strengthening capacities of self-evacuation, is recommended.
- Returning to 'normal' life in the aftermath of a disaster is often hindered by socio-economic and political vulnerabilities. Building back better strategies need to interpret the concept as building back well-being and capacities –not just physical infrastructure. Therefore, ideally, future programs would be informed by risk assessments that incorporate these contextual vulnerabilities. Being prepared to build back better corresponds also to the availability of and access to funds from financial protection instruments, ensuring a swift and timely return to normal life minimizing impacts on fiscal stability, wellbeing, and/or development goals. In most cases, the general lack of vulnerability and exposure data in developing countries leads to high uncertainties that can make insurance unaffordable. Improving knowledge of the risk can make risk financing and insurance a more accessible solution for financial resilience to governments.

Relevant studies on tsunami risk communication and perceptions are still much needed, building from a solid understanding of evacuation behaviours, including those corresponding to both large scale and moderate tsunami events, the different responses between the natural and official warnings, and also on how public education can make significant differences. With the wider use of probabilistic hazard and risk assessment, and by incorporating these studies, one could potentially help to improve risk communication and continuous public education practices.

Author contributions

All Authors contributed to the early stages of the manuscript by individual contributions from their respective research fields. Major contributions are listed as follows: Early compilation of text: FJ, IR, AC, LC, MB, DS, IAA, ÖN, FL, SL, MS, JS, JB, MDZ, SB, IAQ, AA; Abstract and Conclusions: IR, FJ, DS, ÖN, MSG; Introduction: IR, FJ, AC, LC, MB, DS, FL, AB, UH, IAA; Lessons Learnt: IR, FL, AB, DS, MB, MS, FJ, SL, JB, IRP, AA, IAA; Risk Communication: AC, LC, IR, ÖN, SL, DS, AB, FL, IRP, JB, AA; Preventive Measures: FJ, MB, ÖN, MDZ, SB, IAA, FL, IAQ; Capacity Building and Preparedness: IR, SF, MASG, AB, FJ, IAA; Early Warning: SF, SL, IAA, MB, AB, JS, FL, RDR, ÖN; Evacuation Planning: IAA, SF, SL, JS, FJ, AB; Building Back Better: IR, MASG, FJ. Substantial revisions: IR, FJ, AC, SL, AB, ÖN, FL, DS, LC, SF, MASG, IRP, MB, RDR, MDZ, SB; internal review: all authors.

Funding

This article is based upon work from COST Action CA18109 AGITHAR, supported by COST (European Cooperation in Science and Technology). IRP obtained support through the Royal Society, UK (grant number CHL\R1\180173). MASG acknowledges the support through the Severo Ochoa Centers of Excellence Program (CEX 2018-000797-S) funded by MCIN/ AEI /10.13039/501100011033. DS acknowledges support from the Lloyd's Tercentenary Research Foundation, the Lighthill Risk Network, and the Lloyd's Register Foundation-Data Centric Engineering Programme of the Alan Turing Institute.

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.

Acknowledgments

This highly interdisciplinary work is made possible with strong teamwork from all the contributing researchers, scientists, and practitioners. We would like to also thank all the members of COST Action AGITHAR for ideas, conversations, interactions, and dialogues in the topic of risk communication and management, during and beyond AGITHAR workshops. The authors would like to thank Dr. Sally Potter –GNS New Zealand for her review.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2021.102771.

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