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Enabling people-centered risk communication for geohazards

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Enabling people-centered risk communication for geohazards

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Editorial: Enabling people-centered risk communication for geohazards

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Editorial on the Research Topic
Enabling people-centered risk communication for geohazards

Introduction

In the field of natural hazards, communicating science with the public and stakeholders (i.e., interested parties) involves entering the challenging and complex world of hazard and risk communication, the ultimate purpose of which is to reduce the impact of impending hazards on people and property at risk. Hazard and risk communication are adequate if they reach people with the information that they need, at the right time, and in a form that they can use. This task appears to be particularly difficult when decisions by the public and stakeholders have to be made in the presence of uncertainty about what could happen, as is often the case with geohazards. Moreover, decision-making is complex when there are time pressures, human and economic resources are limited, and multiple sources of information need to be considered. This poses several challenges for the development of two-way and people-centered risk communication for geohazards.

The "Enabling People-Centered Risk Communication for Geohazards" Research Topic analyses these challenges and identifies innovative pathways to address them. More precisely, it draws together 13 state-of-the-art articles from around the world on improving communication practices, strategies, and understandings relating to a range of various geohazards and weather-related hazards.

Summary of papers

The first two papers we discuss are meta-analyses of tsunami risk and earthquake early warning system perceptions. Cugliari et al. provides a review of tsunami risk perception studies from around the world and found that although lower severity tsunamis are damaging, they are not regarded as dangerous by the public. They note that it is important to use local terms for tsunamis to improve communication, and they found that more assessments of tourist risk perceptions is needed, and a more homogeneous survey data collection strategy can be used worldwide to enable global comparisons. Tan et al. reviewed 70 manuscripts relating to earthquake early warning (EEW) systems and found that the role of stakeholders' involvement in developing EEW systems is an important factor to consider when assessing the benefits of these systems. Further research on EEW is needed to enhance public understanding, examine earthquake resilience benefits, and investigate best practices for engaging, educating, and communicating with the public.

Five articles in this Research Topic focussed on social media. Stovall et al. and Goldman et al. describe the approach used by the U.S. Geological Survey (USGS) for managing social media during the 2018 Kīlauea eruption in Hawaii. The former describes the details of the social media strategy formed and used during the eruption, finding that the use of Facebook and Twitter platforms acted as a virtual community meeting, with timely conversations able to take place. The latter analysed the USGS Facebook posts and comments throughout the eruption and found that users expressed positive sentiment for the communications and that the communication was effective at answering questions and correcting misunderstandings. Fathi and Fiedrich present the use of a Virtual Operations Support Team (VOST) initiative to assist situational awareness of personnel in Emergency Operation Centers (EOC) in a case study for a flood in Germany. By monitoring social media platforms and interviewing decision makers, they found that the integration of VOST information into EOC improves perception and comprehension of decision makers. Pignone et al. describe the development and use of a social media platform developed by the National Institute of Geophysics and Volcanology (INGV) in Italy to aid two-way communication between scientists and citizens. Consisting of a coordinated suite of social media channels and a blog, the platform enables regular updates and for misinformation to be addressed. The development and use of a social bot to provide rapid answers to users' questions after an earthquake is described by Bossu et al. The social bot has helped to fight against misinformation and enhance risk awareness and preparedness.

Three papers looked at misinformation and rumours relating to earthquakes. Dryhurst et al. elicited opinions from scientists to categorize common public statements about earthquakes as misinformation, debatable, or supported by scientific consensus. Findings reveal the need to clarify whether earthquake prediction are deterministic or probabilistic and specify key parameters (e.g., induced *versus* naturally occurring) as well as the magnitude of the earthquake. Fallou et al. describe the Euro-Mediterranean Seismological Center (EMSC) experience in addressing misinformation during two earthquake case studies, describing how EMSC has improved their communication strategies. The strategies used by scientists to combat rumours in another case study in Italy are described by Crescimbene et al. They found that multi-agency coordinated outreach meetings with communities have helped build relationships on several occasions.

In a similar vein, Rödder and Schaumann studied interdisciplinary collaborations and engagement with stakeholders in tsunami-related fields. Their interviews indicated that there is strong collaboration between engineers and scientists, while interactions with social scientists and stakeholders is still limited.

The final two papers that we discuss are on the topic of citizen science in the communication of hazards. The strengths of web-based flood information portals were analysed by Mostafiz et al. They found that social media, citizen science, and mass media allow flood information to be communicated for short-term benefit, but a tool is needed to widely communicate flood information for long-term planning purposes. Citizen science was found by Tan et al. to have a potential role in response to high impact weather, based on the results from two workshops. Despite the challenge of data quality control, citizen science projects can contribute along the chain of observations; weather, hazard, and impact forecasts; warnings; and decision making. An additional benefit of citizen science is increasing awareness and creating a sense of community to help bridge gaps along the value chain.

Conclusion

By drawing together 13 state-of-the-art articles, this special Research Topic provides an overview of old and new challenges in risk communication for geohazards. Examples of these challenges include managing mis- and dis-information effectively, monitoring social media, formalizing involvement with stakeholders, communicating across disciplinary boundaries, leveraging social media platforms, and encouraging citizen science. The articles analyse these challenges and often identify innovative solutions to address them. By doing so, they provide contributions not only to enable people-centred risk communication for geohazards, but also to consolidate risk communication theories and methodologies.

Author contributions

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Actionable Information in Flood Risk Communications and the Potential for New Web-Based Tools for Long-Term Planning for Individuals and Community

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Because of its ubiquitous nature and catastrophic impacts, flood information should be readily available and continually evaluated, to maximize utility for the public and professionals. Web-based tools can fill existing needs for actionable information to inform decisions regarding flood damage mitigation for new and existing structures. The goal of this research is to identify the current capabilities, gaps, and future demands of Web-based flood communication systems. To understand the current and potential niche of Web-based flood tools, a review of the literature concerning the effectiveness of mass media, grassroots-based "citizen science" efforts, and social media in communicating flood risk is conducted. Then, the strengths of 50 major, freely-available, Web-based flood information portals are reviewed. Results suggest that mass media often provide actionable information, especially for short-term benefit immediately before, during, and immediately after the flood for individuals and community leaders. Citizen science and grassroots efforts encourage planning strategies to prevent or mitigate flood. Social media is most beneficial in raising awareness of the flood hazard and communicating short- and long-term mitigation and adaptation strategies. However, while mass media, citizen science, and social media have revolutionized the way that people plan for, survive, and recover from floods, their utility is largely restricted to addressing short-term information needs at the meso-scale or broader and/or conveying information about singular events to scientists and/or other professional interests. Actionable information to inform long-term planning and mitigating flood, for both the public and community leaders, remains lacking. A particular need is for communication mechanisms that satisfy several criteria simultaneously: wide broadcast, appealing delivery method, and focus on enhancing decision-making for long-term needs rather than solely for short-term benefit. Particularly useful would be a new, webtool that provides sufficient functionality to enhance flood risk reduction decision making, considering both the costs and benefits of mitigation.

Keywords: web-based tools, website, flood insurance and cost, flood forecasting and monitoring, flood zone, social media, mass media, citizen science

INTRODUCTION: COMMUNICATION FOR MINIMIZING FLOOD RISK

Perennially the world's most ubiquitous and expensive natural hazard, flooding increases in notoriety as populations and economic investment in coastal and other flood-prone areas continue to climb sharply (Dewan et al., 2006; Bushra et al., 2021). One way to enhance flood risk preparedness is through improved flood risk communication (Maidl and Buchecker 2015), especially that which provides actionable information such as previous, current, and future flood damage (Mostafiz et al., 2021a) and hazard risk, mitigation and adaptation approaches, and cost-benefit analysis. Actionable information enables informed decision making for disaster preparedness, mitigation, response, and recovery. Among the challenges in this regard are that judgments about whether a piece of information is actionable vary (Zade et al., 2018) and that "actionable" information must be filtered from "noise" (He et al., 2017), although automated categorization information based on actionability is possible to assist with these challenges (Zahera et al., 2021). Technological advances and enhanced grassroots efforts have traditionally improved communications regarding the flood risk, before, during, and after flood disasters. Such endeavors *via* mass media, citizen science, and social media are helpful but continue to fall short in some ways, as evidenced by the fact that losses in flood-prone areas continue to increase (Mostafiz et al., 2021b, 2021c).

The overarching goal of this research is to identify the publicly available, actionable information on existing flood risk communication tools that might help to fill the communication gap regarding the flood hazard. To accomplish this goal, we address three questions about communicating the flood risk: 1) What information exists about the success (or lack thereof) of various vehicles for communicating the flood hazard and their effects on flood hazard mitigation? 2) What actionable information is available online and required for citizens and community leaders? 3) What is the functionality for the intended users of online tools to provide actionable information to aid flood risk reduction decision making?

To support the goal, this research addresses the gap in summarizing and synthesizing the existing literature. We analyze strengths and weaknesses in each of the traditional areas of mass media, citizen science and other outreach, and social media, vis-à-vis flood risk communication. We then review online webtools that can address some of these existing gaps, with emphasis on analyzing the strengths and areas for improvement of existing Web-based portals, particularly as these relate to functionality for the intended user. Finally, we discuss the actionable information needed for laypeople and community officials to enhance long-term flood planning and mitigation strategies to build safer structures and reduce flood loss. This research provides a snapshot of the current state of flood risk communication, so that in future years when such websites are no longer available or are in greatly changed form, the scientific community will have a documentation of the state of the science and art in 2022.

ACTIONABLE INFORMATION

Actionable information as defined here refers to relevant data that span flood magnitude and occurrence, damage resulting from flood hazards, alternatives to minimize flood damage, and the associated cost of these alternatives. The time scale on which information can be "actionable" ranges, but a distinction can be considered here between short-term and long-term actionable information, with "short-term" referring to information that informs decisions in the immediate preparation and aftermath of the flood hazard, and "long-term" referring to that information that is useful for mitigating the impacts of the hazard, at the preparation or recovery stages. This distinction is important because short-term actionable information enhances the prospect of survival of the hazard, while long-term actionable information enhances resilience. In addition, both short- and long-term information can be characterized based on the primary intended audience of the message. Here we distinguish only between "individual-" and "community-" level audiences, with the former dominated by homeowners or prospective homeowners concerned about enhancing flood resilience for their investment and the latter consisting of elected officials, builders, and planners seeking to enhance the quality of life for their constituents. The present research directly considers the following as specific types of long-term actionable information, at both the individual- and community-level, against which the risk communication outlets are measured: hazard properties (i.e., flood frequency and magnitude), effects of hazards (i.e., flood damage and loss), mitigation options (e.g., flood barriers), structure resiliency (e.g., elevation, wet flood proofing), effectiveness of combinations of both hazard and building mitigation (e.g., sandbag plus elevated structure) customized for the individual's particular situation (e.g., livable area, presence of basement, number of stories, length of time that the user plans to use the structure, whether structure is insured and if so, amount of coverage and deductible), community information (e.g., community rating system (CRS) score and steps needed and benefits of enhancing the community's rating, existing community freeboard requirements), and economic parameters (e.g., interest and discount rates, mortgage period).

MASS MEDIA EFFECTIVENESS

The wide audience of mass media allows it to provide critical information for short-term flood mitigation and response, particularly at the individual level, such as in broadcasting official forecasted flood warnings and in post-disaster relief distribution. Altinay et al. (2021) reminded that mass media can also assist in long-term flood communication, particularly by informing risk perception (e.g., Wahlberg and Sjoberg 2000; Fleming et al., 2006; You and Ju 2017; Martins et al., 2019; Heidari et al., 2021) and disaster preparedness (Tekeli-Yeşil et al., 2011). In general, consumers tend to feel that mass media provide more information about natural hazards that are experienced locally and frequently (Karanikola et al., 2015). The demand for mass media-generated public information, including a widening scope of roles, increases during and after disaster events (Miller and Goidel 2009).

Sources of information broadcasted *via* mass media vary widely in degree of expertise, influence, and perceived credibility, including topical experts, community leaders, public eyewitnesses, and anecdotal comments from broadcasters or citizens. The extent to which expertise/influence of the source (Takahashi and Tandoc 2016) and the admission of uncertainty in broadcasted statements (Gustafson and Rice 2019) affect public credibility has been examined. However, differences in perceived trust of such sources regarding flood risk perception and actionability remain uninvestigated.

The mass media has been criticized for its coverage of local flood events, particularly in the last 2 decades. Using the example of the North Sea Flood of 1953, Hall (2011) suggested that catastrophic events in the infancy of instantaneous mass media were initially likely to have been presented as opportunities for community resilience and solidarity, but later gave way to opportunities for assigning blame and accountability. Perez-Lugo (2001) concluded that the media fell short in communicating warning due to a 1998 flood in Puerto Rico, but that even proper warnings of impending disaster are likely to be misinterpreted as merely nuisance. Karanikola et al. (2015) cautioned that exaggerations of hazards by media sources in their own self-interests can be problematic. Bright and Bagley (2017) noticed that election cycles can impact the extent of coverage of media events. Valencio and Valencio (2018) somewhat apologetically highlighted the many dilemmas involved in mass media reporting of catastrophic events, with the need to balance different expectations, perspectives, and needs desired by mass media consumers, all amid various logistical and financial limitations, leading to possible reduction of trust in the mass media. Consumers have also perceived that mass media effectiveness is less than ideal (Ajaero et al., 2016).

On the whole, Vyncke et al. (2017) confirmed that mass media remain important, even in present times, particularly through elimination of misinformation and quelling of fears, perhaps as a counterbalance in an environment of escalating importance of social media. Information from mass media sources may contain actionable information, especially for short-term benefit immediately before, during, and in the direct aftermath of the disaster, and especially for laypeople. However, there remains a lack of actionable information for the long-term mitigation and decision-making process for individual homeowners and community officials (e.g., cost-benefit analysis of flood mitigation options). The utility and credibility of mass media-generated products could be improved by individual and local customization *via* Web-based data-sharing systems that would enhance awareness of long-term flood mitigation and adaptation options (e.g., as the wisdom of purchasing flood insurance, building outside of flood zone, and elevating new or existing homes).

EFFECTIVENESS OF CITIZEN SCIENCE AND RELATED GRASSROOTS EFFORTS

While mass media information can be regarded as a “top-down” information flow, grassroots efforts are usually “bottom-up” flows. Grassroots efforts that include public information fairs, Earth Day events, peaceful rallies, educational programs, outreach programs, and other similar efforts are termed “citizen science.” Intended consumers can be both at the individual and community levels, for both short- and long-term benefit.

Citizen science has been particularly useful in data collection about past, present, and future floods, for minimizing flood risk. Regarding understanding of past floods, Usón et al. (2016) used participatory interviews to understand relationships among actors and agencies involved in the flood risk management in Santiago, Chile. Glas et al. (2020) also used citizen science-based survey completion about floods in the past, but with a focus on Haiti. Citizen science has proven particularly useful in “heat of the moment” flood danger, such as storm surge monitoring (Spicer et al., 2021), identifying flooded areas in real time (Sy et al., 2019; Yang et al., 2019), and recognizing spatial variability in urban flash floods (Smith and Rodriguez 2017). Efforts at understanding future risk have taken the form of clarification of flood scenarios (Dhiman et al., 2019), improving spatial coverage of pluvial flood events (Michelson and Chang 2019), community mapping (Petersson et al., 2020), and data collection in remote areas (Pandeya et al., 2020).

Other citizen-science-based research has the potential to crosscut efforts to understand past, present, and future flood hazard mitigation. For example, cultural and linguistically diverse community leaders were found to serve as important gatekeepers in communicating flood details (Shepherd and van Vuuren 2014). Hamilton et al. (2018); Keech et al. (2019) examined the role of public ad campaigns and informal communication, respectively, as a means of deterring the dangerous behavior of driving within floodwaters. Citizen engagement in implementing flood risk governance has proven to be successful and shows potential for future success in Europe (Wehn et al., 2015a; Wehn et al., 2015b; Mees et al., 2016; Mees et al., 2018) and elsewhere (Matczak and Hegger 2020), along with other “bottom-up” flood risk management initiatives (Paul et al., 2018; Seebauer et al., 2019).

The shortcomings of citizen science and related grassroots approaches have also been noted. A major disadvantage is data reliability (e.g., Lukyanenko et al., 2016), particularly in evaluating flood risk (Sy et al., 2019). Alves et al. (2021) found that consuming messages from such grassroots efforts was associated with a low coping capacity even among those who had experienced flood. However, other recent work has shown that such uncertainties can be ameliorated to provide valuable information about the flood risk (Tian et al., 2019). In summarizing the state of citizen science and related grassroots approaches regarding flood risk communication, Cheung and Feldman (2019) reaffirmed the importance while also calling for more collaboration between scientists and the lay public on applied problems using theoretical principles.

On the whole, citizen science appears to have an important and growing role in flood risk management. Its strengths are in enhancing public awareness of the necessity for long-term planning strategies to prevent or at least mitigate the flood hazard, thereby enhancing both individual- and community-level efforts. Toward this end, modern Internet capabilities allow for additional advances in citizen-science-based data collection for natural hazards (De Longueville et al., 2010), including flood risk assessment. Likewise, modern communication tools such as Web apps (Ferri et al., 2020) simultaneously across wide geographical areas (McCallum et al., 2016; Hicks et al., 2019) offers increased promise for citizen science as a means of mitigating the flood hazard. However, citizen science and grassroots efforts generally lack the provision of direct actionable information to individual homeowners or community officials at the micro-level, including cost-benefit analysis of mitigation options (e.g., elevated home, wet proofing, dry proofing, and sandbags).

SOCIAL MEDIA EFFECTIVENESS

As social media share the advantage of mass media in reaching a wide audience quickly, it is not surprising that in recent years, flood information conveyed by social media has received increasing attention. The 2011 Bangkok flood may have been the first major flood event for which the role of social media was studied extensively, with the conclusion that flood losses were reduced by an average of 37 percent due to social media-acquired information (Allaire, 2016). Social media's role in mitigating the flood hazard has been praised, especially for its timeliness (Kwon and Kang, 2016), which provides short-term benefits.

In recent years, Twitter® has become a particularly important social media platform for flood communication and for analysis of its effectiveness in mitigating disaster risks, including that due to flood. Niles et al. (2019) reported that use of Twitter varies by the various stages of disaster and by the type of disaster, with use in hurricane events peaking at the preparation stage and in flood and tornado events at the "during" or recovery stage. Wang et al. (2021) found that Twitter use has a positive correlation with hurricane resiliency, suggesting that it can be a tool to enhance resilience. Machine learning techniques have revealed the temporal evolution of the various "stages" of Tweet applications in the context of a single disaster (Arapostathis, 2021), with other research calling for further integration of machine-learning-derived information in this regard (Dwarakanath et al., 2021).

Social media-derived data can also be effective in managing long-term flood risk through enhancing scientific data availability. For example, social media are useful for identifying water height points (Li et al., 2018) and areas likely to be submerged (Smith et al., 2017), serving as a proxy for streamflow (Restrepo-Estrada et al., 2018), and monitoring flood waters (Sattaru et al., 2021), including mapping by use of images circulated on social media itself (Rajeshkannan and Kogilavani 2021). Bayesian statistical modeling has been conducted to consider data of various types (i.e., remotely sensed, high-resolution maps, and social media) in estimating flood inundation probability (Rosser et al., 2017).

Social media can minimize flood risk during the human component of the disaster in both short and long terms through optimization of the quality and quantity of communication (Lovari and Bowen, 2020). At the planning stage, information planning and training possibilities gathered *via* social media are most effective on enhancing flood preparedness, and flood response and recovery (Abimbola et al., 2020). During the flood, social media can disseminate news about sudden onset of the disaster (Vieweg et al., 2014) to provide more effective warnings. The most effective niche for social media may be at the response stage (Stephenson et al., 2018), though Cheng et al. (2019) found that disaster response has been a largely underutilized tool in China. Social media has been found to be useful for immediate-post-disaster damage assessment (Kryvasheyeu et al., 2016), relief and rescue attempts (Basu et al., 2021), and recruiting and managing volunteers and gathering equipment in the flood aftermath (Sharp and Carter, 2020). At even longer time scales, the recovery process can benefit from greater investment in and more efficient information utilization from social media (Yeo et al., 2020). Anderson (2020) noted that evidence of success during the recovery process can be derived from social media communications, in the form of a shift of pronouns from first person singular to first person plural (i.e., from "I, me, my" to "we, us, our"), as the former set of pronouns provides evidence of self-preservation (Pennebaker, 2013) while the latter signifies collectivity (Pavlidou, 2014).

Among all stages of these uses of social media associated with the flood hazard, the analysis of consumer preferences is an important consideration (Feldman et al., 2016). To that end, development of network structures of information dissemination among civilians has been characterized (Olanrewaju et al., 2016), including use of agent-based modeling to identify structures (Du et al., 2017). Perhaps chief among such structures are cultural groups that go beyond ethnicity to include faith-based groups, non-profits, and others, all of which may create both conduits and barriers for communication among victims (Yeo et al., 2018). Perhaps the next development will be to characterize spatio-temporal response stages based on a large collection of events.

In general, social media is most beneficial in raising awareness of the flood hazard and communicating short- and long-term mitigation and adaptation strategies. It is the easiest and quickest way for local authorities to assimilate actionable information to the masses before, during, and after the flood event. However, reliance on social media for mitigating flood impacts has also taken criticism in some of the same ways as for other natural disasters, particularly for providing slowing rates of information diffusion as the crisis continues (Yoo et al., 2016), for being a source of information overload during a stressful period of information processing (Imran et al., 2020), and for the lack of identifiability of direct actionable information (McCreadie et al., 2019), especially for long-term planning. One specific type of actionable information missing from social media sources is user-defined, point- or polygon-specific, flood

TABLE 1 | Flood risk web resources sampled with major attributes.

Objective	Web portal name	Geographic coverage	Analysis level	Information types
Flood forecasting	Global Flood Awareness System (GloFAS)	Global	Station	Flood risk forecast
	Global Flood Monitoring System (GFMS)	50°N to 50°S	Regional basin	Rainfall, streamflow, and flood detection/ intensity
	Iowa Flood Information System (IFIS)	U.S. State of iowa	Community, watershed, and city	Precipitation and flood forecast
	Flood Forecasting and Warning Centre (FFWC)	Bangladesh	Station	Water level
Flood zoning (Digital Flood Insurance Rate Maps (DFIRMs))	Georgia Flood Map Program	U.S. State of Georgia	Individual building	Flood zones, 30-years flood risk probability, and flood depths
	Digital Flood Insurance Rate Map of City of Galveston	City of Galveston, Texas	Individual building	Flood zones
Flood insurance	FloodSmart	United States.	Individual	Flood insurance importance, coverage, premium, andclaim.
Historical flood analysis	U.S. Flood Inundation Map Repository (USFIMR)	United States.	Historical flood event	Historical flood inundation area
	Global Flood Inundation Map Repository (GloFIMR)	Global	Historical flood event	Historical flood inundation area
	WaterWatch	United States.	State or hydrologic unit	Past flow/runoff, current streamflow, flood, drought
Flood monitoring	Dartmouth Flood Observatory (DFO)	Global	Individual building	Flooding status
	NRT Global Flood Mapping	Global	10 × 10° tiles	Daily surface and flood water
Flood hazard risk and cost	Aqueduct Global Flood Analyzer	Global	Country, state, city, and river basin	Flood-induced urban damage, affected GDP, and affected population
Water management	Corps Water Management System (CWMS)	United States.	City, state, and zip code	Current stage, flow, and daily change in storage
General flood information	Flood Victoria	Province of Victoria, Australia	Province	Before, during, and after flood information

mitigation cost-benefit analysis at the individual- and community-level.

RESOURCES AND FUNCTIONALITY OF WEBTOOLS

Publicly-accessible webtools have become important for communicating and minimizing flood risk, especially as a means of addressing the shortcomings of the more traditional sources of flood information (i.e., mass media, citizen science, and social media). As hundreds of webtools provide information related to floods and search engines may point to some more readily than others, the inclusion criteria here emphasize the most popular webtools and those that provide the most valuable flood-related information, while excluding any that are non-English language. A review of the available resources reveals several categories based on the primary objective, with some overlapping functionality: Flood forecasting, flood zoning, flood insurance, historical flood analysis, flood monitoring, flood hazard risk and cost, water management, and general flood information. Although this research is not intended to include all of the existing webtools for flood risk communication, a review of the major attributes of 15 sampled online flood risk resources is shown in **Table 1** by objective. The resources included in **Table 1** and among the 50 sampled here were selected based on the authors' pre-existing knowledge, along with the prominence of the tools as revealed in online searches by the authors.

Flood Forecasting

The Global Flood Awareness System (GloFAS; Hirpa et al., 2018; Chen et al., 2019; Baugh et al., 2020; Harrigan et al., 2020; Passerotti et al., 2020; Senent-Aparicio et al., 2021), produced by the Copernicus Emergency Management Service (CEMS), is an operational system for monitoring and forecasting floods globally. GloFAS consists of a hydrometeorological forecasting system that is connected to a monitoring system for providing forecasts out to the monthly and seasonal scales (Alfieri et al., 2013). The system provides a quick overview of current and forecasted hydrometeorological events, including floods. GloFAS output can be used for streamflow forecasting and flood early warning (Alfieri et al., 2013) at the macro-scale, but based on the information available, a user would be unlikely to be able to use the tool to mitigate long-term flood impacts at the micro-scale. Enhancing Flood Early Warning Services (EFEWS, 2022) increases flood forecast lead time with an operational 15-days flood forecast using GloFAS, thereby supporting flood resilience in the Hindu Kush Himalaya region. Likewise, the Flood Forecasting and Warning Centre (FFWC, 2022) provides flood forecast and flood warning information using GloFAS for Bangladesh.

The Global Flood Monitoring System (GFMS; Wu et al., 2018), developed at the University of Maryland, inputs real-time precipitation data from the Tropical Rainfall Measuring Mission (TRMM; Santos et al., 2019) Multi-satellite Precipitation Analysis (TMPA) and the Integrated Multi-SatellitE Retrievals for Global Precipitation Measurement (IMERG and GPM; Kidd and Huffman 2011; Tapiador et al., 2012; Guo et al., 2016; Mahmoud et al., 2018) to produce hydrological runoff and routing model output, at a gridded spatial scale of 0.125° from 50°N to 50°S. TRMM includes an array of international satellites that generate global observations of rain and snow by combining data from all passive-microwave instruments in the GPM suite (Huffman et al., 2015). Flood detection/intensity forecasts are based on 13 years of retrospective model runs with TMPA input, with flood thresholds derived for each grid point using surface water storage statistics (95th percentile plus parameters related to basin hydrologic characteristics). Streamflow, surface water storage, and inundation variables are also calculated at 1-km resolution (Wu et al., 2014). The latest real-time GFMS couples the satellite-derived precipitation totals, runoff magnitude estimation and routing, and flood identification. Wu et al. (2019) found that GFMS offers complementary information with the Soil Moisture Active Passive (SMAP) satellite data, available since 2015, to provide enhanced flood forecast information. GFMS data have been used for localized flood extent mapping, including in combination with U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center's River Analysis System (HEC-RAS; Kumar et al., 2020). Kar et al. (2020) integrated output from GloFAS and GFMS to classify flood severity at the drainage basin scale. The flood forecasting, based on precipitation forecasts and streamflow modeling, assists in short-term disaster preparedness by facilitating flood monitoring, including floods that can result from other hazards, such as tropical cyclones, and cause still other hazards, such as landslides. However, long-term actionable information is missing at the micro-scale for use by laypersons.

The iowa Flood Information System (IFIS; Demir and Krajewski 2013; Demir et al., 2018) is a Google Maps®–based Web platform developed by the iowa Flood Center (IFC) and represents one of the most comprehensive state-level resources of its kind. IFIS integrates and displays real-time meteorological, hydrological, and soil moisture conditions and forecasts by stream and watershed. This comprehensive data-driven system offers a flood hazard calculator tool with user-defined annual probabilities, to calculate the likelihood of a point flooding. One advantage is that IFIS helps to dispel the common misunderstanding that the flood return period determines the number of floods that can occur in a given return period. A shortcoming of IFIS is that even though it serves over 1,000 iowa communities, it has limited utility at scales more localized than the community level.

National Oceanic and Atmospheric Administration (NOAA) has had a leading role in interactive hydrologic forecasting since the early 1990s (Adams, 2016). NOAA developed the Advanced Hydrologic Prediction Service (AHPS; McEnery et al., 2005; National Research Council, 2006), an accurate, information-rich, Web-based forecast product. AHPS is particularly useful for generating extended probabilistic stream forecasts using ensemble precipitation and temperature forcing (Mullusky et al., 2003; Schaake, 2003; Schaake et al., 2004) to inform risk-based decisions (Connelly et al., 1999). The most recent version of AHPS displays the magnitude and uncertainty of flood/drought events at time scales from hours to months, *via* user-friendly graphical products including hydrographs. Output includes flood forecast levels and time to crest, along with the likelihood of minor, moderate, or major flooding of a selected stream, the probability of stage exceeding a certain level, along with forecasted discharge during 90-day periods and an inundation map showing nearby infrastructure such as roads, railways, and landmarks relative to past floods. Gronewold et al. (2011) used AHPS to characterize seasonal and inter-annual Great Lakes water levels but cautioned that AHPS dampens the variability relative to observed values. NOAA also produces the Automated Flood Warning System (AFWS; Keeney et al., 2012), which uses gauge data from various sources including the U.S. National Weather Service (NWS), and other federal, state, and local agencies. AFWS data are incorporated not only into emergency planning, but also such routine and fundamental services as enhancing navigation and trade, evaluating water supply, treating wastewater, generating power, and enhancing structural integrity, often in situations for which no other data are available (NWS, 2022).

Other flood forecasting tools are specifically designed for use at the regional scale outside the U.S.A. and particularly across political boundaries. For example, NOAA's (2022) Sea Level Rise Viewer shows the sea level rise and potential coastal flooding and inundation depth. Another useful webtool for flood forecasting is European Flood Awareness System (EFAS), provided by CEMS (2022). EFAS emphasizes the large watersheds that cross national boundaries in Europe. In general, planning and decision-making regarding transboundary flooding issues are facilitated by Global Environment Facility (2022), which sponsors an online tool for integrating present and future hydrometeorological scenarios including both flood and drought. The scenarios are useful even at the local (water utility) level. A notable example of a meso-(i.e., watershed-) level flood forecasting tool for the Global South is the Outil de Prédiction des Inondations dans la Delta Intérieur du Niger (OPIDIN. 2022), which forecasts flood inundation in the Inner Niger Delta.

These flood forecasting Web resources are designed for assessing flood risk and for promulgating real-time information regarding upcoming floods to professionals such as scientists, researchers, government officials, emergency managers, and media. While the webtools described above offer an important indirect service to the lay public *via* the mass media, they stop short of providing actionable information to enhance long-term individual or community resilience. For example, none of the tools described above make recommendations on the height to which particular buildings should be elevated.

Flood Zoning

Most U.S. counties provide online Flood Insurance Rate Maps (FIRMs) for the 100-years flood. For example, the Georgia Flood Map Program (2022) shows FIRMs for any property. A main advantage of such websites is a generally quick and easy determination of the flood zone, which fixes flood insurance rates and availability. A major disadvantage of such sites is that they generally lack interactivity and detailed information, especially on a near-real-time basis. Local or city-level products are also available for similar purposes to assist in flood zoning/ insurance needs in the form of "Digital FIRMs" (DFIRMs). One example is that for the City of Galveston (2022), which helps homeowners and prospective homeowners to identify their flood zone.

Two Federal Emergency Management Agency (FEMA) products are also useful for flood zoning and other similar applications. The National Flood Hazard Layer (NFHL) viewer (FEMA, 2022a) depicts the current effective FIRM, flood zone, base flood elevation, levee location, and other information for the U.S., where maps have been modernized. NFHL compiles spatial data from the most recent FIRM database with Letters of Map Revision (LOMRs). The Flood Map Service Center (MSC; FEMA, 2022b) is the official public source for flood hazard information, including flood zones, produced in support of the National Flood Insurance Program (NFIP). MSC provides not only flood maps but also an array of other products useful for mitigating the flood hazard and communicating flood risk. The second product, FEMA (2022c) FloodMaps, provides new and preliminary FIRMs. The current flood map, FEMA standard flood hazard determination form, and FEMA's letter of map amendment are all available.

Another tool that falls into the category of flood zoning is the Virginia Flood Risk Information System (VFRIS; Virginia Department of Conservation and Recreation, 2022). VFRIS incorporates data from the NFIP, DFIRMs, NFHL, and other sources. Flood zone delineations, base flood elevation, sea level rise inundation areas, dam break inundation zones, 100-years return period flood depth, and parcel and building footprints are all depicted graphically. A similar product is available for Louisiana, called Louisiana's FloodMaps Portal (Skinner, 2022) that includes flood zone, ground elevation, effective FIRM, and historic FIRM data for that state at the individual building level.

The primary advantage of such flood zoning Web resources is that the flood zone information is typically shown at the micro-scale or even at the individual building level. Such flood zone information alerts users to the need for purchasing flood insurance and other regulatory requirements. However, in general, like the tools or websites described above, these tend to provide little actionable information (e.g., the flood zone category for each building) for individual homeowners or community for long-term, flood-resilient construction.

Flood Insurance

Several useful tools are available for consumers to evaluate the economics of flood insurance for their properties. For example, FEMA's (2022d) "FloodSmart" provides details of flood insurance including its importance, types of flood insurance, coverage and premiums, insurance providers, and the process of purchasing insurance and filing claims. National Flood Services LLC's (2022) "My Flood Quote" also provides information regarding flood insurance (i.e., importance, cost, and process of purchase), claims, and assistance in the different stages of flood disaster. In general, these and similar sites are directed toward a lay public audience, but they also provide useful information for local-level community planning. For example, individual buildings where flood insurance is mandatory in the U.S. due to location within the 100-years flood zone are often identified. A shortcoming of flood insurance sites is that they typically lack quantitative information availability, such as the short- and long-term insurance premium savings for constructing above the minimum required elevation (i.e., freeboard).

Historical Flood Analysis

Archived information for historical flood events is available through the U.S. Flood Inundation Map Repository (USFIMR) project (Johnson et al., 2019) housed at the University of Alabama. This product includes 10-30 m-resolution satellite-based imagery of past U.S. flood events (Cohen et al., 2018), with shapefiles available for download. Such information can be used as a basis of comparison for flood modeling and prediction. USFIMR does not attempt to integrate real-time meteorological or hydrological information. The extension of this project, known as the Global Flood Inundation Map Repository (GloFIMR), is also administered by the University of Alabama.

Similarly, U.S. Geological Survey (USGS) provides the WaterWatch (Beigi and Tsai, 2014; Oubeidillah et al., 2014) service, which includes a Web-based map, graphs, and tables describing historical as well as near-real-time streamflow conditions in the U.S. at over 3,000 long-term USGS stream gauges. WaterWatch can also bundle streamflow output by hydrologic region, for daily, weekly, bi-weekly, or monthly mean periods for more precise analysis of hydrometeorological conditions back to 1901 (Jian et al., 2008).

The United Nations Satellite Centre (UNOSAT) flood portal [United Nations Institute for Training and Research (UNITAR. 2022)] provides vectorized GIS files for satellite-derived historical flood data since 2007. Functionality includes the ability to import, incorporate, and analyze additional data to enhance decision-making for risk reduction.

All of the above historical flood webtools offer advantages for establishing precedents for flooding at the location of interest. Potential homeowners may use this information to build safe and stronger homes. However, the resources provide little other actionable information for the individual homeowner, such as the current and future probability of flooding, and damage and loss estimates from floods of various magnitudes.

Flood Monitoring

In addition to GloFAS and other tools described previously in the context of other objectives, Dartmouth Flood Observatory (DFO; Lin et al., 2017) provides not only historical, but also near-real-time, maps of flooding globally, based on satellite imagery and data such as total precipitable water (i.e., precipitation that would fall if the entire column of water vapor above it condensed and precipitated), observed rainfall, and river and reservoir levels (Kettner et al., 2021). Kundzewicz et al. (2013) used this product to develop a flood climatology for Europe, and Chen et al. (2020) did similar work for mainland Southeast Asia.

Another useful product is from NASA Goddard Space Flight Center's (GSFC) Hydrology Laboratory, which operationalizes near-real-time global flood mapping using available satellite data resources. Currently, the system utilizes the twice-daily overpass of the Moderate-resolution Imaging Spectrometer (MODIS) instrument aboard the Terra and Aqua satellites. This system produces global daily surface and flood water maps at approximately 250-m resolution, in $10 \times 10^{\circ}$ tiles (Nigro et al., 2014). Brakenridge and Anderson (2006) described early uses of MODIS in flood monitoring. Regional flood potential has been derived using terrestrial modeled water storage from the Gravity Recovery and Climate Experiment (GRACE) along with precipitation observations from the Global Precipitation Climatology Project (GPCP; Reager and Famiglietti, 2009.

The Automated Disaster Analysis and Mapping system (ADAM; World Food Programme (WFP) 2022) provides current flood alerts, events, and monitoring information globally. ADAM also tracks longer-term flood events that could have catastrophic consequences for human health, food security, and/or transportation.

Many websites, such as that of the Australian Government Bureau of Meteorology (2022a), monitor floods at the national level. Likewise, the Government of Canada (2022) monitors the water level and discharge data at the Canadian province and territory level. Pakistan (Flood Forecasting Division, 2022), France (Vigicrues, 2022), and Germany (Bundesanstalt für Gewässerkunde, 2022) are other examples of nations with similar offerings. These flood monitoring websites and webtools provide actionable information for the individual and community officials to prepare for imminent disaster. However, they generally lack information for long-term planning to promote resilient site selection and construction.

Flood Hazard Risk and Cost

Samu and Kentel (2018) recently produced a comprehensive economic analysis of flood in Zimbabwe, but similar micro-scale analyses are difficult and lacking. In a useful overview of the advantages and limitations of global flood risk models (GFIRMs), Ward et al. (2015) cautioned that GFIRMs are often mismatched to their intended uses, especially at the local level. The Aqueduct Global Flood Analyzer (AGFA; Iceland, 2015; Sutanudjaja et al., 2017; Ward, 2017) represents a zoomable, meso-resolution offering for determining riverine or coastal flood risk and cost-benefit analysis for either an "optimistic" or "pessimistic" scenario, for 2030, 2050, or 2080, according to the user-defined projection model. The tool provides a customizable, expected, annual urban damage and potential avoided loss by flood protection mechanisms (e.g., levee, dam; Ward et al., 2015). Samu and Akıntuğ (2020) used AGFA successfully to assess economic risk of flood and drought in Zimbabwe. Nevertheless, as with many other systems described above, AGFA does not offer analysis at scales more localized than the watershed level.

USGS (2022) provides the Flood Inundation Mapper (FIM), which shows flood locations and potential loss estimates interactively, based on user-selected stream conditions. Historical flood information is also available. The "what if" flood scenarios available through FIM provide useful risk assessments and flood planning tools at the community level.

The main limitation of existing flood hazard risk and cost webtools or websites is that the analysis is typically at city-to-global level instead of at the micro–level, which limits the utility for decision making by individuals before constructing or purchasing a home. Flood Factor®, produced by First Street Foundation (2020a), addresses such shortcomings by offering a micro-scale (i.e., individual building-level) analytic approach to understanding the flood risk for homes and other structures. First Street Foundation (2020b) also produces a national-level flood risk assessment from these data, which is now being used in as a tool for other research, such as that by Armal et al. (2020), who used Flood Factor to quantify past and future economic impacts due to flood.

Water Management

One useful tool for water management is USACE's Corps Water Management System (CWMS; Hu et al., 2006), which is an information system that integrates data management and short-term modeling tools. CWMS collects, validates, and stores information such as precipitation, river stage, and floodgate settings, on a real-time basis from platforms *via* Geostationary Operational Environmental Satellite, NWS Advanced Weather Interactive Processing System, and other sources. The values are then disseminated to users primarily through Web technology and are used to calibrate hydrologic and hydraulic models to represent current conditions. Stage and runoff forecasting is done using several engineering models. The control and visualization interface (CAVI) provides user functionality, such as in executing model runs, visualizing data, and selecting outputs (Charley and Luna, 2007). Agriculturalists can benefit greatly from such water management websites, not only because of information needed to inform planning regarding irrigation water availability, but also for harvest scheduling, reservoir water supply budgeting, and flooding following opening of dam reservoir gates. The constraint of such resources is that the utility is for a limited audience of agriculturalists. However, flood forecasting from water management websites may have untapped potential for assisting communities in flood preparation.

General Flood Information

Many websites provide general flood information for education and public awareness of flood impacts. For example, the Australian Government Bureau of Meteorology (2022b) includes flood warning services and text regarding flood preparation and understanding floods. Such information was useful to Australians before, during, and after Flood Victoria (Molino, 2009). In addition to its use for flood insurance described previously, FEMA's (2022d) "FloodSmart" includes more general information regarding cost of flooding and flood maps. Ready (2022), an official website of the U.S. government, provides useful information for the preparation, action, and recovery stages of flood. Colorado Division of Homeland Security and Emergency Management Department of Safety (2022) includes basic

TABLE 2 | Types of long-term actionable information at the micro-scale in selected existing web resources.

Category	Long-term actionable information at micro-scale (for individuals and community)																
	Flood properties			**Effects of flood**	**Mitigation options**			**User customization information**					**Community information**		**Financial parameters**		
	Inundation area	**Depth**	**Zone**	**Flood damage and loss**	**Hazard**	**Structure**	**Combined**	**Basement**	**# Of stories**	**Livable area**	**Time frame**	**Insurance**	**CRS**	**Freeboard**	**Interest rate**	**Discount rate**	**Mortgage period**
Iowa Flood Information System	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Georgia Flood Map Program	–	–	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Louisiana FloodMaps Portal	–	–	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Flood Factor	√	√	√	√	√	√	√	–	–	–	–	–	√	–	–	–	–
Aqueduct Global Flood Analyzer	√	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
U.S. Flood Inundation Map Repository	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Global Flood Inundation Map Repository	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Global Flood Awareness System	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Global Flood Monitoring System	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Dartmouth Flood Observatory	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Corps Water Management System	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
WaterWatch	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Advanced Hydrologic Prediction Service	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Automated Flood Warning System	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
FEMA Flood Maps	√	–	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–

(Continued on following page)

TABLE 2 | (*Continued*) Types of long-term actionable information at the micro-scale in selected existing web resources.

Category	Long-term actionable information at micro-scale (for individuals and community)																
	Flood properties			Effects of flood	Mitigation options			User customization information					Community information		Financial parameters		
	Inundation area	Depth	Zone	Flood damage and loss	Hazard	Structure	Combined	Basement	# Of stories	Livable area	Time frame	Insurance	CRS	Freeboard	Interest rate	Discount rate	Mortgage period
Flood and Dought Portal	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
UNOSAT Flood Portal	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
National Flood Hazard Layer	–	–	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–
FloodSmart	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
My Flood Quote	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Flood Victoria	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Flood Inundation Mapper	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Virginia Flood Risk Information System	√	√	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Digital Flood Insurance Rate Map of City of Galveston	–	–	√	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ready	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Flood Forecasting and Warning Centre	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

"√" represents availability of long-term, actionable information at the micro-scale, while "–" represents unavailability of such information.

flood information along with similar guidelines on what should be done before, during, and after a flood. Another example is City of New Orleans (2022), which offers information on flood insurance, flood risk reduction, and flood resilience for new construction. These and similar websites serve the public in an education/outreach capacity regarding the short-term actions that should be taken to reduce the flood impact, but they offer limited actionable information for long-term planning, such as location specific comparative cost-benefit analyses under different mitigation options.

Overall Assessment of Webtools

Comprehensive assessment of the relative usefulness of the webtools is difficult. While data regarding use statistics and the types of data that users felt were most and least helpful would provide valuable information for webtool comparison, such data would likely be biased toward the webtools that serve areas that have the highest population density and experienced the most flooding. Few would use even the most comprehensive webtool if no ominous flood event exists in the region that it covers, and many would use even the least comprehensive webtool if there is an ominous flood event in the region that it covers. Similarly, the variety of scales covered across the webtools is also likely to bias any assessment of usefulness based on "hit" statistics. Moreover, while assessing what the users gain from the webtools would be useful, such an analysis would be most appropriate for an interview or questionnaire format on the webtool itself, but such data are unavailable to the authors.

Nevertheless, it is clear that the existing tools provide some actionable information for enhancing resilience, but with much room for improvement (**Table 2**). A major shortcoming is that, with the notable exception of Flood Factor, they tend to be useful only at the meso-scale or broader, and most tend to be geared toward short-term flood danger mitigation. While progress made in webtool development in recent years to mitigate the flood hazard, especially with applications such as Flood Factor, represents impressive advancement of science communication, there remains an absence of tools that optimize freeboard benefit-to-cost ratio at the individual building scale, for both new and existing residence owners, renters, developers, engineers, architects, and planners, in a bottom-up approach. Such a flood risk communication webtool is urgent so that individuals and community leaders can make decisions based on quantitative, long-term actionable information. However, as Salvati et al. (2016) cautioned, such a development should not come at the expense of advances in other forms of flood communication designed for the layperson.

Recently, researchers at Louisiana State University and University of New Orleans began developing the Flood Safe Home (2022) webtool to assist individual homeowners in the decision-making process based on life-cycle cost-benefit analysis (Dong and Frangopol, 2017). Available information will include the optimal elevation above ground level for the residence, for deriving the maximum benefit from not only avoiding flood loss but also from savings on insurance premiums. Such tools seem to be the next step in the provision of actionable information regarding flood hazard mitigation.

SUMMARY AND CONCLUSION

Results of this analysis suggest that while mass media, citizen science, and social media have revolutionized the way that people plan for, survive, and recover from floods, their utility is largely restricted to addressing short-term needs for information and/or conveying information about singular events to scientists. More robust applications of these well-established forms of media might include broadcast of more specific, actionable information based on sound science from trusted voices to enhance long-term planning. However, availability of such actionable information to both community leaders and the lay public to satisfy needs for long-term planning for and mitigation of the flood hazard remains limited. A particular area of need is media that satisfy several criteria simultaneously: a delivery method that reaches the most people and that people find most appealing, while enhancing decision-making for long-term needs rather than for short-term gain. The most likely solution is a webtool that builds on Flood Factor by providing additional functionality to support improved flood risk reduction decision making, especially one that considers both the costs and benefits of mitigation. Such a tool would enhance resilience to the world's most widespread and impactful hazard.

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RM developed the detailed methodology, collected and analyzed the data, and developed the initial text. RR helped in the literature review, and edited early and late drafts of the text. CF helped to organize the paper and tables, and revised the text. Y-CL provided oversight on analysis and edited the text.

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Understanding the social aspects of earthquake early warning: A literature review

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Earthquake early warning (EEW) systems aim to warn end-users of incoming ground shaking from earthquakes that have ruptured further afield, potentially reducing risks to lives and properties. EEW is a socio-technical system involving technical and social processes. This paper contributes to advancing EEW research by conducting a literature review investigating the social science knowledge gap in EEW systems. The review of 70 manuscripts found that EEW systems could benefit society, and the benefits may go beyond its direct function for immediate earthquake response. The findings also show that there are social processes involved in designing, developing, and implementing people-centered EEW systems. Therefore, social science research should not just be concerned with the end-user response but also investigate various stakeholders' involvement throughout the development process of EEW systems. Additionally, EEW is a rapidly evolving field of study, and social science research must take a proactive role as EEW technological capacities improve further and becomes more accessible to the public. To improve EEW effectiveness, further research is needed, including (1) advancing our understanding of why people take protective action or not, and ways to encourage appropriate action when alerted; (2) enhancing public understanding, investigating best practices for communicating, educating, and engaging with the public about EEW and overall earthquake resilience; and (3) keeping up with technological advances and societal changes and investigating how these changes impact communities' interactions with EEW from various standpoints including legal perspectives.

KEYWORDS

earthquake early warning, social science, warning systems, literature review, earthquake resilience

Introduction

When an earthquake occurs, an earthquake early warning (EEW) system can warn end-users further afield of the incoming ground shaking. The several tens of seconds of warning (to potentially as much as 120 s) from such systems provide potential benefits such as reducing injuries and fatalities, protecting infrastructure, reducing disruptions to services, and improving overall earthquake preparedness and resilience.

The last decade has seen the rapid development of methodologies and technologies that have given us a deeper physical understanding of earthquakes and improved EEW processes to achieve better earthquake warnings (Allen and Melgar, 2019). As a result, many locations worldwide already have operational EEW systems that broadcast warnings to the public before strong ground shaking arrives. Examples of governmental or official EEW services include Japan (Kodera et al., 2020), Mexico (Santos-Reyes, 2019), Taiwan (Wu et al., 2017), South Korea (Sheen et al., 2017), and the West Coast of the United States of America (Chung et al., 2020). In other places, such as India, Turkey, and Romania, EEW systems do not yet issue alerts to the public but send warnings to 'advanced users', such as governmental units or industrial users (Wang et al., 2020). Italy's EEW system is active in the Campania Region but is not yet available to the broader public (Velazquez et al., 2020). Many other locations in the world are also exploring, developing, and testing EEW systems, for example, various regions in China, Europe and South America (Wang et al., 2020).

Furthermore, EEW development is no longer limited to geographical jurisdictions. The ubiquity of technology allows EEW to be implemented across borders. The earthquake network (EQN) initiative, one of the earliest smartphone-based EEW systems, has provided EEW services across 25 countries since 2013 (Finazzi, 2020; Fallou et al., 2022). Commercial counterparts can also provide EEW products and services. For example, a Google initiative introduced the Android Earthquake Alerts System in New Zealand and Greece in April 2021 (Voosen, 2021) without the involvement of warning authorities from those countries (McDonald, 2021).

The success of an EEW system relies on the end-users, such as the general population, accepting and reacting appropriately to the system and its warnings (Minson et al., 2018). Thus, as EEW systems become increasingly available and transboundary, there is also an ever-increasing need to understand the social aspects of effective EEW systems, their design, development, implementation and use. In this paper, investigation of social aspects means considering factors from various branches of the social sciences including, but not limited to, sociology, behavioral science, psychology, geography, law, economics, and communication. This paper seeks to contribute to the current discourse on EEW by reviewing the literature and the state of research on the social facets involved in EEW systems. This literature review starts with the broad question: "What research has been conducted on the social aspects of earthquake early warning systems?"

This paper is structured as follows. Section Background on earthquake early warning systems contextualizes the review by providing a background to the study, briefly discussing EEW concepts and EEW in the context of broader warning systems. Section Method outlines the methodology. Findings from the literature review are presented in Section Findings. The discussion (Section Discussion and conclusion) examines the findings regarding current and future social research trends for EEW and concludes with a summary of recommendations for future research.

Background on earthquake early warning systems

EEW systems provide real-time information about ongoing earthquakes. Based on two primary concepts, information about earthquakes can be supplied ahead of ground shaking. First, information can travel faster than seismic waves (Cremen and Galasso, 2020). Second, different types of seismic waves travel at various speeds. The P-waves (primary waves) travel fastest, but the damaging energy from an earthquake usually comes from S-waves (secondary waves) and surface waves, and for locations far from the epicenter, they arrive much later than P-waves (Cremen and Galasso, 2020). EEW systems use these concepts to warn users at a distance of incoming ground shaking. People can take protective action, and automated systems can execute pre-programmed responses before the damaging ground shaking arrives (Allen and Melgar, 2019). Timely warnings and appropriate responses can potentially reduce injuries and damage to property (Allen and Melgar, 2019) and help with people's psychological preparedness for ground shaking (Nakayachi et al., 2019).

Traditional EEW systems rely on fixed sensors with configurations that are based on regional systems, on-site systems, or a hybrid of the two (Cremen and Galasso, 2020). Regional (or network-based) systems have dense seismic networks where an array of sensors is deployed in areas with high seismicity potential. The system's warning window starts when the first wave is detected at a source point. The network sends warning to target areas further afield; it allows several tens of seconds of warning depending on the distance between the source and the target sites (Zollo and Lancieri, 2007). On the other hand, on-site systems have sensors instrumented at a single station. The lead time for the warning is estimated using parameters from a few seconds of recorded P-waves on the station's location to predict the ground motion for S-waves or surface waves (Bindi et al., 2015). An EEW system can also be a hybrid of the two; for example, California and Taiwan have hybrid systems (Wu et al., 2019). In recent years, another aspect of EEW research has been conducted on systems that are not based on fixed sensors but instead rely on mobile sensors (e.g., using people's smartphones). Crowdsourced EEW is an evolving domain where EEW systems utilize the participation of people and use mobile and low-cost technologies (e.g., accelerometers of mobile phones) and send warnings through apps or programs built into the mobile's operating systems. Examples of crowdsourced EEW systems are the Earthquake Network (Finazzi, 2020), MyShake (Allen et al., 2019), and the Android Earthquake Alerting System (Cardno, 2020).

UNISDR (2005) and UNDRR (2015) priorities in developing and implementing people-centered early warnings as integral to disaster risk reduction. EEW systems resemble other forecast and warning systems for other natural hazards. These warning systems need to have robust scientific and technical bases, and they must also have a strong focus on the people at risk and have an approach that incorporates all of the relevant risk factors, such as understanding social vulnerabilities and short-term and long-term social processes (Basher et al., 2006). Similarly, an effective EEW system relies not solely on the reliability and accuracy of technological capabilities and processes but also on its embeddedness with human and social systems (Dunn et al., 2016; Velazquez et al., 2020).

EEW systems, however, have unique challenges compared to other warning systems. Due to the physical processes of an earthquake, EEW can only commence once an earthquake rupture has started. Thus, EEW systems can only give short warning times of up to several tens of seconds, in contrast to other hazards, such as weather or tsunami warnings, for which warnings can come days, hours, or a few minutes before the events occur (Strauss and Allen, 2016). The short period also implies a high degree of automated processing and near-instantaneous warning, which does not afford time for further human validation (Gasparini et al., 2011; McBride et al., 2020). The nature of short warning time impacts how EEW systems are designed to effectively communicate the hazard (McBride et al., 2020) and how people and automated systems respond and make decisions (Velazquez et al., 2020).

EEW generally follows the "Goldilocks principle" (Cochran and Husker, 2019). Too far from the earthquake rupture, warnings can become more accurate and lead times longer, but the intensity of shaking is weak and not dangerous. Too close to the rupture, intensity is expected to be more dangerous, but little to no advanced warning may be sent out. Furthermore, predicting impending ground shaking is still an ongoing scientific feat, with multiple methods still being developed and refined (e.g., Hoshiba, 2021). Thus, EEW systems inevitably will have false and missed alerts from the perspective of their end-users. False alerts occur when alerts are issued but the user does not observe the expected ground motion; missed alerts occur when ground shaking is felt but no alert is received (Minson et al., 2018; McBride et al., 2020). Challenges for EEW systems include controlling false and missed alerts, managing expectations, and communicating about the uncertainties and limitations of EEW.

Research advances on the social aspects of EEW are still relatively young. One recent study is Velazquez et al. (2020) state-of-the-art review of the technical and socio-organizational components of EEW. The review covered selected established EEW systems–Italy, United States (U.S.) West Coast, Japan, and Mexico–where it was concluded that although there has been increased awareness of people-centered EEW systems, multi- and cross-disciplinary research on EEW remains relatively unexplored. However, Velazquez et al. (2020) review only covered existing EEW systems and did not include those under exploration, planning, and implementation. Further research is needed to understand the social processes and interactions when establishing EEW systems. This systematic review contributes to the literature as it investigates EEW more broadly. It covers not only established systems but includes research papers that are exploratory and projected toward future EEW systems. This review provides an overview of past research and explores future directions for social EEW research in the context of evolving environments.

Method

The literature review method followed the scoping review process defined by Arksey and O'Malley (2005). Scoping reviews, also known as mapping studies, frame the nature of existing literature on a particular topic (Kitchenham et al., 2011; Par et al., 2015); in this study's case, to frame the social science research of earthquake early warning literature. The scoping review starts at a broad level, frames a research trend, and develops inclusion/exclusion criteria to scope a particular topic (Kitchenham et al., 2011; Par et al., 2015).

This study started by defining a broad research question: "What research has been conducted on the social aspects of earthquake early warning systems?" Then relevant studies were identified by conducting a literature search using the Scopus database to ensure coverage of significant publications on EEW systems. The scope of the review only includes papers published until September 2021–the time the search was conducted. Table 1 summarizes the search and selection of relevant studies for this literature review. Only peer-reviewed manuscripts were considered. As the researchers have fluency in English and Chinese, manuscripts in both languages were included in the review. A keyword search was used to filter for relevant manuscripts. The search criteria included the term "earthquake early warning" combined with a set of keywords to cover social aspects such as *social*, *behavio** (behavior, behavior, and other variants), *perce** (perception, perceptions, and other variants), *accept** (acceptance, acceptable, and other variants), *user*, *people*, *community*, and *public*. The initial search resulted

TABLE 1 Literature search results.

Search	2nd Keyword	Number of results	Duplicates removed	Unique results	Excluded	Included
1	Social	29	0	29	19	10
2	Behavio*	40	5	35	25	10
3	Perce*	34	5	29	20	9
4	People	60	19	41	27	14
5	User	72	25	47	31	16
6	Accept*	13	6	7	5	2
7	Community	48	23	25	19	6
8	Public	69	41	28	25	3
	Total	365	124	241	171	Final: 70

*A search logic that returns all words that begins with the stem truncated by the asterisk.

in 365 documents. After the removal of 124 duplicates, a total of 241 manuscripts remained.

The 241 manuscript abstracts were reviewed and subjected to inclusion and exclusion criteria. Technically focused papers that did not discuss any social aspects of EEW systems were excluded. Examples of exclusions were: papers with abstracts focused solely on algorithms; magnitude characterization; prediction models or methods; network infrastructure; sensors; routing protocols; automated structural response; use case of EEW to infrastructure (dams, buildings); simulations; artificial intelligence; and machine learning. Manuscripts included had abstracts that discussed stakeholder collaboration, public perceptions, user tolerance, user acceptance, user requirements, community impacts, social benefits and challenges, the potential use of EEW for communities, public education, risk reduction, behavior response, and similar themes. Seventy manuscripts (68 in English and 2 in Chinese) were considered for the review after the inclusions-exclusion criteria.

A limitation to this exclusion-inclusion method is that only the abstracts' contents were considered for filtering out the articles. Some articles may have been dropped even if they had social science components in the body but may not have explicitly mentioned those aspects in their abstract. Consequently, technical papers (e.g., Cua and Heaton, 2007; Böse and Heaton, 2010) were picked up because their abstracts contained a reference to user perspectives (e.g., user-specificity, communication to users, or subscriber's perspective). Despite the technical focus on algorithms of such papers, the qualitative analysis investigated the sections that discussed social or user standpoints.

The 70 articles were subjected to qualitative analysis using thematic coding (as per Flick, 2018). Two of the authors conducted the analysis. The thematic coding process involves sequentially building the case summaries for each article, where the manuscript details are organized according to themes (Flick, 2018). To answer the main research question, the case summaries for each manuscript were built around these three base sub-questions:

- What social aspects of earthquake early warning systems are discussed in this article?
- Does the article discuss end-users and broader societal acceptance, use, and perspectives of EEW systems?
- Does the article discuss collaboration between different stakeholders and decision-makers on the design and development of EEW systems?

The thematic analysis used these questions but was also reflexive in gathering other insights into themes. The identified themes were then continuously re-checked and modified after analyzing each case, with this process repeated for each manuscript (Flick, 2018). The findings of the qualitative analysis provided insights into what has been investigated in social research of EEW systems.

Findings

Summary of the papers

The 70 manuscripts included in this review primarily discussed or had a significant portion of the paper that discussed the social components of earthquake early warning.

Most of the papers included in this literature review were published from 2007 onwards—20 in the last 2 years (2020 and 2021). Figure 1 illustrates the number of articles included per year. Only one paper from the literature search was published before 2000. Goltz and Flores (1997) paper was on public policy and behavioral response to Mexico's Sistema de Alerta Sismica – one of the earliest EEW systems that issued alerts to the public EEW, initiated in 1989 and completed in 1991.

The articles from 2007 to early 2011 concentrated more on EEW algorithms and relating them to user-specific decision-making (e.g., Cua and Heaton, 2007; Böse and Heaton, 2010), future application prospects (Iervolino et al., 2007; Kamigaichi et al., 2009), and estimation of people's willingness to pay for a hypothetical EEW (Asgary et al., 2007).

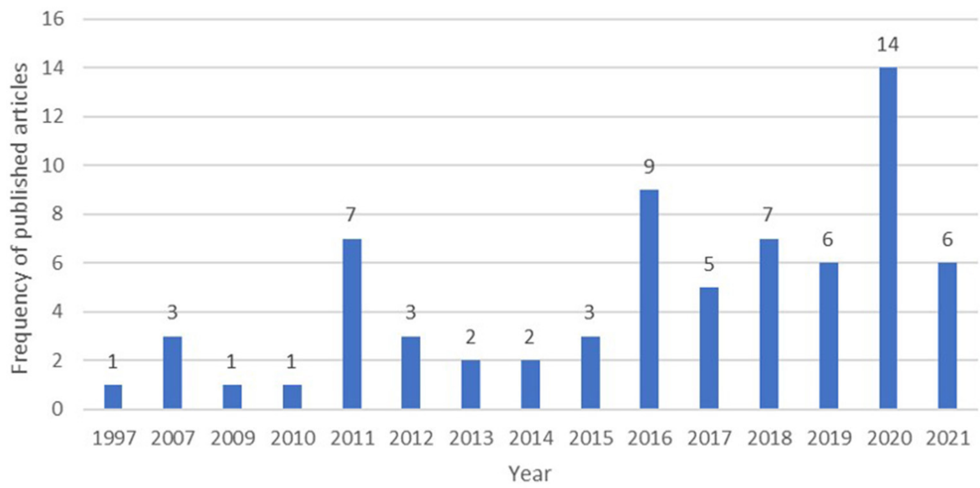

FIGURE 1
Number of published articles included in this review per year.

After the 2011 Tohoku-oki earthquake and tsunami event, several publications included in this review looked into Japan's EEW performance (Ritsema et al., 2012; Fujinawa and Noda, 2013; Ohara and Tanaka, 2013; Hoshiba, 2014). Also, after 2011, as evidenced by the surge in academic publications from different parts of the world on EEW, more countries and territories were exploring and implementing EEW. The articles included in this review discussed EEW performance or prospects from various geographical locations (See Figure 2), including the U.S. West Coast (14), Japan (11), China (3), Mexico (3), New Zealand (3), Ecuador, India, Iran, Italy, Kazakhstan, Pakistan, Taiwan, and Turkey. Nineteen articles did not specify any location, but the EEW concepts and observations could be applied generically. Five articles investigated the broader European region, while another five discussed or compared EEW systems from multiple locations (e.g., Japan and Italy, etc.).

The 70 articles focused on varying topics within EEW research, each with its own objectives. See Supplementary materials for the list of articles included in this study and the objectives of each paper. Because of the varying focus of each article, a comprehensive appraisal of the EEW systems' technical performance is not within the scope of the review. However, the paper covers research themes resulting from the analysis of the articles as guided by the research questions. The resulting overarching themes are (1) EEW benefits and challenges, (2) end-users' perceptions, (3) multi-stakeholder involvement, and (4) crowdsourced EEW and its implications. See Table 2 for the summary of these themes; note that each theme is not mutually exclusive from the other. Each theme will be discussed in detail in the succeeding sub-sections.

EEW benefits and challenges—social perspectives

Most articles in this review discussed the implications of having or developing EEW systems ($N = 50$), arguing for the benefits and highlighting the associated limitations and challenges of having EEW systems. The following 2 subsections discuss the findings on EEW benefits and challenges.

EEW benefits in the disaster lifecycle

Most of the articles discussed the potential benefits of EEW systems to society. The articles highlighted that the main potential benefit of EEW systems revolves around the ability of people and systems to respond to the alert, thus minimizing harm to life and property. Thirty-eight of the 70 articles mentioned the benefit of taking personal protective action. Twenty-eight of the 70 articles mentioned that systems can benefit from EEW if pre-programmed tasks can be performed to minimize impacts (e.g., slowing down of bullet trains, allowing elevators to stop at the nearest floor). People also see the benefit of EEW to mentally brace themselves for the incoming shaking (Nakayachi et al., 2019). Specialized users can also use EEW for situational awareness when responding to earthquake events. Emergency responders can utilize EEW systems to get quick information that will allow them to improve situation awareness through understanding the disruptions and cascading hazards (Allen and Melgar, 2019). Urban Search and Rescue (USAR) teams can use EEW systems to reduce surprise effects and stop dangerous operations (Auclair et al., 2021). EEW can also prompt people to evacuate buildings (Wu et al., 2017) or

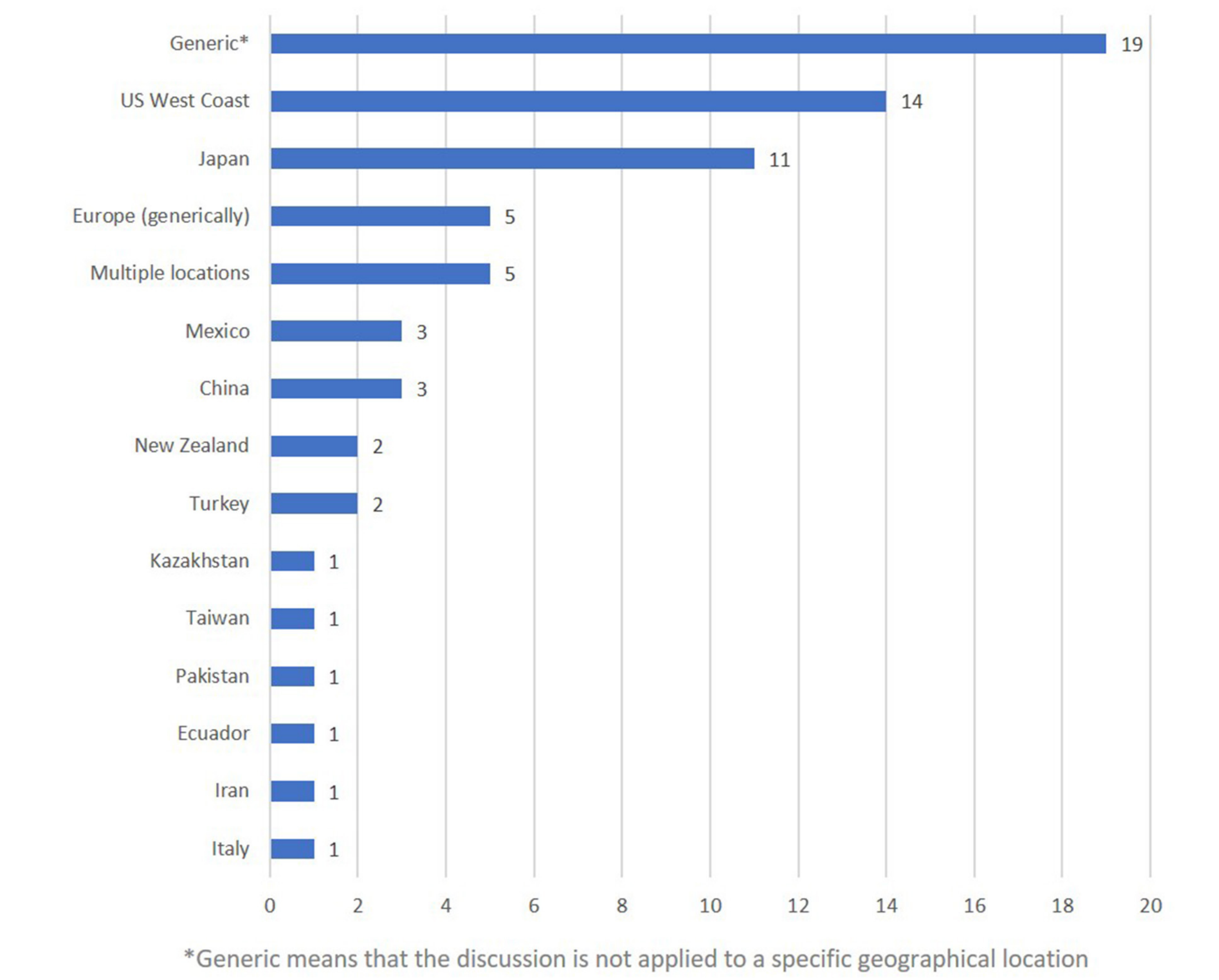

FIGURE 2
Locations of focus for the articles included in this literature review.

evacuate coastal areas in preparation for a tsunami (Necmioğlu, 2016).

Many of the articles included in this review also discuss EEW systems' potential benefits beyond the immediate response to the warning to other stages of the disaster lifecycle. Table 3 summarizes the potential benefits EEW can provide during various disaster phases. For recovery, EEW systems can be incorporated in protecting critical structures, transport, and lifelines from secondary (e.g., fires) and aftershock effects; protecting infrastructures would help society return to normal after an event (Gasparini et al., 2011). For mitigation, setting up EEW systems would help decision-makers know more about exposure and vulnerability, thus potentially helping play a role in policies managing risks (Iervolino et al., 2007). Mitigation can be applied in managing critical infrastructures using EEW systems. For example, the public might have more confidence in a nuclear facility if they know that it is equipped with an EEW system to minimize risks (Cauzzi et al., 2016). Finally, having an EEW system can also promote a culture of preparedness. Public education regarding the system can encourage people to think about earthquakes and their impacts and prepare for them (Dunn et al., 2016; Allen and Melgar, 2019).

Benefits of EEW can be seen from an economic point of view based on savings or loss reduction–computing potential losses when EEW is implemented and comparing the results with the estimated losses if EEW is not implemented (Oliveira et al., 2015). Some attempts have been made to measure and estimate the benefits. A case example of a semiconductor facility in Miyagi prefecture investing USD 600,000 in retrofitting and EEW automation demonstrates EEW cost savings. The facility had estimated losses of USD 15 million from two moderate earthquakes before implementing earthquake mitigation measures, compared to $200,000 losses after experiencing two similar-sized earthquakes

TABLE 2 Research themes of the study.

Research theme	Description	N*	Sample papers
EEW benefits and challenges	The papers discussed the benefits, challenges and limitations of existing, developing, or future EEW systems	50	Allen and Melgar, 2019; Becker et al., 2020a; Wald, 2020
End-users' perceptions	The papers looked into end-users' perspectives and expectations on EEW. Topics in this theme include perceptions on useful lead time, risk and decision making, and alerting issues.	36	Le Guenan et al., 2016; Nakayachi et al., 2019; Auclair et al., 2021
Multi-stakeholder involvement	The papers considered social processes with various stakeholders in the design, development, or implementation of EEW, not limiting social considerations only to the alerting aspect of EEW.	25	Parolai et al., 2018; Herovic et al., 2020; McBride et al., 2020
Crowdsourced EEW and its implications	The papers in this theme discussed using crowdsourcing for EEW systems, including the potential and challenges.	9	Minson et al., 2015; Kong et al., 2019; Finazzi, 2020

*Themes are not mutually exclusive.

with retrofits and EEW automation (Strauss and Allen, 2016).

However, measuring savings on a broader scale is challenging as not all losses can be measured monetarily, and any projection of losses will be based on a landscape of possibilities (Oliveira et al., 2015; Strauss and Allen, 2016). Estimating benefits on a broader scale may work with some indicative assumptions. For example, Strauss and Allen (2016) anticipated that EEW could reduce injuries by more than 50% if everyone acted to drop-cover-and-hold after an alert. The saving is estimated at USD 200 million per year on costs the U.S. government would have to expend to address earthquake-related injuries (Strauss and Allen, 2016). Measuring such benefits should be taken with caution, as it is necessary first to have a clear idea of what can actually be done with a few seconds of warning (Oliveira et al., 2015).

Despite the potential for EEW, the benefits of public alerting make assumptions about people's reactions; there is still limited proof of its actual effectiveness in terms of people's responses (Nakayachi et al., 2019; Cremen and Galasso, 2020). Wald (2020) expressed two concerns about EEW on the U.S. West Coast: (1) effective warning times of EEW systems are often less than claimed, and (2) the suggested actions responding to the alerts are more challenging than anticipated and thus not as effective as expected. The short warning times of EEW limit the possibilities for effective response (Wald, 2020). A study shows that despite the successful issuance of EEW alerts in the cases of Gunma and Chiba – Japan, the alerts did not motivate people to take action as recommended by official agencies (Nakayachi et al., 2019). In the same cases, the tangible benefit of EEW from people's perspectives is for mental preparation rather than the suggested and anticipated physical response for personal protection (Nakayachi et al., 2019). Thus, the review shows that despite claims EEW is beneficial, there is still a need to understand the nature of the benefits in-depth. Most of the success metrics for EEW have been on the seismological aspects, but EEW's success should also be scrutinized from the end user's lens (Cremen and Galasso, 2020).

TABLE 3 Summary of benefits discussed by the articles on having an EEW system through the disaster management phases.

Phase	Benefits	N*
Response	Personal protection	35
	Automated responses for systems to reduce impacts	27
	Situational awareness (for emergency responders, industrial users, decision-makers. etc.)	11
	Mental preparedness for earthquake shaking	6
	Prompt evacuation	2
Recovery	Help with the returning to normal after an event	2
Mitigation	Knowing exposure and vulnerability	5
	Build public confidence in systems	1
Preparedness	Create a culture of earthquake awareness and preparedness	8

*Number of articles that mentioned the benefit.

Challenges for public-facing EEW systems

EEW systems are complex as they include both technical and social attributes (Li and Jia, 2017). Implementing EEW comes with financial, political, and sociological challenges (Allen, 2011). The papers reviewed also recognize social challenges in achieving effective EEW systems. Some articles discuss various issues that impede the success of EEW systems. The most commonly identified social challenges were (1) the culture of awareness and preparedness education, (2) users' actions in

TABLE 4 Top three social challenges to overcome for effective EEW systems.

Challenge	N*
Culture of awareness and preparedness education	21
Users' actions in response to warnings	18
Implications of alerting errors	16

*Number of papers that mentioned the challenge.

response to warnings, and (3) implications of alerting errors. There are other challenges identified, but these three were identified most frequently by the articles in the review (See summary in Table 4).

Twenty-one articles mention the challenge of creating a culture of awareness about the system and preparedness education. It is widely recognized that installing and operating EEW technology requires substantial investment (Ahn et al., 2021). Still, sometimes the costs of public education campaigns are overlooked. Public education for EEW systems must be accounted for to teach people how to use EEW information (Allen, 2015). For example, in Washington State, USA, people have an appetite for EEW but have low earthquake preparedness (Bostrom et al., 2018). Educational and training programs are needed to develop people's ability to know the appropriate self-protection actions (Herovic et al., 2020; Sutton et al., 2020). The designers of Japan's public EEW system recognized that EEW would have very short warning times (up to several tens of seconds). Hence, people need to know the principle, purpose, and technical limits of EEW beforehand to ensure effectiveness without causing unnecessary confusion (Kamigaichi et al., 2009). Nakamura et al. (2011) emphasized the need to educate the public about EEW's limitations and integrate comprehensive earthquake preparedness education. It is essential to avoid overreliance on EEW for disaster prevention. The public must be encouraged to have reasonable self-management for earthquake protection beyond an earthquake warning itself (Nakamura et al., 2011). However, even with awareness and education, intended action may not result in actual behavior (Becker et al., 2020b) and may still result in inappropriate actions (Becker et al., 2020a).

Eighteen articles highlighted the challenge of understanding how users respond to alerts. These articles discussed whether alerts translated to appropriate user actions. Anticipated mitigating actions to alerts may not materialize as expected. For example, in Japan, Nakayachi et al. (2019) study (n = 359) showed that more respondents used the alerts to mentally prepare for shaking (25%) than to take physical action of moving nearby to a safe place (7%).

Some responses may be affected by the mode in which EEW is delivered. Alerts can be delivered *via* different means (e.g., sirens or wireless broadcasts), but often they are delivered in the form of short messages. The short message style might mean that people may feel they are only receiving partial information. Consequently, they may result to *milling*–looking for additional information or confirmation–before taking protective action (Goltz and Flores, 1997; Sutton et al., 2020). Responses may also be affected by personal attributes or experiences; for example, different people may also have different thresholds on the level of shaking that would trigger them to take action (Minson et al., 2017). Despite public training and education, it is uncertain how many people perform the official protective action advice of drop-cover-and-hold upon receiving an alert, as highlighted by literature from the West Coast, USA (Porter, 2018), and the Japanese study by Nakayachi et al. (2019). In another case study from Japan, a proportion of the people intended to take action during the Mw9.0 Tohoku-oki earthquake but could not because of the short warning time before the arrival of the shaking (Hoshiba, 2014). Some studies also highlight the importance of understanding how long a user needs (e.g., seconds, tens of seconds) to take useful action before shaking begins (Minson et al., 2019).

Sixteen articles discuss the challenge of alerting errors, as they can affect people's perceptions and have broader implications for EEW. One often raised risk is that false alerts may trigger mass panic, which is why systems must be configured to reduce false alerts (Asgary et al., 2007). Due to the technicalities of EEW systems, there is a trade-off between missed alerts and false alerts (Saunders et al., 2020). False alerts occur when alerts are issued, but no shaking follows, while missed alerts occur when shaking happens, but no alerts are issued. An optimized alerting strategy needs to consider community tolerance of these false and missed alerts (Saunders et al., 2020). False alerts can negatively impact trust in the EEW system. McBride et al. (2020) note that the issuer (i.e., alerting agencies) and recipients (i.e., end-users) may have different perceptions and thresholds for false alerts.

Scientists expect that the more educated people are about EEW, the higher the acceptability of information error, blind zones, and false and missed alerts (Guo et al., 2012). In Guo et al. (2012) study in China, a survey with 214 participants from all over China, only 23% of respondents accept information errors. In comparison, in a 2012 questionnaire by the Japan Meteorological Agency (n = 12,000), Japanese respondents had higher acceptability of errors; a significant proportion of the population (78%) is aware of EEW's shortcomings and understands the possibility of false alarms (Fujinawa and Noda, 2013). The difference between Chinese and Japanese respondents can be attributed to the Japanese being more exposed to and experienced with earthquakes and EEW information (Guo et al., 2012). From multiple EEW experiences, researchers have found that despite false and missed alerts, the public in Japan has some acceptability of alerting inaccuracy. A large proportion (85.6%) of respondents (n = 3,000) from Ohara and Tanaka (2013) study accept the possibility of missed warnings. Despite false and missed alerts, the majority in Japan – more than 90% in Tohoku ($n = 817$) and 80% nationwide ($n = 2{,}000$) in Hoshiba (2014) study feel that EEW is useful.

Furthermore, there are situations where multiple EEW issuers are at play (e.g., government authorities vs. private companies in Mexico). One party's false or missed alerts can reduce trust in EEW in general (Reddy, 2020). Liability questions arise on who should send the alerts and who is responsible for false or missed alerts (Gasparini et al., 2011). If false or missed alarms are poorly handled, it can cause chaos and financial loss; therefore, a sound legal framework must be considered for EEW effectiveness and accountability (Li and Jia, 2017). In this regard, only six of the 70 articles mention the legal aspects of EEW. This is an area ripe for further research.

End-user perceptions

A proportion of the articles ($N = 36$) include in their discussion an investigation of end-users' and broader societal acceptance, use, and perspectives of EEW. EEW systems have various end-users, including advanced users and the public.

Advanced users' perceptions

Advanced users (i.e., not the public), such as governmental agencies or industrial users, use EEW information for decisions that often have broader implications that may impact society and infrastructure. Advanced users have different contexts for decision-making. For example, a nuclear facilities manager might need to decide whether to shut down a reactor, emergency managers might use EEW information to deploy resources for emergency response, and urban search and rescue teams may decide whether to stop or continue rescue. Advanced users will have different views, depending on their contexts, on what are meaningful EEW lead times between warning and shaking (Oliveira et al., 2015) and on their tolerance for false or missed alarms (Le Guenan et al., 2016). Oliveira et al. (2015) survey showed that 83% of industry operators think 12 se provides sufficient time to take actions to minimize risk for the facility, while 17% did not feel confident that 12 s is sufficient. Le Guenan et al. (2016) study showed that decision makers' risk behavior affects their tolerance for false alarms. A decision-maker with a risk-neutral attitude can tolerate as many as five false alarms a year, but decision-makers with a more risk-prone attitude can handle more (Le Guenan et al., 2016).

In facilities management, the decision on how EEW is approached depends on the vulnerability of the facility and the costs of inaccuracies of estimated ground shaking (Böse and Heaton, 2010). For example, shutting down a nuclear reactor will be costly and have significant consequences (Cauzzi et al., 2016; Minson et al., 2019). Operators would like to know an EEW system's reliability beforehand and the system's propensity for false and missed alarms. The chance of missed and false alarms would need to be weighed with the costs and benefits before EEW can operationally be used for nuclear facilities (Cauzzi et al., 2016).

On the other hand, more tolerant users may prefer to get an earlier warning in other contexts even if they are more likely to receive false alerts. For USAR, teams working in high-risk environments (i.e., in unstable and vulnerable structures) find false alarms tolerable if the EEW system overall benefits the life-safety of the rescuers (Auclair et al., 2021). In a study of USAR personnel, 50.9% of respondents considered false alarms to have a low to very low impact in terms of loss of time and efficiency in USAR operations. However, repeated false alarms rather than isolated ones would affect a USAR team's confidence in a system (Auclair et al., 2021).

Two papers included in this review studied advanced users and quantitatively modeled their risk perceptions and decision-making. Le Guenan et al. (2016) emphasized that a participatory viewpoint is necessary for EEW since such systems can affect many groups, including infrastructure owners and elected officials. Le Guenan et al. (2016, p. 318) study tried to account for end-user preferences using a 'combination of multi-attribute utility theory and a Bayesian network for earthquake loss assessment'. Their method looks at the different views on acceptable risks, investigating setting a ground motion threshold for decisions to trigger an alert that would have benefits outweighing costs. Cremen and Galasso (2021) pointed out that while Le Guenan et al. (2016) method accounts for risk tolerance, it only works for binary actions (i.e., to trigger or not trigger an alarm). Cremen and Galasso (2021) then proposed an advanced methodology using a multicriteria decision-making (MCDM) approach coupled with a performance-based earthquake engineering framework incorporating Bayesian real-time seismic hazard analysis. Cremen and Galasso (2021) approach goes beyond binary decisions and enables multiple mitigation actions to be evaluated for various dimensions of uncertain risks. These two papers show that modeling risk-based decision-making will help EEW systems become end-user-driven tools to become more effective in promoting seismic resilience.

Public perceptions

Several studies in this review investigate public perceptions of EEW. Four recurring themes relate to public perceptions of EEW end-users. Generally,

(1) The public has favorable views of EEW.
(2) The public's views and level of support are critical to EEW's success.
(3) People's lived experiences with earthquakes affect their views on EEW.
(4) There are concerns regarding public alerting.

Positive public reception

Despite people's mixed responses to warnings (Huggins et al., 2021), people's perceptions of EEW are positive in areas with operational EEW systems available to the public. Studies in Japan (e.g., Fujinawa and Noda, 2013; Ohara and Tanaka, 2013; Nakayachi et al., 2019) show that the public generally views EEW as useful. Similarly, studies in Mexico (Santos-Reyes, 2019) and West Coast USA (Saunders et al., 2020) show that even with limitations in warning times and shaking thresholds, people deem EEW beneficial. In Taiwan, where EEW sensors are installed in schools, teachers view EEW as a valuable tool for promoting and teaching disaster prevention (Wu et al., 2017).

Public views and support for EEW success

National interest will vary dependent on the context of each country (Clinton et al., 2016). In Europe, at the time of writing, EEW was "not yet a product demanded by the general public or even the scientific community (Clinton et al., 2016, p. 2442)." The critical variable for the success of an EEW system is whether the public perceives the indispensability of EEW to keep them safe (Goltz and Flores, 1997). Gaining the public's insights is critical in the early stages of considering or developing EEW. A survey ($n = 3{,}084$) exploring the potential for EEW in New Zealand (Becker et al., 2020b) shows a different public perception of EEW compared to Europe. The survey in New Zealand, a seismically active nation, shows that most respondents supported an EEW system, signaling an opportunity to move EEW conversations forward (Becker et al., 2020b). Aside from considering public perspectives, the social context in which EEW is being developed should also be understood (Becker et al., 2020b).

Furthermore, the U.S. West Coast experience shows the successful spread of ShakeAlert was attributed to local stakeholders gathering support and funding to operationalize EEW at the early stages (Kohler et al., 2018). EEW also requires public funding, at least partially, for which public support is needed (Ahn et al., 2021). Where there may be user-pay models of funding, people's willingness to pay depends on their perceptions of earthquake risks and the level of protection they perceive EEW will provide (Dunn et al., 2016; Ahn et al., 2021).

Lived experience affects EEW views

Another recurring theme in public perceptions is that people's lived experiences affect their views on EEW. Ahn et al. (2021) study shows that people with lived experiences of earthquakes also perceive a higher risk of harm from earthquakes, thus influencing their views on EEW's usefulness and willingness to pay for EEW. Similar observations can be inferred from Hoshiba's (2014) paper, where it was observed that Tohoku residents, who were most impacted by the 2011 earthquake, were more likely to view EEW positively compared to the national average. Moreover, after earthquake events, there is heightened awareness and recognition of earthquakes among the public, especially in affected regions (Fujinawa and Noda, 2013; Ohara and Tanaka, 2013).

Concerns about public alerting

Despite the generally positive reception from the public about EEW, there are concerns related to the public's perceptions and knowledge of EEW alerts. The examples below show that the public may have misconceptions about EEW and associated information and sources that will impact their perception and trust in EEW, thus potentially delaying them from taking appropriate protective action when alerts are issued.

Not all shaking warrants an alert. The alert parameter for ShakeAlert in Los Angeles (LA) to issue a warning is set at Modified Mercalli Intensity Scale Level four (MMI-IV) or above. Yet, this may not be common knowledge for users. During the 5 July 2019 Mw7.1 Ridgecrest Earthquake, many LA residents felt the earthquake and were left unimpressed when no alert was delivered, even though the intensity in LA was MMI-IV and thus below the delivery threshold (Saunders et al., 2020). Because of public pressure from the perceived 'poor' performance of the ShakeAlert, the target parameter for the system was lowered for the LA area to MMI-III (Cochran and Husker, 2019; Saunders et al., 2020). However, shaking at MMI-III is considered weak where it may not be easily recognizable as an earthquake. Setting the system's threshold at this level will pose a different challenge; people may then receive an EEW alert but not feel or recognize the earthquake–which may lead to a perception of false alerts (Cochran and Husker, 2019; Saunders et al., 2020).

There may also be pre-conceived notions about earthquake alerts that may not necessarily be helpful. For example, in Mexico City, residents believe that an alert would always give them at least 60-s of warning before shaking arrives (Santos-Reyes, 2019). This belief is partly because of how the Seismic Alert System of Mexico (SASMEX) was designed from the Guerrero Gap to Mexico City, allowing for a close to 60 s prevention time if the rupture comes from the subduction zone along the Pacific coast. The risk of large earthquakes for Mexico City mainly originates from the Pacific coast, which has resulted in SASMEX issuing alerts with warning times of 60 to 90 s in most felt earthquake events. However, earthquakes in Mexico do not only originate from the Pacific coast, such as the 19 September 2017 Mw7.1 earthquake near Mexico City (Santos-Reyes, 2019). In such a case, confusion among the public can ensue when the system does not provide as much warning time as anticipated (Santos-Reyes, 2019). There should be basic public education on how EEW functions; education should be provided on EEW Systems and seismic hazards (Santos-Reyes, 2019).

The public also may struggle with delineating EEW information to warrant responsive action. Many people did not know the difference between EEW and standard earthquake information (Fujinawa and Noda, 2013). Furthermore, in areas where multiple parties can issue EEW alerts, the public finds

TABLE 5 EEW Stakeholders identified by the articles.

Stakeholders	Mentioned in *N* articles
Emergency managers	5
International/national seismic networks and research groups	5
Seismologists	5
Private sector	4
Social scientists	4
Communication practitioners	3
Government agencies	3
Policymakers/ political stakeholders	3
Researchers/scientists (generic)	3
Engineers	2
Technologists	2
Telecommunication sector	2

it difficult to differentiate the authorities from other players (Reddy, 2020).

Multi-stakeholder involvement

Although many of the papers included in this review focused on EEW end-users, some articles ($N = 25$) also covered different stakeholders' involvement in the design, development, and deployment of EEW systems. The stakeholders may also be advanced end-users but play a role in influencing the design and use of EEW systems. The findings show that multiple players are involved in EEW conversations. Table 5 summarizes the various stakeholders mentioned by the articles and shows the frequency of articles that refer to them.

EEW involves a multi-disciplinary effort. Research is not only conducted by seismologists and physical scientists, and cooperation is needed for the various stakeholders involved in the design, development, and implementation of EEW. For example, Parolai et al. (2018) emphasized the need for better cooperation between seismologists and engineers to deliver better EEW applications. Technology experts are also needed for the technological factors of the software and hardware interfaces of EEW systems (Goltz and Flores, 1997; Minson et al., 2015). Collaboration with social scientists is crucial in optimizing public warning systems (Allen and Melgar, 2019; Minson et al., 2020). McBride et al. (2020) showcased the value of an interdisciplinary working group that allowed the development of best practices in post-EEW alert messaging.

EEW collaboration also means working across borders with different seismic networks and research groups. In Europe, the project REAKT brought about a consortium of EEW researchers from seismic networks and research groups in the region (Oliveira et al., 2015). Because of the limited capabilities of smaller seismic networks, building effective EEW in Europe will require coordination and sharing of resources in the community (Gasparini et al., 2011). Similarly, for ShakeAlert to work across different states in the U.S., it needs to leverage the Advanced National Seismic System, a federation of cooperating seismic networks throughout the nation (Kohler et al., 2018). Developing an earthquake and tsunami monitoring network and an exploratory EEW system in Central America also saw invaluable data exchange and cooperation across borders between seismological institutions in Central America and Japan (Strauch et al., 2018).

EEW is not purely a research endeavor. Its effectiveness in society also requires close collaboration with various practitioner-based sectors. Earnest partnership between government agencies, policymakers, telecommunication operators, and researchers is indispensable for implementing warning systems (Malik and Cruickshank, 2014). The emergency management sector and communications specialists also play vital roles for EEW in ensuring public safety through appropriate messaging and educational strategies (Allen et al., 2019). EEW conversation must also include the private sector. In some locations, such as Mexico, commercial entities can issue EEW alerts alongside official agencies (Reddy, 2020). There also should be a good relationship between the officials and private providers to avoid confusion with end-users (Reddy, 2020). Furthermore, as advancements in technology allow smartphone devices for crowdsourced EEW, cooperation is crucial with device manufacturers to adapt to technological changes and commercial demands (Minson et al., 2015).

The findings show that aside from end-users, multiple stakeholders are involved in the various stages and processes of EEW systems. This implies that research on the social aspects of EEW should not be limited to downstream alerting and post-alerting communication to the public. It must also investigate the multi-stakeholder and interdisciplinary social dynamics in the design, development, and implementation of EEW systems.

Crowdsourced EEW and its implications

A recurring theme, especially in the more recently published articles, is the concept of crowdsourced EEW. Crowdsourced EEW is a developing area where EEW systems utilize the distributed participation of people and use mobile or low-cost technologies (e.g., smartphones or portable sensors). Nine articles included in this review have revealed advancements in EEW in using portable sensors and mobile devices (e.g., laptops or smartphones) for crowdsourcing EEW. Community-owned commercial or off-the-shelf devices have been recognized as powerful resources for sensor networks (Faulkner et al., 2011). In addition to these community-owned sensors, the ubiquity of mobile devices has expanded the scale of crowdsourced EEW in recent years, as networks can potentially use data from consumers' smartphones rather than solely relying on installed sensors (Minson et al., 2015).

The review has shown that the social challenges to crowdsourced systems include (1) public participation and user retention and (2) liability issues, and (3) commercial demands and ramifications.

Public participation in crowdsourcing

For some of these crowdsourced EEW systems, public participation is necessary. Users need to download an app and register their phones to become sensors in the network and receive warnings (Allen et al., 2019). Example of such system includes MyShake (Kong et al., 2019) and the Earthquake Network project (Finazzi, 2020). One of the challenges for opt-in systems is user retention (Finazzi, 2020). Such systems need to consider how they can keep users interested in installing and keeping the apps on their phones (Allen et al., 2019). EEW systems should find ways to incentivize users to contribute to crowdsourcing efforts (i.e., not uninstalling the app) (Panizzi, 2016). Smartphone app design should consider user interaction as customer satisfaction becomes crucial. For example, how the app consumes energy directly relates to satisfaction (Zambrano et al., 2017).

Liability concerns

EEW, whether crowdsourced or official, has not been fully utilized in many parts of the world because of liability issues; emergency managers are reluctant to automate EEW because of accountability in case of false or missed alarms (Gasparini et al., 2011). For crowdsourced EEW, it also becomes a blur on who is responsible for false or missed detections (Finazzi, 2020). Moreover, privacy and data protection must also be considered when handling user location information for crowdsourced systems (Finazzi, 2020).

The existence of official, crowdsourced, and privately-run EEW can confuse matters. Multiple parties, official and non-official, can issue alerts, but the public cannot usually distinguish between them (Reddy, 2020). Sometimes, alerts from different sources are also not delivered to their intended recipients, and one party's false or missed alerts can reduce public trust in EEW as a whole (Reddy, 2020). There may also be no barriers limiting competing parties from sending intentional false alerts to subdue competition (Reddy, 2020). Such liability considerations and issues impede EEW progress (Finazzi, 2020).

Commercial demands and implication

Finally, the use of smartphones for EEW comes with the pressure to keep up with commercial demands (Minson et al., 2015). Using smartphones provides opportunities for crowdsourced EEW systems, as they do not need significant capital outlays for equipment (Minson et al., 2015). However, this also means that crowdsourced EEW systems should align and keep up with the multiple existing mobile operating systems and their levels of permission access to data (Minson et al., 2015; Zambrano et al., 2017). Minson et al. (2015) also point out that the objectives of crowdsourced EEW systems might not align with the commercial intent of smartphone devices. Any implementation issues may have ramifications for the commercial products.

Discussion and conclusion

The results and subsequent discussion have several limitations that must be acknowledged. The interpretation of results is limited to the 70 papers written in English and Chinese texts found in the Scopus database. The research gaps identified herein are within the context of these 70 papers. Therefore, there may be papers or subject areas unexplored. Additionally, EEW is a rapidly evolving field of study, and there will inevitably be papers published since September 2021 that were not included in this review (e.g., Becker et al., 2022; Fallou et al., 2022; McBride et al., 2022; Vaiciulyte et al., 2022). Future research should consider expanding the literature coverage by including different databases and more recent publications. The focal point of this paper is to determine the extent of research thus far on the social aspects of earthquake early warning.

The 70 articles have touched on a breadth of social science research topics. However, multiple gaps still exist in investigating the social aspects of EEW. Three fundamental areas to further investigate: (1) understanding EEW effectiveness from the social standpoint, (2) uncovering integrated multi-stakeholder approaches throughout the disaster lifecycle and the EEW design cycle, and (3) understanding how EEW and society adapt to innovations and changes–including legal perspectives.

EEW effectiveness

The effectiveness of EEW systems has been measured from seismological and technological standpoints. They can be evaluated on the accuracy and timeliness of ground motion estimates (Meier, 2017) or using the latency of alert time and lead time (Kamigaichi et al., 2009; Minson et al., 2018). An economic valuation can also estimate effectiveness by measuring the estimated loss reduction in relation to investment (Oliveira et al., 2015). From the human behavior perspective, the view of effectiveness is in how end-users recognize, interpret, and respond to EEW (Wald, 2020).

End-users' reactions to warnings are crucial to EEW systems' effectiveness in society. However, twenty of the papers in this review presumed that EEW would provide benefits (e.g., individuals will use the lead time to drop-cover-and-hold). However, those that reported the actual outcomes of EEW, such as in the Japanese contexts, indicated that fewer than the expected number of people took the prescribed protective action. As Nakayachi et al. (2019) indicated, despite numerous indications of the potential utility of EEW, there is limited evidence of the actual (not potential) benefits of warnings to the public. Research thus far, to some extent, has relied on the potential benefits of EEW (Wald, 2020). Future EEW research must operate beyond these assumed benefits and should work with realistic representations of the EEW benefits to society. Further investigation is needed on the actual effectiveness of EEW from a social standpoint.

It must be acknowledged that gathering data for people's actual reactions can be challenging, as people's response to an earthquake is dependent on the specific conditions that it is difficult to compare across earthquake events. Furthermore, it is hard to compare groups of people (who got the warning to those who did not) in a particular situation. Therefore, the usual way, so far, to gather such data is through surveys that require respondents' introspection. Future studies should investigate improving the data gathering methods and finding innovative ways to capture end-user perspectives on EEW effectiveness (e.g., earthquake simulation or analysis of alternative data such as CCTV or social media).

More importantly, researchers should investigate why there are low numbers of people taking protective action with EEW. A recent study in Peru ($n = 2,625$) confirms the past studies' findings that most alert recipients do not take protective action (Fallou et al., 2022). To improve the effectiveness of EEW, more study is required to understand why action is taken (or not) and how to motivate more people to take appropriate protective action. A people-centered EEW means building social capacity in people's disaster risk knowledge and their ability to respond to warnings appropriately. People-centered EEW also challenges system designers and researchers to consider the heterogeneity of end-users. Different groups' accessibility to the system (for example, the elderly and differently-abled) should be considered. More research is needed to understand people's experience, knowledge, and capability to respond to the alerts.

Involvement throughout the disaster management lifecycle and EEW design cycle

This study has shown that most social research on EEW has focused on the response stage of the disaster management phase. However, the articles have also revealed that people also interact with EEW in the other phases of disaster management. Further research should explore EEW's role beyond the response stage of the disaster lifecycle. Particularly, EEW can be used to promote earthquake preparedness and create a culture of earthquake awareness and readiness. Improving risk communication pre-crisis and throughout the earthquake crisis lifecycle could potentially improve EEW's overall effectiveness (Herovic et al., 2020). For EEW, pre-crisis education could provide (a) information about the potential for earthquakes, EEW and its limitations, and possible impacts on the community, (b) how to prepare, and (c) campaigns about appropriate self-protection actions during earthquakes in general and when receiving alerts (Becker et al., 2020a; Herovic et al., 2020). Future research should investigate integrating EEW public education across the disaster management phases of recovery, mitigation, and preparedness to improve earthquake resilience. Another area for research investigation is the design, implementation, improvement, and evaluation of the EEW education programs toward the overall effectiveness of EEW and earthquake resilience of communities. More research could expand on the best practices for EEW public education, considering different types of users and their context of use for EEW.

Any disaster risk reduction effort needs to incorporate awareness, education, training, and collaboration mechanisms (Malik and Cruickshank, 2014). Research on EEW should not focus only on communicating to end-users but also needs to investigate the interactions between various entities involved in the EEW design process. EEW research often involves a design science process–where the design of a solution (i.e., EEW system) also produces generalizable knowledge that can be appropriate to a research community (Johannesson and Perjons, 2014). Creating an EEW system requires strong foundations in the technical knowledge base. Still, for EEW to be effective, it must also be appropriate to its application domain (i.e., relevant to its stakeholders). Implementing EEW suitable for society will require engagement with multiple stakeholders throughout the process, including the public, scientific experts, and sectoral and industrial partners. A collaborative framework is needed to engage EEW research and practice. Tan et al. (2021) formed a community of practice for earthquake early warning discussions in New Zealand; the collaborative framework shows the value of diversity of perspectives to enhance knowledge exchange toward developing an EEW system. Future research should investigate integrated stakeholder approaches for advancing EEW. Research is also needed to enhance communication and collaborations for EEW researchers and stakeholders across disciplines throughout the system design, development and implementation.

Social EEW research should adapt to the fast-changing trends

With innovation in technologies, many opportunities arise for EEW design and implementation. This review has shown that smartphones are now being used for crowdsourced EEW. The ubiquity of smartphones means that EEW is becoming transboundary. EEW design and development are no longer limited to geographical jurisdiction and can be implemented across borders. For example, the Google initiative introduced the Android Earthquake Alerts System in New Zealand and Greece in April 2021 (Voosen, 2021). This also raises the concern of EEW players' civic responsibility, and a step further is the concern of legal liability. As of writing, minimal research has focused on the legal aspects of EEW systems. Articles in this review may have included some legal topics in their discussion, but only two articles (Li and Jia, 2017; Valbonesi, 2021) in this study focused primarily on the legislative components of EEW. But with the changing contexts due to technological trends, evidenced-based research is needed to inform regulation, policy, and planning of effective EEW in countries and territories.

Multiple countries and territories now have official EEW systems. Still, most of those capable of having official operational EEW are high-income countries/territories (e.g., Japan, West Coast USA, Taiwan etc.). These EEW systems are costly to deploy, implement, and maintain (Given et al., 2014; Prasanna et al., 2022). Because of high costs, lower-income countries have not had the same opportunity to access EEW as an earthquake mitigation tool. However, low-cost alternative technological solutions, such as using micro-electromechanical systems (MEMS) (Cochran et al., 2011), smartphones and apps (Cardno, 2020; Bossu et al., 2022), and decentralized architectural networks (Prasanna et al., 2022) can make EEW more accessible to lower-income countries. Future social science research should investigate how these low-cost technological solutions will be utilized by various countries (e.g., high-income and low-income) as mitigation tools. Social challenges arising from low-cost solutions should also be monitored and investigated.

Low-cost alternatives such as smartphones and other low-cost devices for crowdsourced EEW imply that more players can issue EEW alerts. While more options can generate benefits, they can also create problems. As in the case in Mexico, a false alert issued by an independent app caused confusion, created concerns for the official authority and raised the question of what civic responsibility might mean for people behind EEW systems (Reddy, 2020). Technological changes bring about new ways to design and implement EEW systems, and it also changes end-users perspectives. EEW research would need to reassess and update knowledge and assumptions as it applies to new and changing contexts.

Conclusion

Across the world, EEW systems already exist, and more countries are considering designing and implementing EEW for earthquake resilience. The rapid development of technologies and methods has provided a deeper physical understanding of earthquakes and improved the EEW processes for better warnings. As EEW innovates further and becomes more accessible and transboundary, social science research must also take a proactive role in the research advances of EEW, including legal perspectives.

This paper addresses the social science knowledge gap on EEW by reviewing the literature. Each of the 70 articles included in this review had different objectives, but collectively they have provided insight into the social science research relating to EEW systems. The articles in this review look at EEW from different perspectives, such as advanced end-users, the public, and the various EEW stakeholders. The findings reiterate that public education is critical for effective warning systems. The articles show that despite the various potential benefits of EEW to society, there is still a further need to understand EEW's impacts and interactions with society.

Social research in EEW is not just about delivering alerts to end-users. Social science research is needed to improve EEW systems further; in understanding how people, stakeholders and end-users, interact with EEW throughout its development process and when implemented through the various phases of disaster management. Suggested topics for future research include (1) advancing our understanding of why people take action or not and ways to encourage appropriate action when alerted with EEW, (2) enhancing public education – best practices for communicating, educating, and engaging with the public about EEW and earthquake resilience, and (3) keeping up with technology advances and societal changes, investigating how these changes impact how EEW interacts with society from various standpoints including legal perspectives.

Author contributions

Conceptualization and funding acquisition: MT, RP, JB, KS, AB, CK, and EL. Methodology, writing—original draft preparation, and visualization: MT. Formal analysis: MT and AC. Investigation: MT, JB, KS, RP, and AC. Writing—review and editing: MT, JB, KS, RP, AB, CK, AC, and EL. Project administration: MT and RP. All authors have read the manuscript agree to be accountable for the content of the work.

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Conflict of interest

Author EL is employed by Sysdoc Ltd., Wellington, New Zealand.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2022.939242/full#supplementary-material

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"It's something that I do every day." Exploring interdisciplinarity and stakeholder engagement in tsunami science

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Tsunamis are natural hazards that can have devastating societal impacts. While tsunamis cannot be prevented, their risk to coastal communities can be mitigated through targeted measures such as early warning, evacuation training or tsunami-aware spatial planning. The particularities of tsunamis–being rare events with high impact and a short yet operable time span for warning–structure the associated research approaches and sociotechnical innovations. In this paper, we explore interdisciplinary knowledge integration and stakeholder engagement in tsunami science based on interviews with researchers from various tsunami-related fields. We find that the interviewees' academic identities are typically grounded in a disciplinary core, out of which they subsequently cross boundaries. For all respondents, however, it is a matter of course that becoming and being a member of the tsunami community includes the need to communicate across boundaries. Our results show that the idea of early warning unites the tsunami field. Notably, however, it is not the material technology but the political goal of effective early warning that holds an integrative function across disciplines. Furthermore, we find modelling to be seen as the "backbone of everything" tsunami-related, which in combination with visualisation techniques such as a global map of tsunami risks also serves to integrate stakeholders beyond the tsunami research community. Interviewees mention the interaction between scientists and engineers as the exemplary interdisciplinary collaboration in tsunami science. There were fewer examples of collaborations with social scientists, rendering this a demand rather than a lived reality in current tsunami science. Despite the widely shared view that stakeholder engagement is an important element of tsunami science, respondents emphasise the associated challenges and indicate that this practice is not yet sufficiently institutionalised.

KEYWORDS
tsunami, interdisciplinarity, stakeholder engagement, geohazard, early warning

Introduction[1]

Tsunamis are natural hazards and pose societal risks, as evidenced by the 2004 Boxing Day and the 2011 Tohoku events. While tsunamis cannot be prevented from happening, their risk to coastal communities can be mitigated through targeted measures such as early warning, evacuation training or tsunami-aware spatial planning. These applications require both basic and applied research efforts to understand tsunami sources, wave propagation and local inundation dynamics, as well as efforts to understand the social dynamics around tsunami warning, local governance, public education and trust. Several sciences, including geology, geophysics, oceanography, physics and mathematics study the creation and evolution of tsunamis. Social sciences such as political science, human geography, economics and sociology, but also civil engineering and urban planning, are involved in tsunami risk assessment and mitigation on shore. The peculiarities of tsunamis lie in that they are rare events with often catastrophic impacts and a short yet operable time span for warnings. It is thereby the goal of scientists of different backgrounds involved in tsunami research to bridge disciplinary divides and work together to mitigate tsunami risks.

The paper at hand aims to explore interdisciplinary and stakeholder integration by reflecting on current practices and challenges in tsunami research. We are interested in understandings of interdisciplinarity, risk and uncertainty among tsunami scientists, and base our analysis on problem-centred interviews with participants of the EU COST Action "Accelerating Global science In Tsunami HAzard and Risk analysis" (AGITHAR) complemented by observing participation in AGITHAR's initial meeting. In the following, we firstly revisit the challenge of interdisciplinarity from a sociology of science perspective (2). We then review the literature on interdisciplinarity in tsunami science and derive a set of research questions for the interview study (3). Subsequently, we introduce the study's methodology and sample (4). The main part of the paper presents the results (5), discussion and conclusions (6).

Scientific disciplines and the origins of interdisciplinarity

The emergence of modern scientific disciplines dates back to the 18th century and there is no doubt as to their ongoing structural significance for both research and education. The complexity of disciplines as a phenomenon requires a multidimensional definition. In social terms, disciplines are communities of specialists whose infrastructure includes university chairs and departments with associated training programmes in the form of degree courses, and journals with disciplinary members as authors and editors (Stichweh, 1984: 449). In epistemic terms, a discipline can be described as a self-reproducing context of concepts, theories and methods, which are confirmed, modified or discarded in time through research. In communicative terms, one observes publications that link to one another by means of citations and continually redefine the boundaries of the discipline by means of principally contingent acts of referencing (Stichweh, 2013: 2).

Yet, the advent of disciplines and their role in the production of scientific knowledge have always been accompanied by *interdisciplinarity* (Abbott, 2001: 121). Due to its historical character, the disciplinary scheme "cannot be conceived as a perfect order of knowledge" (Luhmann, 1992: 456), and the condensation of attention within disciplinary boundaries has disadvantages: "As soon as the disciplines burst apart like ice floes and, albeit in the water, bob along their own paths: what then becomes of the "in between"? What becomes of "overarching questions" that can only be dealt with when the expertise of several disciplines comes together?" (Luhmann, 1992: 456). Interdisciplinarity can then be seen as the attempt to address these "impediments to vision" and to reintroduce them into the research (Luhmann, 1992: 459). Another motive for interdisciplinarity links to societal interests. In addition to blue-sky research, scholars seek to develop solutions to real-world problems. For this, collaboration between disciplines (interdisciplinarity) is seen as a prerequisite, as is crossing the boundary between science and society by including non-scientists, an approach often associated with the labels *transdisciplinarity* or *stakeholder engagement*.

The science policy discourse around inter- and transdisciplinarity often frames disciplines as obstacles in the way of real-world problem-solving and useful knowledge production (Weingart and Stehr, 2000). Inter- and transdisciplinarity then are repair phenomena to remove knowledge-limiting disciplinarity, and research policy promotes the production of integrated knowledge. The pre-disciplinary 17th and 18th centuries and the disciplinary 19th and 20th centuries are now said to be superseded by post-disciplinary times (Weingart and Stehr, 2000: xi; Klein, 1999), characterised by a plurality and diversity of places, methods and actors in knowledge production. Criteria such as social relevance and robustness (Nowotny, 2003) complement quality assurance by peers, and extended peer communities come into play (Funtowicz and Ravetz, 1993). While the disciplines have so far enabled the accumulation of knowledge within paradigmatic "normal science" in Kuhn's sense, the new "post-normal science" is characterised by uncertainties, value conflicts and an urgency of political decisions (Funtowicz and Ravetz, 1993). Climate sciences (Bray and von Storch, 1999) and tsunami science are cases in point. The question then is not *whether* but *how*

1 We use UK spelling throughout the manuscript.

interdisciplinary knowledge integration and stakeholder engagement are to be pursued by scientists in the tsunami field.[2]

Why is interdisciplinary integration such a challenge? The fact that knowledge integration is a challenge is rooted in the principles of disciplinary differentiation. The neo-Kantian philosopher Wilhelm Windelband (1904) for example, distinguished the natural sciences from the humanities by attributing the search for general laws to the former and the description of unique individualities to the latter as their epistemic goals. Another answer to the question of how disciplines differ is by their methods. Mathematics, for example, can be characterised by the methodology of proof (Heintz, 2000). Physics, however, also sometimes uses proof, which shows that specific methods are not discipline-exclusive. Furthermore, methodological pluralism prevails within most disciplines. In a tradition of thought that began with Fleck's (1979) reflections on scientific styles of thought in the 1920s, Kuhn proposed the term paradigm to describe how communities of specialists group around a theory and make it the basis of their research activity (Kuhn, 1962). According to psychologist Heinz Heckhausen (1987) it is this conceptual level of integration that constitutes disciplinarity and goes hand in hand with specific types of abstractions. This results in incommensurability–a level of difference that even makes comparisons impossible–both between historically successive paradigms of a discipline and between disciplines. These challenges are exacerbated in transdisciplinary settings. By definition, transdisciplinary projects should meet and adequately address scientific *and* other demands, such as political, economic or public interests. This leads to a default expectation of challenges, as Maasen and Lieven (2006) have put it, based on an in-depth study of transdisciplinary practice: "Notably, negotiating, coordinating and integrating heterogeneous types of knowledge, values and interests are bound to cause complexities that border on the irresolvable task of rendering incommensurabilities commensurate" (2006: 402).

The different lenses that the disciplines apply to natural and social phenomena go hand in hand with socialisation processes into disciplinary communities: over the course of their training, junior researchers acquire specific sets of values and beliefs, such as in quantification and modelling. This is in line with organisational theory (Whitley, 2000), which finds that scientific reputation–gained by publications in prestigious, mostly disciplinary journals–is the key mechanism that controls the institutionalisation of a field as an epistemic community (Gläser, 2006). Anthropologists of science have thus come to describe disciplines as "academic tribes" (Becher and Trowler, 2001: 39) that defend knowledge monopolies on certain territories. The sense of belonging to an academic tribe, typically evidenced by a formal academic degree, creates academic identities at the disciplinary level, which include interaction preferences as well as a certain sense of humour, dress and lifestyle. Science & Technology Studies scholar Sheila Jasanoff puts the resulting challenges as follows:

"[W]e academics, whatever our disciplines, tend to be rather a lazy lot when it comes to tending our relations with those outside our own disciplinary enclaves. Conversations with close colleagues are ever so much easier, more efficient, and often just plain more fun, because even quite fundamental disagreements are grounded in a common matrix of shared concepts and commitments. Why bother with the far more difficult task of engaging outsiders in one's most passionate pursuit when the results are bound to be time-consuming and by no means guaranteed to win understanding, let alone friends?" (Jasanoff, 1996: 264).

The field of tsunami science and its integration challenges

Knowledge production in tsunami science

Throughout the last decades, the field of marine geo-hazards–which include tsunamis–has been experiencing a continuous rise in publication activity (Camargo et al., 2019). Tsunami science in particular has seen a strong increase since 2005. The spike in this specific year can be traced back to research taking place in the aftermath of the Sumatra Tsunami on Boxing Day 2004 (Chiu and Ho, 2007; Sagar et al., 2010; Jain et al., 2021). The 2011 East Japan Tsunami triggered another rise in tsunami-related research activities, especially in Japan (Imamura et al., 2019). Yet, the surge in research activity after a tsunami event is often not sustained for more than a few years (Sagar et al., 2010).

Since the early 1990s, the development of tsunami early warning systems (TEWS) is pursued as one of tsunami science's key objectives (Synolakis and Bernard, 2006; Kânoğlu et al., 2015), on the basis of hazard and risk assessments and alongside other precautionary measures such as evacuation maps and tsunami signage installed at the inundation zone. The short, yet operable time span between the causing event and the incidence of the wave at the coast distinguishes tsunamis from other natural hazards. While hurricanes and other meteorological events can often be predicted days in advance, earthquakes are barely predictable at all. The resulting challenge for tsunami science is twofold. First, coastal communities must be equipped with hazard and risk assessments to initiate precautionary measures (Løvholt et al., 2019). Second, in the case of an event, the warning must reach local communities in

2 Throughout this paper, we refer to any research that involves two or more disciplinary perspectives as interdisciplinary research. We furthermore differentiate narrow interdisciplinarity, which refers to the interaction of neighbouring scientific fields, such as geology and geophysics or sociology and communication science, from broad interdisciplinarity, which describes the interaction of fields with very different disciplinary cultures such as physics and sociology.

time and lead to an immediate evacuation. Both challenges contain natural and social elements that cannot easily be disentangled (Bradley et al., 2019; Rafliana et al., 2022). For the necessary precautionary measures to be in place, the science must be sound and the political and administrative processes must work. In the case of an event, successful evacuation not only depends on whether the warning has been issued and transmitted to local communities on time, but also on whether the local infrastructure is working properly and whether local communities have enough trust in the warnings to indeed evacuate (Pescaroli and Magni, 2015; UNDRR and UNESCO-IOC, 2019; Rafliana et al., 2022). With regard to evacuation it is furthermore important to distinguish between self-evacuation without an alarm being issued (can happen in the case of near-source or non-seismic tsunamis) and evacuation after an alarm is being issued by the authorities. Also the question arises how the implementation of early warning systems impact the capacity to self-evacuate. A dilemma, especially in densely populated areas and areas with infrastructures such as power plants, ports or refineries, is *not to evacuate* in the case of no wave, because the damage caused by an incorrect evacuation (which can be the more frequent case) is greater than that caused by a non-evacuation. This dilemma complicates matters for TEWS developers and decision-makers because of the high uncertainty and the short warning time.

Models play an important role in integrating different sources of knowledge that are important to tsunami science. Given the lack of empirical tsunami observations–since large tsunamis are rare events–numerical modelling is a key "tool to establish links between source parameters and hazard metrics" (Grezio et al., 2017: 1170). Tsunami modelling increasingly takes the form of a Probabilistic Tsunami Hazard Analysis (PTHA; Grezio et al., 2017; Løvholt et al., 2019, Behrens et al., 2021), which aims to estimate the probability of exceeding a certain tsunami metric at a given location within a given time period. According to Løvholt et al. (2019), PTHA usually comprises information on tsunami sources in a probabilistic manner, including uncertainties from both natural variability and lack of knowledge, as well as a description of how the tsunami and its associated uncertainties propagate to the impact site. However, the authors state that PTHA–due to its origin in seismic hazard analysis–is more developed in its description of earthquake-induced tsunamis and less developed for non-seismic tsunami sources. While PTHA integrates sources, wave propagation and inundation dynamics in a single framework, Probabilistic Tsunami Risk Analysis (PTRA) goes even further by estimating losses by accounting for exposed values and the vulnerability of coastal societies. As such, PTRA must include geophysical modelling of the source dynamics and hydrodynamic modelling of tsunami creation and propagation as well as geographic, economic and sociological accounts of exposed buildings, damage to critical infrastructure and local preparedness. Especially when considering the risk of mortality, aspects related to the vulnerability of different societies and local tsunami protection measures have a large influence on PTRA results (Løvholt et al., 2019). PTHA can thus be considered a modelling framework that comprises the natural science aspects of tsunamis, whereas PTRA also includes human and societal aspects, and consequently requires input from social sciences as well as stakeholders such as coastal protection agencies and local governments.

Knowledge integration in tsunami science

The applied nature of the tsunami field makes interdisciplinary work indispensable, yet challenges to interdisciplinary research clearly show in the sparse literature on knowledge integration in tsunami science. Yonezawa et al. (2019) studied the International Research Institute of Disaster Science (IRIDeS) of Tohoku University in Japan. IRIDeS was established in the aftermath of the 2011 East Japan Earthquake and Tsunami with a strong focus on multidisciplinarity (Imamura et al., 2019). To assess opportunities and limitations of IRIDeS's approach, Yonezawa et al. (2019) conducted semi-structured interviews with 15 researchers. They conclude that the integrated research focus alone was not sufficient to enable truly interdisciplinary work. Interviewees stated that they feel an obligation to "master the current established discipline as their own expertise first" (2019: 7) because they were not being equipped with a comparable interdisciplinary approach on which to build their careers. Further barriers mentioned include the negative effect of interdisciplinary research on internal evaluation and reputation mechanisms because of difficulties to publish and attract external funding. These barriers were mainly traced back to the organisational structure of the institute, which had four disciplinary-based subdivisions. An administrative restructuring in 2018, however, has redefined research areas based on real-world problems. This restructuring, according to the interviewees, led to more constructive exchanges between researchers with different disciplinary backgrounds. Still, the authors conclude that there are significant barriers to effective interdisciplinary research even in an environment that pursues interdisciplinarity as an organisational goal. Kelly et al. (2019) take a more general approach to enabling mechanisms and barriers in interdisciplinary research. The authors formulate their findings in 10 tips for interdisciplinary researchers related to common barriers. These include language barriers between disciplines, limited guidance for interdisciplinary students and young researchers and a lack of reputation opportunities for interdisciplinary research within established disciplines. Further, they state that interdisciplinary collaboration takes more time initially, is harder to publish and often lacks funding opportunities.

Researchers working in interdisciplinary projects also contribute to the literature. In disaster science, which includes tsunami science, several papers have been published about the relevance of interdisciplinarity, viable approaches towards it and associated challenges. Takara (2018) wrote a discussion paper based on conversations with fellow researchers on disaster risk reduction, in which he emphasises the importance of new knowledge systems, which should be "integrating scientific as well as local and indigenous knowledge" (2018: 1195). Takara views a consistent terminology as the backbone of any such knowledge system and proceeds to define and elaborate basic distinctions in interdisciplinary disaster risk reduction. Disaster risk, for instance, is defined as the product of hazard, exposure and vulnerability (Takara 2018; Løvholt et al., 2019). The paper calls for a harmonisation and shared understanding of the terminology and concludes with five recommendations. These include a call for further interdisciplinarity in disaster science, stakeholder involvement and a stronger consideration of different social vulnerabilities and complex, compounding risks.

In a perspective essay, Ge et al. (2019) had a closer look at interdisciplinary teams in the context of research on disaster response. The three showcased teaming mechanisms are called grant-driven, institute-based and expertise-oriented. Grant-driven teams are multidisciplinary teams, which means that they involve researchers from different disciplines but without developing shared connections, approaches and concepts (Hardy, 2018). Institute-based and expertise-oriented teaming mechanisms in contrast are considered truly interdisciplinary. The difference is that institute-based teams have a rigid and localised organisational structure, whereas expertise-oriented teams are often a loosely structured network aiming for "long-term research proliferation" (Ge et al., 2019). Having established an interdisciplinary disaster research team, the challenge is to find common ground, as Gilligan (2019) puts it. The goal is to "build trust, facilitate communication, and develop interactional expertise." In contrast to contributory expertise (the ability to fruitfully contribute to research within one discipline), interactional expertise describes the ability to interact by processing languages and concepts from different disciplines. Researchers with interactional expertise are useful in interdisciplinary teams because they mediate in communication and translation. Gilligan (2019) further emphasises the role of tacit knowledge, which is a form of knowledge about a field that develops through professional interaction and cannot be spelled out explicitly. In terms of strategies to foster interdisciplinarity in disaster science, the author proposes "intensive focused interactions" (e.g., interdisciplinary teaching, interdisciplinary research, workshops or sabbaticals) and collaborative fieldwork. He suggests a gradual approach, which continuously builds up interdisciplinary skills through meetings, projects and institutions and, through this mutual learning forms common ground in an emerging interdisciplinary research field. In another perspective essay, Hardy expands on strategies of establishing common ground in hazard research. The author proposes a "sharing meanings approach" (Hardy, 2018), an iterative process of sharing, listening and questioning to productively make use of the tensions between disciplines. The article comes up with strategies on how to cope with different worldviews, disciplinary languages and perspectives on the research design and project goals. By employing these strategies, Hardy hopes that implicit assumptions can be made explicit, which in turn helps an interdisciplinary research team to progress towards a "hybrid methodology research design" (2018: 8).

In an empirical paper, Martinez et al. (2018) emphasise the beneficial role of qualitative research for understanding local phenomena and dispositions, both for social and natural scientists. Interviews with researchers participating in an EU project indicated that a shared methodology was considered very helpful across disciplinary backgrounds and helped to establish an encouraging atmosphere for interdisciplinarity. Yet, the authors also note that knowledge integration requires a lot of engagement and is not supported from the start in EU research projects. Specifically, they criticise that individual work packages and deliverables are often centred on established disciplines and that projects lack a pilot phase in which to develop common ground and a shared interdisciplinary research agenda. They conclude that, in practice, this often leads to mere grant-driven teams–multidisciplinary collaborations, where "one discipline works on one aspect of a project and a different discipline on another" (2018: 71). Martinez et al. (2018) had science and social science & humanities researchers work together on qualitative interviews, and natural science researchers stated that this increased their understanding and recognition for social sciences. Kirby et al. (2019), however, found that earth scientists perceive social scientists as significantly less competent than themselves or natural scientists in general, supporting often-held notions of hierarchies between "hard" and "soft" sciences.

Having reviewed experiences with and approaches to interdisciplinarity in disaster science, what are the lessons for tsunami science? As showcased by Takara (2018), disaster risk is composed of a natural hazard component and a social vulnerability component. Tsunami risk is different from other natural disasters in that it is largely influenced by the capabilities of local communities to self-evacuate quickly. This feature has consequences for interdisciplinary tsunami research, e.g., for possible new knowledge systems. Knowledge production across disciplines typically relies on integrating mechanisms, which provide a unifying framework (such as a model or a static or dynamic map) and allow researchers to more easily collaborate (Sarewitz and Pielke, 2001). For disaster response, Ge et al. (2019) propose data collection as an integrating mechanism. Gilligan (2019) suggests that collaborative fieldwork could serve as an integrating mechanism in disaster research. More research is needed, however, to understand the mechanisms that integrate tsunami researchers and provide them with a shared understanding of their field. While insights into teaming mechanisms and the development of common ground through unified terminologies and shared meanings can be adapted from disaster science in general, the focus on numerical modelling and warning systems raises special questions about knowledge integration in tsunami research. An exploratory study of interdisciplinarity in tsunami research is so far lacking yet needed to tackle the challenges that this field poses.

Materials and methods

Methodologically, we employ the problem-centred interview approach (Witzel and Reiter, 2013). This perspective from interpretative social sciences puts the interviewees' understandings, meanings and practices front and centre. From this follows that we developed a semi-structured interview guide, i.e., a set of questions which broadly structure the interview while allowing us to adapt them to the respondents' expertise, interests and reflections. The interview guide was informed by our conceptual considerations on (inter-) disciplinarity and a literature review[3]. From the AGITHAR participants, we selected nine interviewees according to several pre-defined criteria. First, the interviewees have diverse academic backgrounds including seismology, mathematics, engineering, sociology, and statistics. This allowed us to include a broad range of perspectives on the field of tsunami science. Second, we covered different methodological approaches, including fieldwork, modelling, and development of early warning systems. Third, we aimed for diversity in geographical background and gender.

Our final sample includes four female and five male researchers. Three out of nine researchers came to the field prior to 2004, four between 2004 and 2011, and two joined the field after 2011. While our sample includes some early career researchers, the focus was on senior researchers because we expected them to have more years of experiences in collaborations and more insight into long-term developments of the field and the associated research community. All interviews were conducted in June 2020, remotely via Zoom or Skype. Depending on the respondents' preferences, it was an audio or a video call of about 45–60 min length. The audio track of the interviews was recorded and transcribed word-by-word. Throughout the interview process and transcription, we took notes, paying attention to emerging commonalities or conflicts.

For the small number of interviews, we decided not to use any software for qualitative data analysis. Instead, we produced case descriptions of three to five pages for each interview, which were structured along predefined categories. In a second step, this allowed us to compare statements from different interviews. We identified several recurring themes, around which we organised further analyses. In our presentation, we cite from the interviews by referring to the respective number of the interview and the line of the respective quote (e.g., 2: 34).

Results

The tsunami community and boundaries in tsunami science

Tsunami science appears as composed of strong disciplines with firm boundaries and specific disciplinary abstractions of phenomena, such as waves, and concepts, such as risk.

> *It contains the whole geoscientific community, starting from oceanography, seismology, geology, geophysics. Already there you see many clashes, between oceanography and seismology, for example. Their understanding of what a wave is, is so completely different that you have to communicate a lot. And then, when it comes to the impact, you have the disaster managers who are often either military people or social scientists and there again, you have misunderstandings and different approaches to things. (1: 35)*

The way respondents talk about their academic identities implies that they typically are grounded in a disciplinary core, out of which they subsequently cross boundaries.

> *My whole life I have been crossing disciplinary boundaries. (1: 27)*

> *I am a geophysicist by training, a seismologist, and this is what I do well. I don't do, for example, social science research myself, I don't do landslide modelling, but I think I'm good at facilitating interdisciplinary work. And I think that's very characteristic for my view on interdisciplinarity. Being an interdisciplinary scientist doesn't mean that you have to address all these different disciplines, but you have to find the right people and bring them together. (2: 21)*

Some claim to have developed interdisciplinary identities, yet still speak of "other disciplines" as their counterparts:

> *I call myself interdisciplinary researcher because from the beginning of my tsunami research I always collaborated with all scientists, and I shared my data and tools with the experts*

3 We used Web of Science to perform a keyword search based on: " TS = (((interdisciplinar* OR transdisciplin*) AND (tsunami* OR "disaster science" OR "disaster research")))."

> *from other disciplines and I also expect sharing from other disciplines. (9: 32)*

> *I really jumped across fields, and I had to incorporate different methods. (4: 13)*

In the latter case, the interviewee, who is a junior researcher, invokes that it might cause issues if a researcher does not "*fit in a traditional scientific environment*" (4: 263) because he works in different disciplines with no clear primacy of a disciplinary core. For all respondents, however, it is a matter of course that becoming and being a member of the tsunami community includes the need to communicate across boundaries.

> *It's something that I do every day. (7: 246)*

Researchers' understandings of interdisciplinarity, and the need for it

There is no doubt as to the relevance of interdisciplinarity for the field. Unanimously, the interviewees characterise tsunami science as an interdisciplinary field.

> *Interdisciplinarity is one main, essential component of tsunami research. (9: 4)*

> *I think it is humbling to know that we cannot address this problem with one discipline. (6: 27)*

> *There is no way to work in tsunami risk assessment with one discipline only. (6: 33)*

To explore the nature of interdisciplinarity in tsunami science, the researchers' own understandings of the concept are relevant. Throughout the interviews, we find experience-informed and rather sophisticated accounts of the phenomenon, indicating that tsunami researchers indeed work in contexts that they themselves perceive as interdisciplinary. As one interviewee puts it: Interdisciplinarity,

> *It's about different scientific approaches that are discipline-specific and to bridge by language the different approaches and to communicate over boundaries of disciplines in order to gain new knowledge that is not gainable within one discipline. (1: 4)*

A framing of interdisciplinary research that pervades many interviews is to distinguish between basic and applied science, where basic "blue sky" research is done for its own sake and applied research strives to produce benefits for society.

> *Science is not only for the scientists, science is for the benefit of the society in general. (5: 37)*

The judgement that "*most of the new knowledge gain comes from crossing disciplines*" (1: 22) is perfectly in line with the EU's and other funding organisations' dominant science policy discourse. While several respondents indicate an internal motivation–research works better when conducted interdisciplinarily –, the dominating motivation seems to be external: interdisciplinarity is necessary to tackle real-world issues and benefit society.

> *Interdisciplinary approaches to problems involve all the different elements of the problem - the societal as well as the scientific. (8: 9)*

The major understanding of interdisciplinarity entails bringing multiple researchers with different backgrounds and competencies together to jointly solve a problem. According to all interviewees, the topic of tsunamis unavoidably requires knowledge from a range of different disciplines to achieve the field's overarching goal to mitigate tsunami impacts for coastal communities. Because of this, the field's interdisciplinarity is seamlessly expanded to include stakeholders beyond the disciplinary system of science.

> *Interdisciplinarity starts to connect not just scientists of different fields but also people who work more closely to society, connecting different types of scientists to engineers, policymakers and stakeholders, trying to tackle a problem from a more well-rounded and readily applicable approach. (8: 3)*

> *You need to work interdisciplinarily in order to implement new scientific results in society. (2: 18)*

The stated reasons for why tsunami science is interdisciplinary also shed light on organising dimensions within the field. Examples include the difference between the geoscientific nature of the natural disaster and the socioeconomic aspect of its impacts, as well as the associated difference between hazard and risk assessment.

> *To fully understand the hazard in combination with the risk, we must draw from different fields and different disciplines. (4: 37)*

Hazard and risk are often invoked as categories to describe two big camps in tsunami science: the basic science part on the one hand and approaches that include vulnerabilities, impacts and damages on the other. A further differentiation was introduced by a scientist who distinguishes.

> *Source people, [...] tsunami modellers, [...] engineers and [...] social scientists. (2: 150)*

Several respondents distinguish degrees of interdisciplinary collaboration, ranging from the interaction of neighbouring fields to that of science with local communities, i.e., stakeholder engagement.

> *It can be between similar sciences, such as modellers and risk analysts and then it can be between geologists and mathematicians, for instance, which are different sciences. It can be across, but still within the natural sciences; it can be across even these borders, such as between social sciences and natural sciences and this is in tsunami science on all these scales. [. . .] It can also be among practitioners and basic science; it can be between early warning, which is operational, and risk analysts, which is also kind of operational, [. . .] and simply people trying to figure out how things occur in nature. And they all overlap. (7: 5)*

As this example indicates, tsunami researchers typically hold a broad understanding of interdisciplinarity that even includes transdisciplinarity. This broad interdisciplinarity, however, is "*where the big issues lie (. . .) because the mind-set and the culture how to work is so different*" (7: 279/283). Interviewees mention the interaction between scientists and engineers as the exemplary interdisciplinary collaboration in tsunami science. There were fewer examples of collaborations with social scientists, rendering this a demand rather than a lived reality in current tsunami science.

> *We need to cooperate with [...] the social sciences in order to implement many results. (2: 31)*

> *We have to communicate the results to the general public. [. . .] In this, the physical scientists, the natural scientists, should communicate very closely with sociologists, with decision-makers. (5: 257)*

Often, the social sciences seemed to be limited to risk communication, tasked with taking the results of the natural sciences and disseminating them to society. This is also reflected by views on the interaction of social scientists with models, where interviewees stated that "*they use the results*" (1: 214, also 4: 167) and that models are "*a tool to communicate*" (6: 147).

Integrating mechanisms in tsunami science

The way interdisciplinarity in tsunami science is described is sometimes merely additive:

> *I think this gives the opportunity of working together for the same topic but looking at different facets of this topic and to have final results that have many aspects. (4: 38)*

Others, however, have a more integrated understanding:

> *We kind of already blur the boundaries between different disciplines and we try to learn what others are looking at and try to comprehend that and incorporate that into our views, our meanings. [...] It's really by topic and we don't argue anymore about what disciplines we are bringing in, because whatever background is important and is appreciated. (6: 38)*

> *It should be possible to create a common language, but I don't think it's very well established. (7: 121)*

We were interested in whether, and if so, which integrating mechanisms exist in tsunami science, mechanisms that may provide a unifying framework (such as a model or a map) and allow researchers to develop joint projects and goals and to successfully collaborate across disciplinary boundaries. Not surprisingly, modelling is widely acknowledged to have a central role in tsunami science. Respondents describe it as the "*backbone of everything*" (2: 114) and as "*instrumental*" (6: 147, 7: 78). Some integrative functions are reported:

> *Modelling offers a way of assessing multiple aspects of a hazard, for example, earthquakes of different magnitudes that could happen in a particular region. (4: 162)*

At the same time, respondents emphasise that models have clear limitations, can be misleading if applied blindly, and must be employed and communicated properly. Some respondents voice the concern that modelling outcomes might uncritically be mistaken for some absolute truth if the interaction with coastal stakeholders is not mediated by eye-levelled science communication. A social scientist gives an example:

> *What you choose is to do things pragmatically, like "this and this is the modelling, now you develop your evacuation maps" with this guideline. But the thing is, with the lack of science communication, people see that modelling not as a suggestion, but rather as a truth, like "that is exactly what's going to happen and if we don't do something then we're gonna die. (6: 202)*

This researcher displays an empowerment approach to stakeholder engagement, arguing that tsunami risk communication must start with the stakeholders' needs.

> *They want to have things certain, "Should I move or not?," "Should I go or not?." And scientists cannot answer in that way. But then it needs time to explain that these are probabilities and I think it needs a certain level of humbleness to also tell them "We don't know." But bringing in modelling without explaining that I think will create a problem. (6: 221)*

A key aspect of tsunami science that requires interdisciplinary collaboration is early warning. Several respondents indicate that the idea of early warning unites the tsunami field. Tsunami risk mitigation through risk analysis, risk assessment and early warning is considered a vital part of tsunami science by most interviewees:

> *Early warning science in the case of tsunamis would not be possible without interdisciplinary research or interdisciplinary interaction. (3: 108)*

Several respondents, however, emphasise that early warning is "*one branch of it and it's important, but it's not the only thing*" (7: 74), that "*the early warning system itself is the technical approach*" (3: 282) and that it is an "*important component of the science, but it's more standalone*" (2: 127). Asked about whether early warning could serve as an integrating mechanism for tsunami science, respondents were rather sceptical. Because early warning is not a core part of tsunami science, i.e. a genuinely scientific task, but more "*an implementation of the science*" (2: 130), it can serve as "*an important motivation for improving modelling and source descriptions*" (2: 124), but not as something that everyone works towards. In the words of another respondent, "*the dream of effective early warning, that might be the bracket between different communities*" (3: 285), but not the early warning system itself. Notably, it is thus not the material technology but the political goal of effective early warning that holds an integration function across the field.

Another candidate for an integrating mechanism is a global risk map, as obtained by a PTRA. Determining tsunami risk and mapping its distribution is an important aim:

> *The term risk, in tsunami science, is very important; you should determine risk properly and you should map the distribution of risk. (9: 123)*

Besides forming a shared goal, the development of comprehensive risk maps can also serve integration, especially when it comes to extending interdisciplinary collaboration beyond the aspects of hazard, into the domain of the social sciences:

> *When it comes to risk maps, for example, they [social scientists] are also involved, because developing a model for risk contains several parts: that is the hazard part obviously that comes from the natural sciences, but then it also contains the vulnerability part which comes much more from the social sciences. (1: 215)*

The tsunami community's history and relationship with society

Many respondents confirm the tsunami on Boxing Day 2004 to be a central turning point for tsunami science. Some entered the field because of the 2004 event and the subsequent rise in research funding.

> *Until 2004, that was a very very closed, small community, and then many new people came in. (1: 507)*

> *After the Sumatra earthquake 2004, [. . .] tsunami science completely changed. This is when many of us started working on tsunamis. (3: 98)*

> *After 2004 we saw that there are many more components that we need other experts and we saw that the interdisciplinary research makes the tsunami science much more developed. (9: 41)*

Often, this point is linked to reflections about public research funding.

> *Each big disaster in a way fosters research, then you have many people doing something and then only few survive because then funding is decreased again. (1: 510)*

According to several respondents, the current level of funding for tsunami research in Europe is seen as insufficient. Also drawing on the example of the 2011 tsunami event, interviewees complain that "*the interest is after the events, not beforehand*" (5: 103), such that the funding of tsunami-related research peaks after catastrophic events and subsequently declines again. This is linked to the characterisation of tsunamis as low-frequency, yet heavy-impact phenomena, a problem for data collection as well. As an effect of their low frequency, tsunamis "*do not cause a constant coping with tsunami hazards*" (5: 107), which is taken to explain the varying amounts of funding. To highlight the importance of this research and to secure funding, the applied field of tsunami science–paradoxically–depends on the actual reoccurrence of catastrophic tsunami events. This situation is sometimes contrasted with earthquakes, where constant coping with seismic hazard could be observed for several world regions.

> *In terms of hazard modelling, the field of earthquakes is more developed. [. . .] tsunami modelling is not as developed of a field and so there are still a lot of questions [. . .] It's just a younger field. (8: 105)*

Several respondents compare tsunami science to earthquake science. They note that tsunami science is structured differently to earthquake science due to the differences in predictability. While earthquake prediction and early warning is possible, the time between warning and event is much shorter than for tsunamis.

> *The difference between an earthquake and a tsunami is that the tsunami is triggered by the earthquake and then the waves are travelling. Just by the travel time, forecast is possible. Early warning is possible. (3: 85)*

As a result, disaster prevention focuses on construction that can withstand seismic shocks, which explains the high degree of collaboration with engineers.

> *In the case of earthquakes, it's more important to build strong structures that will protect lives inside. So the built environment becomes very important, whereas in the case of tsunamis, there are some solutions like building sea walls [but] it may be more important to train the public to react rather than the engineers to build suitable structures [. . .]. So it may be that the community has to be involved more in the solution. (8: 159)*

For tsunamis, the built environment is also important, but the travel time of tsunami waves additionally allows for evacuating coastlines and getting people to safety. This requires that the warning system is fast enough, populations trust the warning, and evacuation procedures are organised and clear. In case the official warning does not arrive or does not arrive in time, communities should be familiar with natural warning signs as well as with self-evacuation procedures. To understand the dynamics of trainings, power, trust and operational procedures in local communities, tsunami science thus needs–on top of interaction with engineers–collaboration with social sciences. In the interviews, however, examples of collaborations with engineers prevail.

> *If you go to the seismic hazard community, which is probably a bit more mature, [. . .] then you see that to an increasing degree now the engineers are being included in projects, so there is more focus from hazard towards risk, and that you're going more in this direction of urban planning and societal implementation of the results. (2: 100)*

When asked about the extent to which tsunami science is conducted for preventing disasters, as opposed to understanding natural phenomena, interviewees univocally answered that both motivations are relevant. To mitigate disaster risk, tsunami scientists need to collaborate with stakeholders in a transdisciplinary way, where transdisciplinarity means that non-academic perspectives are included in the research process. Of the interviewees, only few were familiar with this terminology. Nonetheless, the value of stakeholder engagement was widely shared. A minority emphasised that stakeholder engagement is not a value in itself, and that it should be important in some areas of tsunami science (preparedness and early warning), but not in all.

Despite the shared view that stakeholder engagement is an important element of tsunami science, respondents emphasise the associated challenges and indicate that this practice is not yet sufficiently institutionalised:

> *No, [there is] not really [a trend towards the involvement of stakeholders]. That's still a big problem. (1: 434)*

Uncertainty as an issue in stakeholder engagement and risk communication

Asked about the concept of uncertainty, respondents gave a technical definition based on the distinction of epistemic and aleatory uncertainties and a more qualitative interpretation of uncertainty as "*everything we don't know or everything where we know we may potentially be wrong*" (2: 198). Most respondents see uncertainty as something inevitable. The goal is to assess and quantify it:

> *They [tsunami scientists] try to reduce it, but more than reducing it - because you cannot really reduce it - it's their job currently to quantify that. (1: 324)*

> *From my perspective, one must find ways of quantifying this uncertainty where it is feasible. (4: 107)*

Regarding the interaction between scientists and stakeholders, most respondents state that stakeholders want definitive answers, and are not interested in uncertainties:

> *The biggest problem is that usually the disaster managers don't want to deal with uncertainty. (1: 316)*

> *Especially people in charge of planning disaster management issues, they are aware of the uncertainties, but they try to neglect or try to hide the uncertainty. (1: 369)*

> *Most stakeholders are not gonna ask for uncertainties. You have to give them actively. Otherwise, they're gonna either believe or not believe in what you tell them, in a very black and white manner. (2: 223)*

> *Communities do not want to have uncertainties as an answer. (6: 221)*

We find different positions concerning the consequences that should be drawn from this assessment. Most interviewees emphasise the importance of insisting on uncertainties when communicating scientific results:

> *One of the duties of the scientists is to make an assessment of the uncertainties involved in their results and to pass to the decision-makers a package with the results along with the uncertainties, if possible, to quantify the uncertainties. (5: 267)*

> A minority, however, disagrees with this view and argues that, while

> *quantifying uncertainty is really important, [. . .] it doesn't necessarily need to be the focus of what's communicated to stakeholders (8: 246)*

Furthermore, another minority position calls for a "humble" way of communicating both what is known and what is not yet known.

Many respondents link the unwillingness of stakeholders to engage in a discussion of uncertainties to the difficulty of communicating probabilistic information. In this view, many people struggle to interpret statistics and prefer avoiding probabilities altogether:

> *Something that's really hard for the general public to interpret are probabilities and in general statistics. (8: 208)*

> *People don't know mathematics, they don't know statistics that well, so they have their own interpretation of numbers, I think they tend to forget about uncertainty unless they are told to. (7: 139)*

> *Communicating this to stakeholders, making them understand the uncertainties around this phenomenon, it might be a bit complex because they're the people who have to make decisions and they need something that they can rely on. (4: 141)*

> *They are not interested in that [uncertainties and probabilities] because they think the message needs to be very clear like a traffic light. (3: 137)*

Consequently, the importance of standard operational procedures (SOPs) is emphasised several times, whereby uncertainties are translated into discrete thresholds and all responsibilities and actions are clearly determined in advance.

> *They want to have clear thresholds when to act and how to act. [...] So I think that the scientists need to translate these uncertainties into thresholds. (1: 317/378).*

> *SOPs follow a certain prescribed scenario. An earthquake occurs, then you look first at the magnitude, second you look at the location and third you look at the depth. [. . .] If the magnitude of the earthquake is below a certain threshold, nothing happens - green light. If the earthquake is higher than, let's say, 6.5, first information. If the earthquake is at the border line between the island arch and the seaside, second information. But if the earthquake is at a depth of 100 or 200 m, we have knowledge that this will not trigger a tsunami. So, two information, one positive, one negative, doesn't meet - it's out. That's a SOP. And that works quite well. (3: 162)*

Challenges of interdisciplinary integration and stakeholder engagement

Communication and language barriers are generally regarded the main challenges in interdisciplinary research and stakeholder engagement. We investigate this aspect by taking a closer look at understandings of the term risk. Most respondents define risk as a combination of hazard, vulnerability and exposure. Some do not include the element of exposure and define risk simply as a combination of hazard and vulnerability. The distinction between risk and hazard, however, is common and regarded by all interviewees as the standard definition in the field of natural hazards. Yet, some mention that this distinction still sometimes leads to confusion among researchers. Almost all respondents mention that the difference between risk and hazard is hard to understand for people outside the natural hazards' community.

> *The description as we discussed it [risk composed of hazard and vulnerability] is sort of an academic and scientific point of view. I sometimes made the experience that for stakeholders, in particular for decision-makers or -takers, it's hard for them to understand. (3: 214)*

> *There is not necessarily a distinction between hazard and risk for people outside the community. (4: 86)*

> *The general public still does not understand risk really well. (9: 135)*

> *For normal persons, hazard and risk is the same thing, right? And therefore, you have to be careful, really explaining what you mean when you talk about risk. [. . .] I think, there's a danger there and you have to be very aware of how you communicate and that you make clear that when you talk about the risk, you really talk about the potential losses, whereas when you talk about the hazards, you don't really care so much about the consequences of an event, but you look more at the event itself. (2: 176)*

Besides the technical definition of risk, several respondents also gave more accessible interpretations of the term. Specifically, the definition of risk as potential losses is shared by several respondents, similar to the interpretation of risk as expected negative consequences brought up by an interviewee. Due to this tangible definition, "*risk may be easier to grapple with by society because then they understand what's at stake*" (8: 182). Several respondents report that stakeholders are more interested in risk as compared to hazard. Therefore, one researcher calls for accessible risk definitions when communicating with stakeholders:

> *Let's be a little bit brave to break the traditions and go beyond our comfort zones in defining risks and bringing in modelling and communicating that to certain people. (6: 310)*

When asked about the challenges of interdisciplinary research in general, several respondents point to issues of language and communication. Some researchers also acknowledge missing recognition for interdisciplinary work and difficulties in publishing. Additionally, respondents diagnose the large amount of time and efforts that are required for successful interdisciplinary research:

> *We don't argue anymore about what disciplines we are bringing in because whatever background is important and is appreciated. But that requires a huge effort, energy as well, including facilitating skills, listening, being eye-levelled with different entities and that's not really the current tradition. So that is very challenging. (6: 38)*

At the same time, interviewees point to several factors that are important and work well in an interdisciplinary research context. Most respondents emphasise the need for few clear goals at the outset of an interdisciplinary project. The importance of finding the right people for a given project and bringing the appropriate kinds of experience together is also mentioned several times, as is the need for interdisciplinary researchers to take time, be open, look beyond their own field and question themselves.

As options for future interdisciplinary projects, interviewees mention compiling a glossary for dealing with different disciplinary vocabulary, allocating time in the beginning to learn about others' work, assigning clear work items and responsibilities to individuals, supporting interdisciplinary publishing, being aware of stakeholders' needs and expectations, looking at the big picture before starting the technicalities of a project and being honest when things do not work as planned.

Discussion and conclusion

Throughout the interviews, we find experience-informed and rather sophisticated accounts of the phenomenon of interdisciplinarity, indicating that tsunami researchers indeed work in contexts that they themselves perceive as interdisciplinary. The way respondents' talk about their academic identities implies that they are typically grounded in a disciplinary core, out of which they subsequently cross boundaries. For all respondents, however, it is a matter of course that becoming and being a member of the tsunami community includes the need to communicate across boundaries. Interviewees mention the interaction between scientists and engineers as the exemplary interdisciplinary collaboration in tsunami science. There were fewer examples of collaborations with social scientists, rendering this a demand rather than a lived reality in current tsunami science. Often, the envisioned role for social sciences seemed to be limited to risk communication, tasked with taking the natural science results and disseminating them to society.

Interdisciplinarity on the team or project level can be clearly distinguished from the interdisciplinarity of individual scientists. The latter seems to be rare yet there seems to be a need for "translators" (8: 301) with diverse backgrounds who speak different languages and understand the respective lenses and paradigms. This is in line with Gilligan's (2019) ideal of interactional expertise in interdisciplinary settings. Several respondents indicate that the idea of early warning unites the tsunami field. Notably, however, it is not the material technology but the political goal of effective early warning that holds an integrative function across the field. This is in line with Sarewitz and Pielke's research framework for disasters in context, which for applied research puts a primacy on good decisions, not on good science (2001). Furthermore, we find modelling to be seen as the "backbone of everything" tsunami related, which in combination with visualisation techniques such as a global map of tsunami risks also serves to integrate stakeholders beyond the tsunami research community. To assess and communicate model results appropriately, however, remains a major challenge (cf. Oreskes et al., 1994). Hazard and risk are often invoked as categories to describe two camps in tsunami science: the science part that does not involve vulnerability and exposure, on the one hand, and the approaches that include impacts and damages, on the other. Because the field's major goal is to mitigate tsunami risk for coastal communities, its interdisciplinarity is seamlessly expanded to include stakeholders beyond the disciplinary system of science. While one position is that the stakeholders need to carefully listen and understand the science, we also find the position that tsunami risk communication must start with the stakeholders' needs and prerequisites. Despite the widely shared view that stakeholder engagement is an important element of tsunami science, respondents emphasise the associated challenges and indicate that this practice is not yet sufficiently institutionalised. The integration of perspectives in tsunami research does not seem to proceed with the desired speed in practice, due to challenges concerning different operational logics and expectations, problems in communication and structural barriers such as missing incentives and reputation mechanisms. Urbanska et al. (2019) studied the effect of previous contacts between the two camps and found that those with interdisciplinary experiences are more likely to recognise the intellectual contributions of other disciplines. They conclude that interdisciplinary encounters must be further incentivised by funding organisations. This is in line with the results of this study.

We find two strategies that are proposed for enhancing interdisciplinary and stakeholder engagement, coming with different roles for the individual tsunami researcher. First, there is a view that scientists should be directly involved in inter- and transdisciplinary collaborations and tsunami governance. Thereby, it is the scientists themselves that take on the role of communicating and organising applications from tsunami science. To some extent, this strategy is already implemented, as many interviewees engage in tsunami governance and assume roles in UN or local governance bodies. Second, there is a view that tsunami science and governance need more institutions and individuals that are capable of translating between scientists and stakeholders. These translators would be familiar with both perspectives and thereby able to switch between different jargons and operational logics. Importantly, having professionals and institutions with an explicit mandate to operate at the interface between science, policy, administration and coastal protection offers a way out of the dilemma that the academic reward system often impedes knowledge transfer engagements by researchers themselves. While these two strategies are not mutually exclusive and are probably both required to some extent, they are qualitatively different and imply different strategic decisions. A discussion about the merits and downsides of both approaches can help to formulate clear goals for future developments in tsunami science and its relation to society.

Problems regarding communication between disciplines and to stakeholders, as well as the nuances of interdisciplinary collaboration and project management, appear to be issues that the community has already reflected upon. However, we find nuances in the conclusions that researchers draw from this reflection. One view emphasises the need to explain the science better. This is related to the diagnosis of a lack of understanding of how the science works among stakeholders, often associated to complaints about widespread ignorance of and disinterest in probabilities and statistics. A slightly different view places more emphasis on the necessity to listen to the stakeholders, such that the burden of changing current practices lies more on the scientists than on the stakeholders. Ideas for improving the current research structure include increased publishing support for early career researchers, e.g., by helping with publication fees and setting up special issues on cross-cutting themes, aspects of project management, such as the assignment of responsibilities and clear communication of goals, assumptions and conflicts, and efforts of individuals, for example, being open and respectful when confronted with other perspectives. While some of these issues can be tackled by individual researchers, much of it relates to research structures. Successful interdisciplinary research and stakeholder engagement thus require funding flows and specific support for the time- and resource-intensive processes that are currently not fully factored into financial and reputation structures.

Using the terminology of Ge et al. (2019), projects and collaborations funded by the European Union (EU) are instances of either grant-driven teams or expertise-based teams. This includes the EU's COST actions. As the funding format of a COST action restricts funding to networking, visiting and other more organisational activities but does not fund research itself, we assume that COST action teams tend to be expertise-based rather than grant-driven. In the case of AGITHAR, researchers explicitly address the need for facilitating tsunami hazard and risk analysis by bridging both social and cognitive gaps in the tsunami field. It has been noted, however, that by how the acquisition of funding works, knowledge integration is not supported from the start in EU research projects. Individual work packages and deliverables are often rather disciplinary, and the projects lack a pilot phase in which to develop common ground and a shared interdisciplinary research agenda (Martinez et al., 2018). The authors conclude that, in practice, this often leads to mere grant-driven teams–multidisciplinary collaborations, where "one discipline works on one aspect of a project and a different discipline on another" (2018: 71). We argue, however, that the normative idea of inter- and transdisciplinarity does not need to be that everybody collaborates with everybody throughout the entire project and for any topic. The task is rather to jointly develop a framework which differentiates disciplinary, interdisciplinary and transdisciplinary knowledge systems and objectives, as well as respective phases in the project, and working groups in line with their corresponding goals. A starting point could be Sarewitz and Pielke's research and policy framework for disasters in context (2001). To this end, training and acquisition of both interactional and contributory expertise in more than one discipline of tsunami science are needed.

This study is limited by its explorative scope and a small number of in-depths interviews. Future research can build on these results and conclusions in various ways. Firstly, a survey of the tsunami research community could shed light on the quantitative composition of the field and associated understandings of risk, uncertainty, interdisciplinarity and stakeholder engagement. Secondly, bibliometric studies of authorship patterns and co-citations could furthermore elucidate the communicative structure of the tsunami field. Thirdly, local action research projects could engage all relevant stakeholders to work towards tsunami risk mitigation in specific geographic contexts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethics review and approval/written informed consent was not required as per local legislation and institutional requirements.

Author contributions

SR conceptualised the research project and FS collected and transcribed the data. SR and FS were both equally involved in analysing the data, as well as drafting and writing the paper.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Social Media Analytics by Virtual Operations Support Teams in disaster management: Situational awareness and actionable information for decision-makers

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Virtual Operations Support Teams are groups of institutionalized digital volunteers in the field of disaster management who conduct Social Media Analytics tasks for decision-makers in Emergency Operation Centers (EOCs) during hazard situations such as floods. Through interagency integration into EOC structures, the volunteers provide analytical support using advanced tools and monitoring various social media platforms. The goal of VOSTs is to increase decision-makers' situational awareness through need-oriented analysis and to improve decision-making by providing actionable information in a time-critical work context. In this case study, the data collected during the 2021 flood in Wuppertal, Germany by 22 VOST analysts was processed and analyzed. It was found that information from eight social media platforms could be classified into 23 distinct categories. The analysts' prioritizations indicate differences in the formats of information and platforms. Disaster-related posts that pose a threat to the affected population's health and safety (e.g., requests for help or false information) were more commonly prioritized than other posts. Image-heavy content was also rated higher than text-heavy data. A subsequent survey of EOC decision-makers examined the impact of VOST information on situational awareness during this flood. It also asked how actionable information impacted decisions. We found that VOST information contributes to expanded situational awareness of decision-makers and ensures people-centered risk and crisis communication. Based on the results from this case study, we discuss the need for future research in the area of integrating VOST analysts in decision-making processes in the field of time-critical disaster management.

KEYWORDS

social media analytics, virtual operations support team, risk and crisis communication, situational awareness, disaster management, actionable information, flood, open source intelligence

1 Introduction

In the sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the authors conclude that the frequency of floods and extreme precipitation has increased in Europe. They note, that their probability will rise even further if global warming reaches two degrees Celsius compared to pre-industrial times (IPCC, 2021). The World Weather Attribution (WWA) also concludes that climate change has increased the likelihood and intensity of extreme rainfall in Western Europe. According to their recent study, the amount of rainfall, i.e. the intensity of extreme precipitation, has increased by between three and 19%, which in turn elevates the resulting risk of flooding (Kreienkamp et al., 2021). Concurrent with these ongoing developments, digital communication are being used to a rising extent during disasters. Eyewitnesses and those affected by disasters intensively utilize social media as interactive platforms to communicate and collaborate in such situations for publicly sharing warnings, psychosocial needs, or rumors, and spontaneously build up community engagement structures (Reuter and Kaufhold, 2018). Systematic analysis of this big crisis data (Castillo, 2016) can thus provide timely and disaster-related information, which can support situational awareness and decision-making in Emergency Operations Centers (EOCs). However, the volume, velocity, and variety of social media data can grow up to a level that EOC staff cannot systematically analyze. With the aim of addressing these challenges by using collaboration technologies, digital volunteers have developed so-called Virtual Operations Support Teams (VOSTs) (St. Denis et al., 2012). These teams work dislocated from the actual disaster area and support EOCs by completing specific tasks using advanced analytical tools and geographic information systems: a VOST identifies, verifies, and visualizes social media data and other publicly available data and creates information products such as evaluation and social media monitoring reports or dashboards of the affected area (St. Denis et al., 2012; Fathi et al., 2020). These information products can be integrated into the EOC's decision-making process, where they contribute to situational awareness or to response actions derived from actionable information. Thus, VOST findings can be used to derive people-centered risk and crisis communication measures that are adapted to the needs of the affected population and take into account the specific disaster situation, e.g. for counterstatements to misinformation (Kutzner and Thust, 2021) or in communicating with those affected (Fire Department Wuppertal, 2021). The German City of Wuppertal was among several districts strongly affected by the July 2021 flooding: Emergency Management Agencies (EMAs) and authorities evacuated parts of the city and set off sirens to warn the public (Zander, 2021). Digital volunteers of the German Federal Agency for Technical Relief's VOST (VOST THW) were virtually integrated as formally trained analysts into the local EOC. This novel interagency participation of digital volunteers as external analysts within an EOC during a flood leads to the following central research question:

How can the integration of Social Media Analytics by Virtual Operations Support Teams in Emergency Operations Centers support situational awareness and generate actionable information for decision-making?

The aim of this work is, on the one hand, to analyze the data generated by a VOST during an operation through a case study and thus to present important findings from the field. On the other hand, we will survey decision-makers from an EOC what impact VOST information has on their situational awareness and actual decisions. The motivation of this research approach consists in the fact that numerous works either address the data analysis of big data from social media, the decision-making processes or the development of machine learning approaches. Therefore, it is essential to better understand practical implementation in this research area in order to obtain valuable insights from implemented solutions. To answer the central research question, we first outline the relevant theoretical background in section 2. We start by looking at the role of social media in disaster management by delineating aspects such as Social Media Analytics (SMA) and risk and crisis communication. We also outline facets of situational awareness, actionable information, and VOSTs before presenting our case study and methods differentiated by the two stages in Section 3. Section 4 illustrates the results of the case study. Section 5 discusses the results, future research approaches, practical considerations for emergency response, and limitations of this work. In the last section 6, we conclude this work and present an outlook.

2 Background

2.1 Social media in disaster management

With the rapid global spreading of digital communication tools, internet access and smartphones, the communication culture has changed fundamentally. Due to immediate availability and transmission, various social media platforms are used in everyday life and increasingly in disaster situations (Reuter and Kaufhold, 2018). Social media are understood as a set of internet-based applications that build on the developments of Web 2.0 and provide opportunities for users to create and share content (Kaplan and Haenlein, 2010). The purposes social media are used for in disaster situations can be differentiated into four areas: information gathering, information dissemination, collaborative problem solving, and processing (Jurgens and Helsloot, 2018). Affected or interested individuals can thus search for reliable information in a complex situation free of charge and on the go. At the same time, information about the current situation can be quickly spread. Studies show that people affected by a disaster share information about roads, weather and traffic conditions, or their emotions and location (Reuter et al., 2017). Interactive social media platforms also offer the opportunity to build spontaneous community engagement structures: The formation of spontaneous volunteer groups is enabled by network functions, who then actively participate in collective disaster response (Nissen et al., 2021; Sackmann et al., 2021). In addition, social media are also used for individual coping, for example in the communication of emotions or as platforms for commemoration (Ebersbach et al., 2016). This bipartite role of passive information consumers and active content producers in social media is described as a prosumer (Ebersbach et al., 2016), which can also be observed in the context of disaster management (Chatfield and Brajawidagda, 2014). Based on this bilateral communication character of social media (Roche et al., 2013) unusual events can be detected at an early stage through the systematic analysis of data using Crisis Informatics approaches (Thom et al., 2016; Rossi et al., 2018; Kersten and Klan, 2020). Crisis Informatics is a growing research area that examines the use of computer-based methods in crises, disasters, and emergencies (Hager, 2006; Palen L. et al., 2007). In the past, numerous fields have been studied in the context of internalizing social media use in disaster management, which Eismann et al. (2021) systematically divide into the following categories: monitoring social media, automatically processing social media data, tapping collective intelligence, accessing information providers, and evaluating crisis response.

Zhang et al. (2019) identify three principal fields in which social media can assist in disaster management: First, they describe the function of using social media to efficiently and effectively generate situational awareness. As a second aspect, they depict the usefulness of networking to engage in coping through self-organized community engagement activities. As a third and final field, they see the ability for EMAs to capture the affected population's sentiment (Zhang et al., 2019). EMAs and other authorities use social media for different purposes: warnings as well as risk and crisis communication with the aim of protective and preventative measures can be disseminated quickly and with wide reach, but EMAs can also gather disaster-related information, such as situational updates (Olteanu et al., 2015; Wu and Cui, 2018). In addition to the use of social media, other approaches also build on new technologies and the use of smartphones applications to reach the public in a disaster situation (Tan et al., 2017; Weyrich et al., 2020) or to communicate bidirectional using mobile crisis apps (Kaufhold et al., 2018). To disseminate information through risk and crisis communication using emerging technologies, there are two aspects that need to be considered in particular: New technologies and machine learning algorithms must be designed for and adapted to human behavior, while their application and use requires learning and training (Kuhaneswaran et al., 2020; Sonntag et al., 2021). In addition, studies show that the public expects that social media will be monitored by EOCs during disasters and that decision-makers will respond to the content (Reuter et al., 2017; Reuter and Spielhofer, 2017). In addition to the general expectation that social media should be monitored (67%), a representative survey of the adult German population by Reuter et al. (2017) indicate that in the event of a disaster, 47% of respondents also expect a response from an EMA on social media within 1 hour. However, systematic analysis of social media poses significant challenges for EOCs in disaster management, which will be discussed next.

2.1.1 Social Media Analytics

Social Media Analytics (SMA) include the design and evaluation of analytics tools to collect, monitor, analyze, summarize and visualize open-access data from social media (Zeng et al., 2010). The objective is to extract intelligence from available data and to identify patterns in order to serve specific needs with information in various areas of interest (Zeng et al., 2010; Stieglitz et al., 2014; Stieglitz et al., 2018a; Stieglitz et al., 2018b). These areas of interest can be quite diverse: besides economics, they might concern journalism, political communication, and especially risk and crisis communication in disaster management (Stieglitz et al., 2018b). Here, Stieglitz et al. see the potential to gather additional previously unknown information from various platforms on which users publish texts, images or videos.

SMA is understood as part of Big Data, with varying terminology being used, such as social big data (Guellil and Boukhalfa, 2015) or social media big data (Lynn et al., 2015). Analyzing such large amounts of data is always fraught with challenges. McAfee and Brynjolfsson (2012) described three often posed key challenges: volume (the amount of data), velocity (the velocity at which the data is available), and variety (different data types, e.g. text, image, video). Additional papers have expanded the challenge collection, e.g. adding veracity (reliability of the data). Lukoianova and Rubin (2014) differentiate this addition into three further levels and describe veracity in objectivity, truthfulness, and credibility.

The actual mass data analysis is conducted in a process with several steps. Fan and Gordon (2014) characterize the process in three successive steps: first, relevant data is collected and preprocessed (capture), followed by analytics, e.g. social network or sentiment analysis (understand), and as a third and final step by the summary and presentation (present). A more detailed model is offered by Stieglitz et al. (2018b), taking into account various studies. The authors distinguish between four steps that build on each other:

(1) Discovery means the (automatic) discovery of latent structures and patterns in text files, whereby text and data mining techniques are often applied (Chinnov et al., 2015).

(2) Tracking includes tactical alignments, for example across social media platforms (e.g., Twitter, Instagram), methodological approaches, and anticipated outcomes (Stieglitz et al., 2014; Stieglitz et al., 2018b).
(3) Preparation differentiates into various approaches, e.g. theme and/or trend-based preparations (Stieglitz et al., 2014).
(4) Analysis comprises e.g. statistical, content, or trend analyses (Stieglitz et al., 2014).

These four steps can be applied to the analysis of data from different social media, where the platforms' interfaces (data crawler) are the Application Programming Interfaces (API) used to apply (partially) automated analysis tools, e.g. for disaster detection (Thom et al., 2016). In the context of disaster management, these tools are used, for example, to identify incidents at an early stage or to conduct sentiment analyses (Fathi et al., 2020). It is particularly important for EOCs to understand communication behavior and current sentiment on social media in order to respond more quickly and efficiently (Stieglitz et al., 2018b).

2.1.2 Risk and crisis communication in social media

Effective risk and crisis communication is crucial to managing disasters. In this context, risk communication needs to be conducted in a people-oriented manner before a disaster occurs to create risk awareness within the population (Basher, 2006; Haer et al., 2016). Affected people do have different information needs, so that a range of approaches for risk communication with the public are required (Fakhruddin et al., 2020). Additionally, these different information needs also change with the different phases of a flood. In the pre-flood phase for example, information is needed on what protective measures to take, how to evacuate, and how to stock food and water. In the dynamic flood situation (response phase), needs shift, for instance, to helping victims, finding emergency shelters or information accompanying siren warnings. In the third, the recovery phase, focus shifts towards topics such as self-organized help of and for the population, protection against epidemics or expressing gratitude towards emergency services (Vongkusolkit and Huang, 2021). Risk communication aims at establishing a long-term relationship of trust between all actors involved in disaster management (Federal Ministry of the Interior, 2014). It intends, on the one hand, to increase the population's awareness of existing risks and hazards and, on the other hand, to inform them about how to deal with risks, and to enable individuals to take preventive measures by providing information and recommendations for action (Federal Ministry of the Interior, 2014). For these purposes, the following aspects must be taken into account: openness, transparency, credibility or consistency, and dialog orientation. Studies show that people-centered flood risk communications can be much more effective than a top-down government communication approach, even if the information reach fewer people (Haer et al., 2016; Haworth et al., 2018; Rahn et al., 2021). Haer et al. (2016) derive from an agent-based model that flood risk communication should aim to use the natural amplification effect of existing offline social networks, in which social media are used deliberately. In addition, EOCs can use the advantages of reaching a wide audience through social media to spread risk-related information via their channels (van Gorp et al., 2015). Haer et al. (2016) identify four different flood risk communication strategies:

(1) Top-down strategy focused on risk.
(2) Top-down strategy focused on risk and coping options.
(3) People-centered strategy focused on risk.
(4) People-centered strategy focused on risk and coping options.

The authors explain the need to have a deep understanding of the factors influencing risk awareness and their relevance for adequate risk communication. Mondino et al. (2020) argue that people-centered risk communication can reduce the population's vulnerability. SMA can be one way to understanding the needs of the affected population, e.g. understanding psychosocial needs. The work of Weyrich et al. (2020) demonstrates that affective response (i.e. feelings) and deliberative appraisal (i.e. understanding of warning) have an impact on the consideration of protective measures, confirming previous findings.

In contrast to risk communication, crisis communication is carried out during or after a disaster has occurred and pursues different goals. Nevertheless, both communication types are closely connected, since risk communication provides the basis for successful crisis communication. However, the main difference consists in the factor of time: while risk communication aims at prevention and preparation, the goal of crisis communication is short-term action to avoid current hazards and to minimize damage (Federal Ministry of the Interior, 2014). For the latter, velocity, veracity, understandability and consistency are crucial (Rahn et al., 2021). These are particularly decisive when authorities and the population affected by a disaster can make intensive use of social media and thus communicate in a dialog-oriented manner.

2.1.3 Building spontaneous community engagement structures

Alongside their potential in risk and crisis communication, social media also offer platforms for spontaneous and self-organized community engagement activities: based on networking functions, e.g. in specific social media groups, spontaneous groups of volunteers can be formed. The general tendency to desire a normalization of the situation after disasters, such as floods, manifests, when thousands of people set up spontaneous structures and participate in collective disaster management for weeks (Sackmann et al., 2021; Bier et al., 2022). However, spontaneous build up community engagement structures in disaster situations are not a new social media phenomenon: Stallings and Quarantelli (1985) described their observation as emergent groups that work collaboratively during an emergency. These groups close a resource gap of professional responders that arises in any large-scale disaster situations. Accordingly, emerging groups pursue common goals in the context of actual or potential disasters, though permanent operational organization structures have not been established (Kaufhold and Reuter, 2014). Nevertheless, with the expansion of social media, the formation of these spontaneous groups of helpers is happening more rapidly and with a wider reach. In the case of heavy rainfalls and subsequent flooding in Germany in 2013 and 2014, it was observed that the first spontaneous groups already became active during the acute hazard conditions (Fathi et al., 2017; Twigg and Mosel, 2017). Large group sizes of several thousands and their agility also created enormous challenges in integrating spontaneous volunteers in disaster management after floods (Sackmann et al., 2021) or earthquakes (Nissen et al., 2021). However, numerous studies allowed for a better understanding of spontaneous volunteers. For example, motivational factors and participation barriers (Fathi et al., 2016) or knowledge and skills transmission in occupational health and safety (Brückner, 2018) were studied. Twigg and Mosel (2017) divide the variety of tasks into search and rescue operations, the transport and distribution of relief supplies, and the provision of food and beverages to victims and responders. Including spontaneous volunteers nevertheless poses considerable organizational challenges for EOCs (Sackmann et al., 2021) as the established operational structures currently do not allow for quick integration (Fathi et al., 2017). This makes it all the more important for EOCs to know about groups developing in social media at an early stage so that they can respond and communicate adequately.

2.2 Situational awareness and actionable information for decision-makers

Decision-making processes in disaster management are complex. They require situational awareness (SA) in a dynamic disaster context and the availability of actionable information in the right time and place. However, these necessary information management processes are influenced by certain challenges and conditions that have already been outlined in the past (van de Walle and Comes, 2015; Comes, 2016). Paulus et al. (2022) describe time pressure, uncertainty, information overload (especially significant in the use of social media), and high stakes (including irreversibility of decisions) as four major challenging elements. These conditions can affect data bias and confirmation bias of analysts' information product which impacts situational awareness and decision-making in disaster management (Paulus et al., 2022). The following two subsections introduce situational awareness for decision-makers in the context of disasters, focusing on the use of social media. Subsequently, we address actionable information for decision-makers in EOC.

2.2.1 Situational awareness for decision-makers

A common description of situational awareness is provided by Endsley (1988) who described it as "the perception of the elements in the environment [. . .], the comprehension of their meaning and the projection of their status in the near future." (S.97). A central aspect in her understanding is the tripartite division of situational awareness into perception, comprehension, and projection. Crisis Informatics also deals with situational awareness, meaning all available information that can be integrated into a coherent picture for the management of a complex disaster situation (Reilly et al., 2007). Hofinger and Heimann (2022) describe situational awareness in the context of disaster management in EOCs as the state of being aware of one's surroundings, the situation, and current processes. They argue that each decision-maker perceives the current operational situation individually. Besides current disaster-related information, this mental model of a disaster situation is also influenced by previous knowledge, experience, and individual evaluations. Therefore, situational awareness is always subjective (even if there is objective situational information, e.g. a crisis maps), varies individually, and can evolve with situational changes (Hofinger and Heimann, 2022). The term situational awareness is closely related to sensemaking, where in the context of information systems it describes the process of how individuals gather and use information and gain a more comprehensive understanding of the current situation (Boin et al., 2014; Stieglitz et al., 2018a).

In 2010, Vieweg et al. investigated how social media, in this case Twitter, can contribute to situational awareness. Based on two scenarios (Red River flood and Oklahoma grassfire, both 2009), the authors classified Twitter posts into 13 categories to provide a better overview. They coded tweets into these categories, each consisting of at least five tweets: warning, preparatory activity, fire line/hazard location, flood level, weather, wind, visibility, road conditions, advice (i.e. advice on how to cope with the emergency), evacuation information, volunteer information, animal management, and damage/injury reports (Vieweg et al., 2010). The categories vary significantly within the two scenarios, which in turn consist of the different scenario-parameters (area, number of people affected, and duration). In the case of flooding, the most frequent categories are preparatory activity, flood level, weather and volunteer information. To automatize such analyses, numerous text mining and natural language methods have been developed to classify social media content (Vongkusolkit and Huang, 2021). The goal is to separate disaster-related information from unimportant information in order to support situational awareness through categorization. Previous studies have examined whether SMA could improve situational awareness in different scenarios, such as floods, hurricanes, tsunamis, wildfires, or terroristic attacks (Fathi et al., 2020; Vongkusolkit and Huang, 2021). Since machine-learning approaches were usually applied to one singular scenario, Yu et al. (2019) developed a cross-event classification analysis method. Further approaches have also been developed to automatize the classification and analysis of images based on artificial intelligence (AI) for disaster management, e.g. the platform AIDR (Artificial Intelligence for Disaster Response) (Imran et al., 2014; Imran et al., 2018). In the literature review conducted by Vongkusolkit and Huang (2021), the majority of studies to date (64%) have been limited exclusively to the microblogging platform Twitter due to the simplified automated analysis procedures. In view of the heterogeneous use of social media, the focus on just one platform does not exactly represent their real-world usage. In Germany, Twitter was used by eight percent of the population in 2021 (4% daily or weekly, 4% monthly or less frequently), with other platforms such as Facebook (38%) (28% daily or weekly, 10% monthly or less frequently) or Instagram (33%) (26% daily or weekly, 7% monthly or less frequently) being used more often (Krupp and Bellut, 2021). Thus, cross-platform SMA enables improved situational awareness: By classifying social media data into categories, the most frequent themes, issues, and communication priorities can be identified and made usable for decision-makers, so that information on people-centered needs or social coping activities can be understood and utilized for situational awareness (Vongkusolkit and Huang, 2021). People-centered needs and sentiments can be differentiated into various subcategories, such as fear, anger, worry, or gratitude (Buscaldi and Hernandez-Farias, 2015; Vongkusolkit and Huang, 2021). Vongkusolkit and Huang (2021) further found that the approach of temporal classification, which means categorizing social media posts according to the time it was published in relation to the disaster phase, is particularly used in studies for hurricanes (36%), followed by a tie between floods and several other events (14%). However, evaluating and applying such categorization in disaster management poses numerous challenges. For example, during a dynamic flood situation, the focus may shift, necessitating supplemental information for situational awareness (Rossi et al., 2018). Furthermore, emergencies can arise and spread via social media, especially in the response phase. Additionally, actionable information must also be considered and evaluated by decision-makers.

2.2.2 Actionable information for decision-makers

Decision-making in EOCs can rely on both joint situational awareness and actionable information. We draw on Zade et al. (2018), to define and delineate actionable information, which they define as information on which decision-makers need to respond and decide. In our work we especially apply short-term actionable information as defined by Mostafiz et al. (2022), because we address the issue of immediate response with flood hazards. Mostafiz et al. (2022) understand long-term actionable information as information that can help coping with hazards in the preparation or recovery phase. Especially concerning short-term actionable information, producing the right information to the right decision-makers at the right time helps members of an EOC overcome multiple challenges such as limited resources in SMA, and information overload in a time- and safety-critical work environment. In a survey of emergency and disaster managers, Zade et al. (2018) illustrated that the interviewees have a broad understanding of actionable information, which might also be information that directly affects them or their organization. In such cases, actionable information can assist, enact or expedite problem-solving, even if the problem is merely theoretical or potential (Zade et al., 2018). However, information gathered during dynamic disaster situations may be or become relevant in the future. Yet, not all information needs to be directly followed by immediate response action. Thus, Zade et al. (2018) state in their conclusion, that all information is important, but only some is actionable. We also argue based on this conclusion: the distinction between actionable information and situational awareness is crucial. Social media data can support decision-making by both contributing to situational awareness and providing actionable information. However, EOCs face challenges such as limited resources in SMA or information overload (Stieglitz et al., 2018b). Digital volunteers have formed VOSTs to support EOCs in addressing these challenges.

2.3 Virtual Operations Support Team

Due to a lack of resources competence, EOCs cannot perform SMA task fully during disasters, which creates a gap in situational awareness. Virtual Operations Support Teams (VOSTs) are being established as a way to fill this gap, with digital volunteers conducting the monitoring and analysis, using semi-automated tools and visualizing mass data (St. Denis et al., 2012; Cobb et al., 2014; Martini et al., 2015). The idea of creating a VOST was born in 2011 in the United States by emergency manager Jeff Philipps with the intention of better integrating the work of digital volunteers into existing structures of EOCs to enable the identification and direct integration of disaster-related information from social media into disaster response by using volunteer work. These VOST analysts are verified digital volunteers of official EMAs who work on a voluntary basis and take on specific tasks, such as the analysis of large amounts of social media data, translations, or the mapping of affected areas. The capability spectrum of VOST can be divided into three main working fields:

- Digital Operation Investigation
  - Information retrieval, processing and visualization from publicly available sources using Open Source Intelligence (OSINT) approaches (Böhm and Lolagar, 2021)
  - Verification and falsification, e.g. identification of false information and rumors
- Crisis Mapping
  - Creating digital maps of affected areas and processing those with additional information (e.g. access routes, flooded area)
  - Visualization, geolocalization and spatial analysis using geographic information systems
- Volunteer Coordination and Cooperation
  - Interface with other national and international teams
  - Establishing technical and collaborative frameworks to enable cooperation

The informational results are prepared by the VOST team leaders and provided to the EOC in different information products, such as situation reports or crisis maps. This work of the team leaders is accompanied for example by the following other activities:

- Information selection, prioritization, and dissemination of actionable information to decision-makers
- Advising EOC staff on the use of social media in risk and crisis communication
- Cooperation with other digital networks and VOSTs

After the first VOST was established in the United States, an overarching umbrella organization called Virtual Operations Support Group (VOSG) formed to help teams in their development and guide new VOSTs in there structuring in an advisory role. At the transnational level, regional associations such as VOST Europe, VOST Oceania and VOST America have subsequently been established.

2.3.1 Virtual Operations Support Team, German Federal Agency

The first German VOST was initiated in 2016 as a pilot project by the German Federal Agency for Technical Relief (THW), subordinated to the German Federal Ministry of the Interior (Fathi and Hugenbusch, 2020). With nearly 80.000 volunteers in 668 local sections, the THW is particularly engaged in disaster management following natural disasters, civil protection, and civil defense tasks (Federal Agency for Technical Relief, 2021). Since 2018, additional VOST groups have been established at the level of federal states, districts, or cities. The THW's goal was to evaluate the operational options and the tactical value of a VOST. This digital unit, which is not tied to a specific location, also provided the first opportunity to test a new form of volunteer commitment for the THW. The VOST THW is a team of 46 specifically qualified THW volunteers who collect disaster-related information from publicly available sources such as social media using advanced analytical software and competencies. The VOST THW's goal is to make information technologies and new potentials of digital networking usable for the operational structure of the THW and other EMAs, which can request this team for specific tasks (Fathi and Hugenbusch, 2020). With the exception of the liaison officer, who brings together the VOST and the decision-makers in an EOC, VOST analysts are not tied to any specific location (Martini et al., 2015). During an operation, they network via their own IT infrastructure and thus do not become active at the operation site, so that they can perform their tasks distributed across the entire federal territory. The liaison officer is usually attached to the situational awareness section in the EOC ensuring that time-critical and actionable information from a VOST can be directly taken into account in the staff's decision-making process. Situation-adapted and additional tasks can also be forwarded to the team immediately. Since 2017, VOST THW has been requested more than 45 times by various EMAs (Fathi and Hugenbusch, 2020) for a spectrum of operational situations ranging from large-scale events to natural disasters. Primary requesters of the VOST are EOCs of districts, municipalities, and federal states. Within the scope of these operations, the following tasks were carried out, for example:

- Classification of disaster-related information that allows for conclusions about the current situation on-site
- Crisis Mapping and image analysis
- Identification of false information
- Advice on situation- and people-centered risk and crisis communication in social media

This new form of digital support requires a variety of adaptations within the operational organizations and an in-depth understanding of the decision-making processes within new VOST units.

2.4 Research gap and research questions

The academic investigation of this topic has so far been carried out in limited depth only. Aspects, such as the challenge of automated analysis of large social media text-data sets using approaches like Natural Language Processing (Buscaldi and Hernandez-Farias, 2015) or machine learning algorithms such as Random Forests (Nair et al., 2017) have been widely researched. In recent years, international research was focused on big data analysis particularly of Twitter (Vongkusolkit and Huang, 2021) and some other social media platforms such as Flickr (Cervone et al., 2016) in disaster situations. Based on this work, a new research area developed under the umbrella of Crisis Informatics (Palen et al., 2007b; Reuter and Kaufhold, 2018).

Crisis Informatics addresses the challenges portrayed mainly using technical approaches, although a number of other studies explore organizational collaboration with digital volunteers. In their work, Soden and Palen (2018) outline how innovative and participatory approaches have found their way into the field of disaster management. Drawing on four recent cases, they explain how information and communication technology has changed the way natural hazards are perceived and responded to, including in the field of research. Soden and Palen (2018) argue that informing affected people, i.e., risk and crisis communication, is not limited to the neutral depiction of disaster situations through data. They base their argument on two theses: On the one hand, they state that the academic discussion of crisis is dominated by technical solution approaches. On the other hand, communities of research institutions, practitioners, and funding agencies dominate the development of solution approaches to scientific problems they formulate. Nevertheless, practical applications of scientific approaches are also taking place in experimental or real-world environments in numerous fields. For example, Kaufhold et al. (2020) presented results from field trials with EMAs in a paper that evaluated a system for cross-platform monitoring of social media that also included automated alerting based on advanced algorithmic analysis. Current work is investigating requirements for dashboards to visualize social media information for instance (Basyurt et al., 2021). The impact of information products generated by virtual communities of volunteers on situational awareness and on decision-making processes of EOCs have not yet been researched in depth. Furthermore, there is a lack of research studies examining necessary organizational requirements for the integration of these digital volunteer units. Initial work has addressed this gap: a case study systematically analyzed organizational, procedural, and technical requirements for the integration of a VOST when collaborating in an EOC during a large-scale event (Fathi et al., 2020). In light of the COVID-19 pandemic and the 2021 flood in Western Germany, various institutions call for strengthened VOST structures and intensified mobilization and utilization of such teams. In Germany, both the Ministry of the Interior of North Rhine-Westphalia, (2022) and the Association of Fire Departments in North Rhine-Westphalia (2021) are advocating the integration of VOSTs in risk and crisis communication activities, including information collection from social media. Parliamentarians of the German Bundestag also call for further strengthening of VOSTs, e.g. to identify false information at an early stage in disasters (Mihalic et al., 2021; Bündnis, 2022). At the same time, a research gap on digital VOST-analysts work, its impact on decision-makers' situational awareness and subsequent decision-making in disaster management persists. To initiate closing this research gap, we conduct a scenario-based case study to examine findings about a VOST's work and the impact of subsequent VOST information in a specific hazard situation. Due to the broad range of topics, this work addresses the following research questions (RQ):

RQ 1: Which categories of information have been identified, prioritized, and contextualized in relation to the specific flood situation, taking into account the factor of time?

RQ 2: How are categories, information format, prioritizations, and platforms related?

RQ 3: How do the information provided by VOSTs impact the situational awareness and response actions based on actionable information in EOCs decision-making?

To examine these research questions, we used two different methods in our case study, which are described in detail in the next section.

3 Case study and methods

This case study uses different research methods to explore the three research questions described above. We proceed in two stages to address the three research questions. In the first stage addressing RQ 1 and RQ 2, we examine the data generated by the VOST during the flood response. In the second stage, we address RQ 3, focusing on the perspective of decision-makers in the EOC. By surveying these decision-makers, we study the impact of VOST information on situational awareness and decisions, as well as risk and crisis communication. A graphical illustration of this case study used along with corresponding stages, research questions, data material, and methods will allow for a structured overview in Figure 1. As we have been scientifically supervised VOST THW since the project was piloted in 2016, we were provided with the VOST data for conducting this research. Furthermore, there are several personnel overlaps between our university and the VOST THW, for example, the first author of this case study is a volunteer in the VOST. In addition to the VOST data, operations orders were also provided that could be used to track the integration of VOST operations into the EOC. This includes the precise times of the alert, the end of the operation and the task priorities. In the following section 3, we first explain our case study concerning the flooding event in July 2021 in Wuppertal, Germany including the interagency setting in which the VOST THW was integrated into the EOC. Following these explanations, the two methods of data analysis and surveying decision-makers are described in detail.

3.1 Case study

3.1.1 Flooding event 2021

Flooding in Germany on July 14 and 15 in 2021 severely damaged several areas in the federal states of North Rhine-Westphalia and Rhineland-Palatinate. Due to exceptionally heavy precipitation, floods were induced that caused substantial damage, especially in the Ahr valley (Kreienkamp

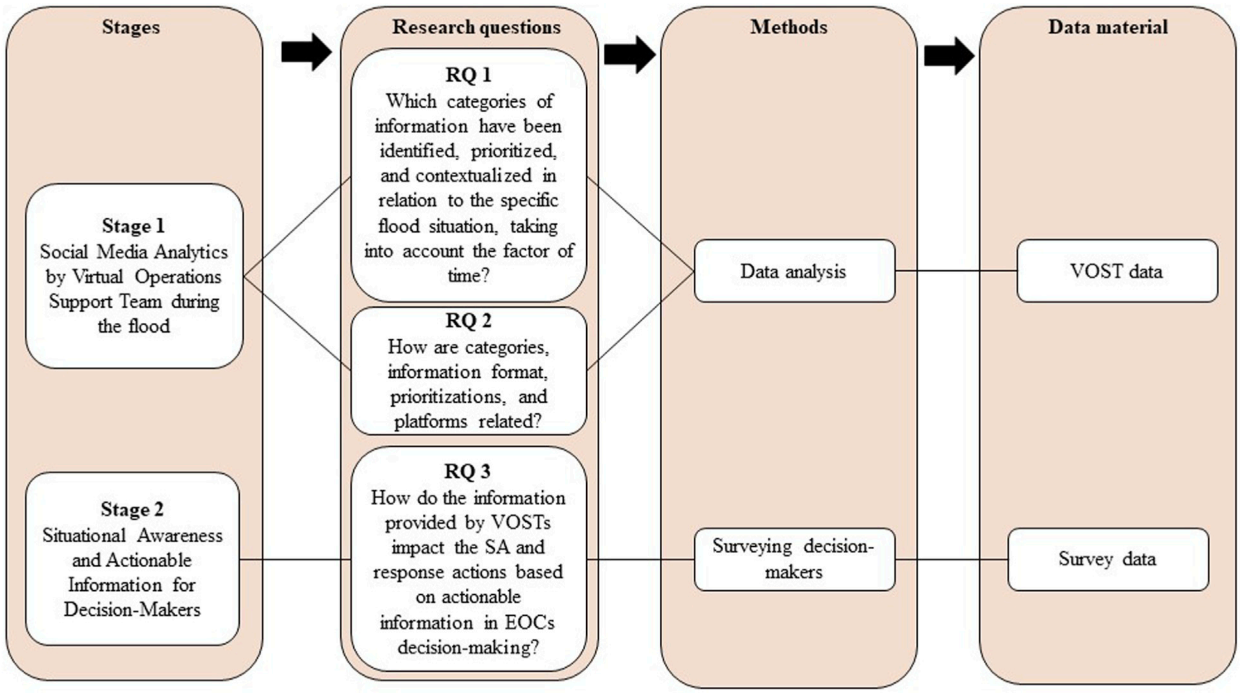

FIGURE 1
Research design.

et al., 2021) and the death of 184 people. The North Rhine-Westphalian city of Wuppertal (361,550 inhabitants) was also seriously affected by strong precipitation (up to 151.5 L/m^2) with subsequent floods on 14 July 2021 (Zander, 2021). The EOC, led by the fire department and including other decision-makers from several EMAs, began its work at 5:00 p.m. on July 14. At about 23:35, the Wupperverband (responsible for water management in the Wupper river catchment) registered uncontrolled overflow of 2 dams (Zander, 2021). The EOC declared a state of emergency in the entire city area due to the amount of precipitation, uncontrolled overflow at the dams and the overflow of the river Wupper. Floods were expected to reach the city area during the night. Due to numerous floods and power outages, the EOC received 4,973 emergency calls within 24 h (Zander, 2021). According to Zander (2021) various approaches were used to warn the population. Besides the involvement of radio and press, the governmental warning app *Nina* was used as well as mobile warning by vehicles, social media and the siren was set off at 00:38 a.m. Thirteen sirens were activated and seven mobile warning vehicles were deployed throughout the city. At 00:20 a.m., the highest warning level 1 was declared. This level includes, for example, media broadcasting the warning immediately and unaltered, and radio programs stopping their shows to warn. In the following days, all emergency sites were processed. Additional to all available staff of the Wuppertal fire department other EMAs were also involved. Approximately 1,125 emergency staff were deployed over a period of 72 h. In Wuppertal, there were no serious personal injuries caused by the flood. The fire department and city authorities were involved in rebuilding and recovery response for several months.

3.1.2 Integration of VOST in an EOC

EOCs are decision-making units of public authorities and EMAs such as fire departments and aid organizations. Due to the professionalization and institutionalization of digital volunteers in the VOST THW described in section 2.3.1, this VOST can be activated rapidly in unexpected ad-hoc situations. The team was alerted by the EOC in Wuppertal at 8:32 p.m. on 14 July 2021 and set up its digital operating structures immediately. These structures primarily stipulate two elements: On the one hand, a liaison officer is sent to the EOC to forward VOST information to decision-makers and to ensure collaboration between the virtual team and the operating EOC. On the other hand, VOST team leaders simultaneously build up the team structure. This includes the coordination of work procedures, information products, and the distribution of tasks. For the development of information products, task priorities and information needs were defined for SMA with EOC decision-makers and the liaison officer as follows:

(1) Information on damages and the current flood situation,
(2) Helpless people and people in danger,

(3) Identification of disaster-related information for risk and crisis communication (including false information and rumors),
(4) Psychosocial needs of the affected population, and
(5) Development of spontaneous build up community engagement structures.

Additionally, it was determined that information prioritized as high by VOST analysts within these five categories would immediately be forwarded by the liaison officer to the appropriate decision-makers in the EOC. Low and medium priority information was forwarded in chronological listings at regular intervals to contribute to situational awareness. Twenty-two VOST analysts were involved in the operation over the specific period until the interagency collaboration with the EOC ended on 16 July 2021 at 02:30 a.m.

3.2 Methods

3.2.1 Stage 1: Analysis of VOST data

In the first stage of this study (concerning RQ 1 and RQ 2), various analyses were conducted based on VOST data. VOST analysts collected social media data from different social media platforms during the operation. Platforms were selected by VOST and included eight different social media: Twitter, Facebook, Jodel, Instagram, YouTube, TikTok, Snapchat and Telegram. In addition to these platforms, websites were captured if, for example, links to news pages were shared on social media. The original source (website) was collected. To acquire this data, some manual search methods were used as well as the semi-automated SMA software ScatterBlogs (Bosch et al., 2011). For the selection of relevant, disaster-related social media posts, VOST analysts used keywords (e.g. wuppertal or "wupper" and hashtags (e.g. #wuppertal or #w1407) as well as the location search. The SMA tool autonomously locates Twitter posts in regions using advanced analytics (Thom et al., 2016). All data was entered into an aggregate file, which we name "VOST data" for the purposes of this case study. VOST analysts separated disaster-related information from unimportant information, applying the task priorities (see five points in section 3.1.2). Data considered relevant was then collected in a central file accessible for all analysts, which we used for the research depicted in this paper. During the flood, VOST classified 536 social media posts as relevant and subsequently evaluated and categorized their relevance into three levels (high, medium, low), first by team member and then by team leaders. In line with the task priorities, the social media posts (text, images and videos) are evaluated on the basis of two factors: first, how important the information is for the decision-makers and, second, whether it is also urgent (e.g., because dangers or changes in the situation may emanate from it). Because the prioritization of data is subjective and depends on the current disaster situation, which in turn can change within a short period, a team leader performs an additional evaluation. The file of data collected during the flood, however, was partially incomplete. To complete the VOST data and for subsequent analysis, we proceeded in the following four steps:

(1) Data cleaning: adding missing metadata (times of posts, information format, and platform)
(2) Summary of categories (e.g. misinformation and disinformation combined in the category false information)
(3) Visualization of the data
(4) Comparative quantitative analysis and contextualization of the data

In addition to analyzing the distributions of the categories (RQ 1), different parameters from the data set were used for more in-depth analyses. These parameters are the prioritization of social media posts by VOST analysts, the format of information (text, image, and video), and the source (social media platform). For answering RQ 2, we have quantified the three levels of prioritization (high = 3, medium = 2, and low = 1) and calculated the mean value for each category. This dataset is unique because it was collected during a real-world flood operation and not during a training or scenario-based simulation. Furthermore, 22 skilled VOST analysts conducted the data collection, so the data collected was always preceded by an evaluation. Compared to datasets from other works, a variety of data from several social media platforms was included here.

3.2.2 Stage 2: Survey of decision-makers

One of the characteristics of the German disaster management system is that it is organized on a regional basis, with local EOCs taking over the management. This means that a large number of EOCs exist for disasters that affect several regions at the same time. In our case study, we only examined the one EOC that collaborated with the VOST THW. In stage 2, an online survey was designed using the application LimeSurvey to answer RQ 3. The objective was to interview all EOC decision-makers who had worked with the VOST THW during the flood in Wuppertal. In selecting these participants, it was also important that they had worked directly with VOST information and thus based their situational awareness and/or decisions on it. A total of nine persons were identified as eligible for this survey. All nine decision-makers from the EOC participated in the survey conducted from Jan. 7 to 21, 2022, preceded by six online pretests. First, demographic data and respondents' roles in the EOC were asked, followed by a matrix of six questions about whether and how VOST information impacts situational awareness. These questions addressed the results gained in stage 1 and examined whether categorizing, filtering, and prioritizing the collected data contributed to situational awareness. Subsequently, another matrix of six questions examined how actionable information influenced decision-making by asking whether faster and better decisions were made based on this actionable information. We also examined whether such information contributed to greater certainty in decision-making and how it impacted people-centered risk and crisis communication. Both question matrixes needed to be rated by the nine decision-makers on a five-point Likert scale. Subsequently, the mean value of these ratings was calculated in order to be able to make a quantitative comparison of the ratings. The calculated mean was categorized as follows (5–1): strongly agree = 5; agree = 4; partially agree = 3; disagree = 2; strongly disagree = 1. Using Likert scales is an established method in the research literature of summated scores to translate individual respondent ratings into an aggregate score (e.g., impact on situational awareness or decision-making) (Schnell et al., 2011). This case study utilizes the five-point Likert scale as a metric scale (strongly agree = 5; strongly disagree = 1) defined as an interval scale with equally spaced units (Backhaus et al., 2021). Therefore, this scaling is appropriate for our survey to use a quantitative research approach to answer the RQ 3 and determine the impact of VOST information on situational awareness and decisions based on actionable information. For this purpose, we apply the descriptive statistics approach in the following section 4. We ended the survey with general questions about information product design and future cooperation with VOST. The following Figure 1 presents our methodological approach in a schematic illustration of our two stages, the respective research questions, the methods and the data material.

4 Results

4.1 Stage 1: Social Media Analytics by Virtual Operations Support Team during the flood

A total of 536 posts from various social media platforms were identified and collected. 56% of these disaster-related posts were shared on Twitter, 15% on Facebook, nine percent on Jodel and seven percent on Instagram. Three percent of the analyzed information was posted on YouTube and one percent on TikTok. In addition to this social media data, 42 datasets from websites were gathered. Almost all posts were in German; only three posts (translations of EOC warnings by social media users) were in English, Turkish, and Russian. The posts' formats were collected as well: More than half (58%) of the information was posted in text-only format, 22% of the posts were images, and 20% were videos. The types of accounts that forwarded the information previously shared on social media were identified as follows: 77% of the posts were shared through citizens' private accounts, 17% by media and press accounts and five percent by EMAs. Other types such as public transport agencies, accounted for the remainder.

4.1.1 Categories

To answer RQ 1, VOST data collected during the flood were analyzed and contextualized in the respective flood situation. For this purpose, data collected by the 22 VOST analysts who classified disaster-related information from the flood into categories during the flood operation were summarized. Categories described with different terms (e.g. spontaneous volunteer and spontaneous helpers combined in the category spontaneous community engagement or misinformation and disinformation combined in the category false information) were merged for a better understanding. This analysis indicated that the information gathered from social media could be summarized into 23 different categories for the examined period. Figure 2 shows these categories and their proportional distribution for the entire operation period in percent. It illustrates that the first five categories' distributions closely resemble one another and account for over half of all identified posts (51.9%). The results also show that four of the five categories (level of the river, warning, flooded traffic roads and power outage) are related to the hazard flood situation. However, the largest category mainly concerns the time after the hazard flood situation (spontaneous community engagement). With regard to the information needs of the decision-makers in the EOC, defined as task priorities (see section 3.1.2), Figure 2 illustrates that information could be found on all aspects. Subdivided into 23 categories, information was found on the extent of damage, level of the river, hazards, and findings for risk and crisis communication, psychosocial needs, and spontaneous build up community engagement structures.

Due to the hazard and dynamic flood situation, which consists of various different elements (e.g. power failure, activation of warning sirens, evacuation), the analysis of the categories under the factor of time plays an essential role for the overall understanding of the summarized categories. To visualize the five most frequent categories, we made use of the posts' timestamps to analyze when they were published on social media (see Figure 3). In addition to these first five categories, the posts about sirens were added. With about four percent of all posts, this category plays a minor role overall. However, looking at the distribution of posts over time, it becomes clear, that the siren warning was a relevant topic of interest. Its activation at 00:38 a.m. is distinctly visible within the data. During the dynamic flood situation, posts about flooded roads and information about the level of the river dominated particularly. This was followed by posts about warnings via various methods (sirens, warning vehicles, and warning app) during the night and in some cases power outages, which were discussed intensively altogether. With the abatement of the hazard flood situation, from the following day on July 15, the flood response of so-called spontaneous volunteers predominated as spontaneous community engagement structures formed in social media especially (see Figure 3). As the day progressed, this topic increasingly dominated social media, partly due to a call to the public by the EOC to participate in disaster response.

4.1.2 Relationships between categories, prioritizations, information format, and platforms

In addition to summarizing the categories and analyzing them with the consideration of time, our processing of RQ

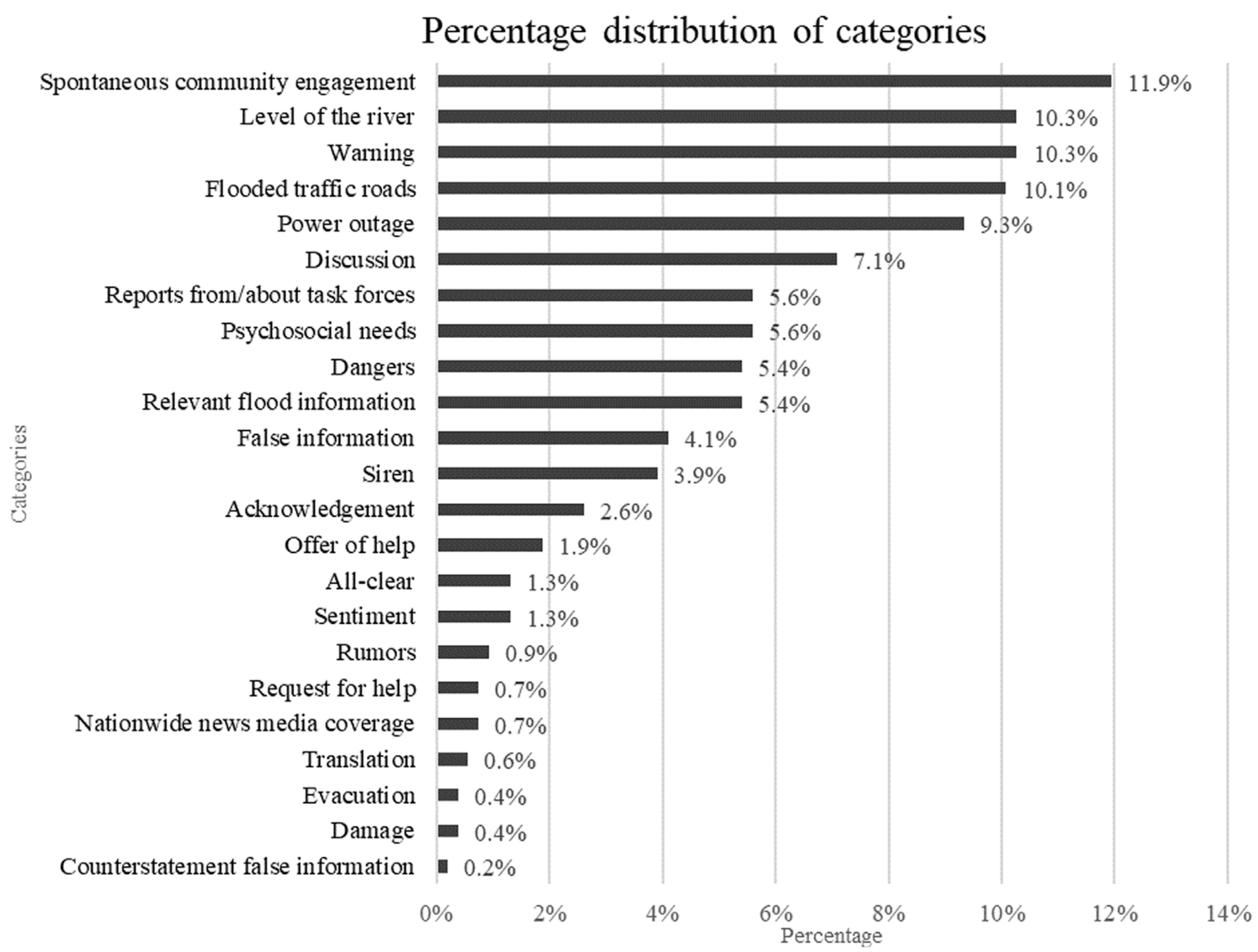

FIGURE 2
Percentage distribution of categories.

2 examined what relationships exist between the categories and other parameters. Table 1 lists the categories (number of posts in brackets) and the mean value of the respective prioritization assigned by VOST. The comparison of the categories' frequency and their prioritization shows that none of the five most common categories discussed above (see Figure 2) were assigned the highest mean priority, while all posts in the categories of false information and rumors (and the one counterstatement) or damage and requests for help were consistently prioritized with the highest level of 3. The top five most frequent categories were rated between medium to high priority (in average $M = 2.13$): spontaneous community engagement ($n = 64$; $M = 2.03$), level of the river ($n = 55$; $M = 2.18$), warning ($n = 55$; $M = 2.07$), flooded traffic roads ($n = 54$; $M = 2.43$)) only with the exception of the category power outage ($n = 50$; $M = 1.92$).

Posts in categories that could have had a direct impact on the health and safety of the affected population (e.g., request for help or false information) were on average rated higher than others. All such posts were classified as actionable information and thus directly forwarded to the decision-makers in the EOC. In flood situations, f alse information can lead the affected population to take wrong and dangerous actions, such as fleeing reactions. While the flood situation was still dynamic in Wuppertal for example, a video supposedly showing the Wuppertal Dam was shared, picturing rushing muddy water and various steel constructions as well as a conveyor belt. It was first published on the evening of July 15 claiming the Wuppertal Dam had busted, and subsequently shared on various social media platforms such as Twitter, Facebook, Telegram and YouTube with wide reach. However, the video does not show the location indicated, but in fact the Inden strip mine 120 km from the Wuppertal Dam. This mine had been flooded by the river Inde due to the heavy rainfall on July 15 indeed causing great damage, but not in Wuppertal.

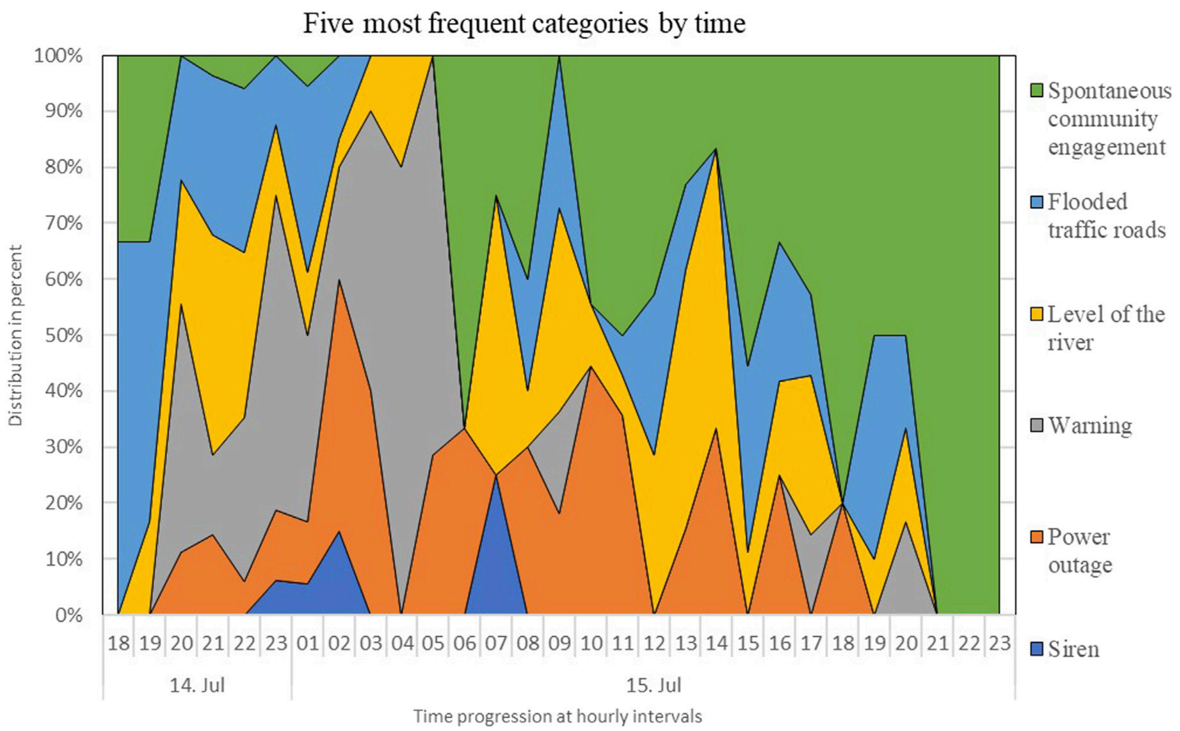

FIGURE 3
Five most frequent categories by time.

Although the situation at the Wuppertal Dam was difficult as described in section 3.1.1, it was not as critical endangering large parts of the population. In a further step to answer RQ 2, we analyzed how the different formats of information can be classified into the categories. Four different formats were identified in the dataset of 536 social media posts: text, image, video, and one gif. Table 2 lists these formats and their mean value of prioritization.

This comparative analysis shows that, on average, information in the format of videos (n = 105; M = 2.25) has a higher priority than information in other formats such as images (n = 117; M = 2.09) and text (n = 313; M = 1.90). Following on from this analysis, we conducted a comparative analysis of the prioritization of the data and the sources on which the information was published (see Table 3). Eight different social media platforms were identified, with disaster-related information from websites also listed (n = 42).

Table 3 illustrates that information from social media platforms that mainly contain images and videos is prioritized higher (e.g. YouTube: n = 16; M = 2.44) than that from text-heavy platforms (e.g. Twitter: n = 300; M = 1.95), with a large difference in distribution within platforms.

Our analysis from various social media platforms indicates that the information can be summarized into 23 categories of which the five most frequently occurring categories have a similar distribution. However, a chronological analysis reveals that the prevalence of categories varies over time: posts about spontaneous community engagement increase strongly as the hazard flood situation passes and finally dominate completely. The investigation of the prioritization by VOST analysts also leads to important findings: Posts with a potential impact on the health and safety of the affected people, such as request for help or false information, are given high priority. Furthermore, it could be established that in the mean prioritization value of all 536 posts, videos are prioritized higher than other formats of information. This is also reflected in the selection of social media platforms: information from those that are more image-heavy are prioritized higher than text-heavy ones.

4.2 Stage 2: Situational awareness and actionable information for decision-makers

In stage 2 of this case study, we examine RQ 3, addressing the question of how VOST information impact decision-makers' situational awareness and how actionable information contributes to decisions. In an online survey, we systematically interviewed all nine decision-makers who had worked with VOST information during the flood. All respondents were men between 32 and 54 years

TABLE 1 Categories and prioritization.

Categories	Mean of Prioritization (M)	Standard Deviation (SD)
Rumors (n = 5)	3.00	0.00
Request for help (n = 4)	3.00	0.00
False information (n = 22)	3.00	0.00
Counterstatement false information (n = 1)	3.00	-
Damage (n = 2)	3.00	0.00
Dangers (n = 29)	2.79	0.49
Nationwide news media coverage (n = 4)	2.50	0.58
Flooded traffic roads (n = 54)	2.43	0.69
Level of the river (n = 55)	2.18	0.75
Warning (n = 55)	2.07	0.66
Spontaneous community engagement (n = 64)	2.03	0.71
Translation (n = 3)	2.00	0.00
All-clear (n = 7)	2.00	0.58
Evacuation (n = 2)	2.00	0.00
Psychosocial needs (n = 30)	1.93	0.78
Power outage (n = 50)	1.92	0.70
Siren (n = 21)	1.90	0.62
Relevant flood information (n = 29)	1.62	0.56
Offer of help (n = 10)	1.60	0.70
Sentiment (n = 7)	1.57	0.53
Reports from/about task forces (n = 30)	1.30	0.65
Discussion (n = 38)	1.16	0.37
Acknowledgement (n = 14)	1.00	0.00

TABLE 2 Information format and prioritization.

Information Format	Mean of Prioritization (M)	Standard Deviation (SD)
Video (n = 105)	2.25	0.72
Image (n = 117)	2.09	0.82
Text (n = 313)	1.90	0.78
Gif (n = 1)	1.00	-

of age (M = 41.7), with an average of 21 years of work experience in EOCs. Three of the interviewees were EOC directors; the other six were executives of specific subject areas (e.g. communication or warning) within the EOC.

4.2.1 VOST impact on situational awareness

In the first step of this second stage, we examined how VOST information contributed to decision-makers' situational awareness during the flood. All statements were generally rated with a strong agreement overall (M = 4.46). The highest level of agreement was expressed for the statement that VOST information contributes to increased situational awareness, with two decision-makers rating the statement with agree and all others with strongly agree (n = 9; M = 4.78). Categorizing, prioritizing, and filtering social media data by VOST analysts also contributes to situational awareness, according to the decision-makers interviewed (see Table 4).

There was also strong agreement with the statement that a liaison officer is necessary to report information from VOST to the EOC (n = 9; M = 4.22). The statement that VOST information forecasts developments of future situations received the proportionally lowest level of agreement (n = 9; M = 3.89).

TABLE 3 Sources and prioritization.

Sources	Mean of Prioritization (M)	Standard Deviation (SD)
Telegram (n = 2)	2.50	0.71
YouTube (n = 16)	2.44	0.63
Snapchat (n = 3)	2.33	0.58
Facebook (n = 83)	2.25	0.71
Instagram (n = 38)	2.11	0.86
Jodel (n = 46)	2.00	0.79
Twitter (n = 300)	1.95	0.80
Website (n = 42)	1.74	0.63
TikTok (n = 6)	1.67	0.82

TABLE 4 VOST impact on situational awareness.

Statement	Mean (M)[a]	Standard Deviation (SD)
1. Information from VOST contributes to expanded situational awareness.	4.78	0.42
2. Categorizing the information (e.g., into "spontaneous volunteers" or "false information") by VOST members helps me gain a better awareness of the current situation.	4.67	0.47
3. Prioritization of information by VOST members helps me maintain a better awareness of the current situation.	4.67	0.47
4. The filtering and evaluation of information by VOST members contributes to an expanded situational awareness.	4.56	0.50
5. A VOST liaison officer is necessary for the transmission of information within the EOC.	4.22	0.79
6. The information from VOST helps me to forecast developments of future situations.	3.89	0.74
Total	4.46	0.14

[a]Explanation Mean (M): The calculated mean was categorized as follows (5–1): strongly agree = 5; agree = 4; partially agree = 3; disagree = 2; strongly disagree = 1.

Overall, the battery of questions on situational awareness was strongly agreed to (n = 9; M = 4.46) with minor differences between strongly agree, agree and partially agree within the statements. However, VOST information products not only contributed to situational awareness, decisions were also made based on actionable information.

4.2.2 VOST impact on decision-making

Decision-making processes are complex in disaster management. In a short period, a large amount of information is available from various sources, so decision-makers need to quickly identify, process, and verify information and derive specific decisions from it. The previous sections show what kind of information from social media is identified, categorized, and prioritized by a VOST and how it impacts situational awareness. In contrast to the more general, medium-priority information that contributes to situational awareness, direct decision-making in the EOC is derived from so-called actionable information. We developed a battery of statements to determine the impact of this actionable information on decision-making. As in section 4.2.1, the statements were rated by the same group of decision-makers (n = 9) in a five-point Likert Scale (see Table 5).

According to these decision-makers' assessments, the VOST's provision of actionable information has helped to enable the implementation of people-centered risk and crisis communication. This statement was most strongly agreed to compared to the others (n = 9; M = 4.56).

The statements that VOST information contributes to confidence in decision-making (n = 9; M = 4.44), to make better decisions (n = 9; M = 4.33), and to identifying alternative decision paths (n = 9; M = 4.11) were also on average rated between strongly agree and agree. Only the last two statements have an average agreement value between three and four: the decision-makers thus do not agree as strongly with the statements that VOST information leads to faster decision-making and reduces complexity as with the first three (see Table 5).

The results stress that VOST information supports decision-making at different levels. Thus, actionable information contributes in particular to the ability to ensure people-centered risk and crisis communication. According to the EOC decision-makers interviewed, VOST information

TABLE 5 VOST impact on decision-making.

Statement	Mean (M)[a]	Standard Deviation (SD)
1. The information from VOST helped to ensure more people-centered risk and crisis communication.	4.56	0.50
2. The information from VOST has contributed to confidence in decision-making.	4.44	0.68
3. The information from VOST has helped to make better decisions.	4.33	0.67
4. Through the information from VOST, alternative decision paths became apparent to me.	4.11	0.74
5. The information from VOST has contributed to faster decisions.	3.89	0.74
6. Information from VOST helps reduce complexity in decision-making.	3.78	1.03
Total	4.19	0.16

[a]Explanation Mean (M): The calculated mean was categorized as follows (5–1): strongly agree = 5; agree = 4; partially agree = 3; disagree = 2; strongly disagree = 1.

contributes to confidence in their own actions when making decisions. This is particularly important in view of potential long-term consequences of decisions in disaster management that need to be considered.

5 Discussion and limitations

5.1 Discussion

Information is crucial for effective disaster management, including decision-making and people-centered risk and crisis communication. However, in a hazard and dynamic flood situation, EOCs are often challenged by the conditions (Comes, 2016) and the enormous amount of data (McAfee and Brynjolfsson, 2012) available on social media. Previous research focused on technological, communicative, and organizational issues, as shown in section 2. Although a few papers investigated other issues, the analysis of such a cross-platform dataset from an urgent hazard situation, collected by 22 VOST analysts with a subsequent survey of decision-makers of an EOC, has not yet been investigated, even though it is crucial to understand how integrating VOSTs impact the situational awareness and decision-making of EOCs. First, this section discusses social media data analysis durin the flood response and subsequently the impact on situational awareness and decision making in light of the relevant literature. Following this, approaches for future research and practical considerations are derived from the findings and outlined.

5.1.1 Stage 1: The data analysis

Through our approach of data analysis of VOST data from an operation, important insights could be gained. Thus, to answer RQ 1 and RQ 2, it was possible to classify a large number (23) of categories of information from eight social media platforms which was relevant to the decision-makers. This allowed the classification of information that played a minor quantitative role but gained relevance to the flood response through prioritization by VOST analysts (e.g. rumors and false information). Other approaches have identified fewer categories (13), also requiring at least five tweets per category (Vieweg et al., 2010) and limiting them to just one platform (Cervone et al., 2016; Vongkusolkit and Huang, 2021). The percentage distribution of categories illustrates that not only information about the flood is communicated and exchanged, but that social media is used intensively for the creation of spontaneous build up community engagement structures, which is in line with results from Nissen et al. (2021) or Sackmann et al. (2021). The increase in spontaneous volunteering over time (Sackmann et al., 2021) is also an observation that has been noted in the past and that we have been able to illustrate in Figure 3 regarding social media content. Another crucial factor of our approach also consists of the prioritization of the data by VOST analysts, which allowed us to analyze how all 536 datasets were actually evaluated. The prioritization of the posts by trained VOST analysts, enables to draw conclusions on how important and urgent social media information was during the flood response, without machine learning approaches taking over this evaluation (Rossi et al., 2018). Furthermore, the results of our case study were not limited to text messages (Buscaldi and Hernandez-Farias, 2015; Nair et al., 2017), images and videos were also included into the analysis. The analysis of images and videos assumes an important part, as these can be time-consuming by human analysts. The content has to be verified, geolocated and interpreted, which can tie up several analysts at the same time; in a VOST operation during a mass-event 2017, a separate group has been formed for this tasks (Fathi et al., 2020). Automated tools, such as the AI-supported AIDR presented in section 2.2.1, are not yet widely implemented (Reuter et al., 2016). In their survey of 761 emergency responders, Reuter et al. (2016) determined that only 23% were using social media to expand situational awareness and some EMA were experimenting with different tools. At the same time, the study by Krupp and Bellut (2021) shows that in Germany, especially among the younger population, image-heavy platforms (such as Instagram) are used instead of text-heavy platforms (such as Twitter). The approach of analyzing and prioritize large mass data by VOST analysts also has its risks. Due to the close integration into an

EOC, the digital volunteers in the VOST are exposed to similar conditions (time pressure, uncertainty, information overload, high stakes) as the decision-makers in the EOC, despite the virtual working methods (Comes, 2016; Paulus et al., 2022). This can cause data bias and confirmation bias to affect the analysts' information products for decision-maker (Paulus et al., 2022). In addition, analyzing disaster-related social media information (e.g., traumatizing images and videos) and working alone creates the possibility of psychosocial burdens on VOST analysts. Due to the integration in an EMA, established structures of psychosocial help also exist for digital volunteers, which Tutt (2021) described in a paper due to the special virtual conditions.

5.1.2 Stage 2: The impact on decision-making

As described in section 2.2.1, Endsley (1988) understands situational awareness in three distinct parts with the aspects of perception, comprehension, and projection. Applied to our survey, the results indicate that perception and comprehension especially are influenced positively. Using the calculated mean, it can be seen in the results Table 4 and Table 5 that most statements receive a high level of agreement from the decision-makers (nine out of a total of twelve statements have a value above $M = 4.00$) and thus contribute to a wider perception. Even though situational awareness is always subjective (although there is objective situational information, e.g., in our case VOST information) (Hofinger and Heimann, 2022) we were able to transform individual respondent ratings into an aggregate score (Schnell et al., 2011). The results illustrate that the interagency integration of a VOST into EOC structures contributes to expanded situational awareness ($M = 4.78$). The high agreement in the use of SMA approaches, such as categorization ($M = 4.67$), prioritization ($M = 4.67$), filtering and evaluation ($M = 4.56$), highlight this result. Thus, our results are in line with Vongkusolkit and Huang (2021) who previously highlighted that SMA can improve situational awareness for decision-makers in disaster management. The high level of agreement indicates that the perceptions of decision-makers at the EOC have been positively impacted. The second part of the survey focused on decision-making based on short-term actionable information (Mostafiz et al., 2022). Decision-making based on actionable information requires that information reaches the right decision-maker in the EOC at the right time and that the decision-maker comprehends it (Zade et al., 2018). Applied to the second of three aspects of the definition by Endsley (1988) our results suggest that VOST information can also make an impactful contribution. This can be argued especially because important decisions could be made based on VOST information (e.g., ensure more people-centered risk and crisis communication, $M = 4.56$) or that information from VOST helped to make better decisions ($M = 4.33$). Collecting data in the decision-makers task priority spontaneous build up community engagement structures contributed to a better assessment of the resource potential within the population and allowed to derive focused measures, such as an active call on social media by the EOC for spontaneous participation in disaster management. According to the four different flood risk communication strategies by Haer et al. (2016) introduced in section 2.1.2, it can be deduced that this approach enabled a people-centered communication strategy focused on risk and coping options. Compared to perception and comprehension, the results of the survey that can be assigned to third field from the situational awareness definition by Endsley (1988), projection, are less strongly positive. Thus, the statements that VOST information helps me to forecast developments of future situations ($M = 3.89$), has contributed to faster decisions ($M = 3.89$), and helps reduce complexity in decision-making ($M = 3.78$) are only in a range between partially agree and agree. Even though the decision-makers at the EOC are experienced disaster management responders with an average of 21 years of work experience in EOCs, the conditions (e.g., uncertainty and high stakes) (Comes, 2016) during such a situation affect them. In addition to these conditions, there is the severity of the flood (Zander, 2021), the night time and uncertain situation developments (see description in 3.1.1). These factors may have contributed to the VOST information not being as positive as the other two aspects (perception and comprehension) in projecting the future. Based on our survey, VOST information contributes in particular to perception and comprehension. Both the expansion of situational awareness and the deduction of immediate measures are indicators for this. Statements, which are concerned with forecast developments of future situations, faster decision-making and reduction of complexities, received less approval. The projection seems to be improvable, e.g. by exercises.

5.1.3 Future research

These results illustrate that a variety of disaster-related information can be found on several different platforms, in this case study eight different platforms and additionally information from websites. Our approach allowed us to analyze in detail a wide range of relevant disaster-related information in social media, in different disaster phases. For future research approaches, more attention should be paid to the fact that the affected population's communication is not confined to only one social media platform, so that detailed insights can be derived that remain hidden when focusing on a single platform. This circumstance must also be taken into account in EMAs people-centered risk and crisis communication, since different age groups, for example, use differing platforms intensively (Krupp and Bellut, 2021). In addition, future approaches designing categorization frameworks for different disaster scenarios from social media data could simplify the classification of these large amounts of data. In addition, exploring the use of AI in the analysis and visualization of big data volumes and creating it to support decision-making is crucial. In particular, research approaches for the use of AI need to be further developed, such as the platform Artificial Intelligence for Disaster Response (AIDR) described in section 2.1.1, particular in the automated analysis of images and videos.

In addition, machine learning approaches need to be explored further, for example, such as those that cluster text messages (Sonntag et al., 2021) or analyze the data of social media comparatively with those of news sites and intend to verify with this approach (Kuhaneswaran et al., 2020). The results revealed that several categories were of particular priority during the hazardous flood situation. Future AI approaches can follow up on this research by capturing information needs of decision-makers and developing automated prioritization methods and algorithm for various disaster scenarios.

The visualization of categories by time enabled us to show that immediate actions, e.g. siren warning, are publicly discussed in social media (see Figure 3). Here, a more comprehensive and in-depth analysis of the affected population's psychosocial needs could help decision-makers in improving their people-centered risk communication. Our results additionally illustrate that image-heavy information is prioritized higher by VOST analysts than text-heavy posts (M_{Video} = 2.25 and M_{Text} = 1.90). In order to understand potential biases in the perceptions and ratings by individual VOST analysts, research into the individual reasons that lead to a lower or higher prioritization can be beneficial.

The results illustrate that the situational awareness is expanded by VOST information (M = 4.78) so that it can be argued that without the integration of a VOST, the information available would not or not completely be integrated into situational awareness. The scope of this situational awareness expansion however, has not yet been examined. To investigate this issue, participatory observations and interviews during future operations or interagency exercises can be used to qualitatively examine both information management and the detailed processes used to gain situational awareness.

Furthermore, we can contribute to improving the understanding of data analytics impact on human performance, in our case situational awareness. Linking data analytics and real-world impact is particularly important in order to realize needs-based analytics. In this regard, a more in-depth study of the information needs of individual decision-makers' work areas (e.g. communication) in EOCs will be valuable.

5.1.4 Practical considerations for disaster management

Based on the results of the two stages, it can be deduced that the analysis of social media offers an opportunity to derive information about the current situation and the needs of the affected population. The integration of VOST analysts in an EOC can help to find and integrate relevant disaster-related information in disaster management, expand decision-makers' situational awareness and enable people-centered risk and crisis communication.

To maintain these positive effects in the future, it seems necessary for EOCs to practice with VOSTs (e.g., tabletop exercise), especially before the need to expand projection skills described in Section 5.1.2. Moreover, as the affected population uses various social media platforms for communication, EMAs ought to observe the trends of different platforms closely for future people-centered risk communication, so that individuals can be reached in a multimedia and dialog-oriented approach. This indicates the necessity, especially in light of the climate change-related challenges for disaster management, that EMAs develop and establish their own analytical, risk and crisis communication competencies. Large-scale disasters, such as the 2021 flood in Germany, demonstrate that the analysis resources of a VOST are not sufficient to parallelly provide all EOCs with appropriate information products.

5.2 Limitations

Two different methods were used in two stages to study RQ 1, RQ 2 and RQ 3. For this case study, the data collected by the VOST during the dynamic hazard situation for the purpose of collaboration among the 22 analysts were studied. To investigate the VOST information's impact on situational awareness, but also for a deeper understanding of actionable information affecting EOCs decision-making, a survey was conducted for this paper. With a subsequent analysis, the results of the two methods used were examined and discussed in the context of previous work. The combination of the two stages in our research approach remains at the level of linking the separate findings so that the results can also be collected and analyzed in isolation and independently of each other. This approach, based on innovative analysis approaches (analyzing operational VOST data) as well as established research methods (survey), ensures that this work contributes to the scientific debate and to the practical discussion in this strongly interdisciplinary research area. The scientific value of this methodological approach is based on the fact that, despite the time- and safety-critical working environment in disaster management, important real world and unique findings could be obtained.

Due to the nature of a case study, there are limitations in generalizing the results to other hazard scenarios and interagency collaborations. It should be noted that integrated SMA by a VOST depends on the task priorities and information needs set by the respective EOC as they can vary according to the particular focus of an EOC. The timing of a VOST operation in a hazard situation is also crucial. During the response phase, information needs differ from those during the recovery phase of a disaster. This becomes visible in the depiction of the identified categories over time, where different task priorities dominate over the course of the acute hazard situation (see Figure 3). Additionally, even if the prioritization was performed by more than one person (VOST analyst and VOST team leader), there is a possibility of cognitive or data bias (Paulus et al., 2022). The dataset is also not representative of all data posted on social media during the flood situation, but rather reflects what the 22 VOST analysts were able to collect in this particular hazard flood scenario based on the EOC task priorities. Despite the cross-platform data, over half (56%) of the disaster-related information comes from Twitter, thus, similar to other papers (Vongkusolkit and

Huang, 2021), a data bias has to be noted here. In addition to data from social media, 42 information shared on websites were also analyzed. For the purpose of completeness, this data was also included in this case study. While it was possible to examine that VOST information contribute to an expanded situational awareness by surveying EOCs decision-makers, detailed insights are missing due to the common limitations of a survey. Additional guided interviews would allow a deeper understanding of situational awareness among individual decision-makers to be explored. In addition, only nine decision-makers from a single EOC were surveyed, interviewing members of different EOCs would also be helpful for detailed findings.

6 Conclusion and outlook

Integrating SMA conducted by a VOST into the decision-making process in disaster management is challenging: On the one hand, VOSTs work on a volunteer basis and are exclusively virtual. On the other hand, virtual work in time-critical environments has not been explored sufficiently, although without the volunteer work of a VOST, SMA could not be conducted in-depth. Thus, VOST information have revealed a new or complementary view of the flood situation to the EOC. Through the unique approach of analyzing VOST data and also surveying the EOC decision-makers who worked with VOST information during the flood response, we were able to gain important insights. Thus, it was shown that VOST analysts utilized a variety of different social media platforms for analysis and was not limited to Twitter. Furthermore, it could be shown that image-heavy posts are prioritized higher than text-heavy posts and that the percentages of the categories change heavily in the course of the flood. The survey highlights that VOST information helps to increase situational awareness and resulting actionable information contributes to the EOC's decision-making. This includes in particular the realization of people-centered risk and crisis communication during a hazard situation. Integration VOST information into the EOC has a positive impact on the perception and comprehension of the disaster situation by the decision-maker overall, although the projection on future developments needs to be improved. This case study demonstrated that the need for SMA does exist and that information can be generated by an interagency collaboration and subsequently integrated into decision-making contributing to operational success.

The research focus of this paper was to investigate the VOST data generated during a hazard flood and its impact on situational awareness and decision-making in disaster management. Thus, this case study with its three research questions contributes to developing a scientifically substantiated understanding of virtual work with social media data in time-critical environments and to exploring its impact on decision-making in an EOC. While previous research was mainly focused on technical aspects of SMA, this case study allows the practical assessment of such teams by analyzing a VOST operation during a flood and by interviewing decision-makers. Furthermore, this work contributes to further developing the understanding of digital participation in disaster management and to generate a foundation for future research, both in technical and social sciences. For the future integration of professionalized digital volunteers, it appears necessary that decision-makers in EOCs more deeply understand the relevance, velocity, and fundamental change in the communication culture due to social media develop their own competencies and resources.

Data availability statement

The datasets presented in this article are not readily available because operational data from VOST cannot be published. Anonymized survey data, in contrast, can be published. Requests to access the datasets should be directed to fathi@uni-wuppertal.de.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Author contributions

RF developed the paper concept and the methodology, analyzed the data and wrote the manuscript. FF supervises this project.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Exploring the potential role of citizen science in the warning value chain for high impact weather

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Preparing and delivering warnings to the public involves a chain of processes spanning different organizations and stakeholders from numerous disciplines. At each stage of this warning chain, relevant groups apply their expertise, but sharing information and transmission of data between groups is often imperfect. In diverse research fields, citizen science has been valuable in filling gaps through contributing local data. However, there is limited understanding of citizen science's role in bridging gaps in the warning value chain. Citizen science research projects could help improve the various aspects of the warning value chain by providing observations and evaluation, data verification and quality control, engagement and education on warnings, and improvement of accessibility for warnings. This paper explores the research question: How can citizen science contribute to the warning value chain? Two workshops were held with 29 experts on citizen science and the warning value chain to answer this question from a high impact weather perspective. The results from this study have shown that citizens, at individual or collective capacity, interact throughout the chain, and there are many prospects for citizen science projects for observations, weather, hazard, and impact forecasting, to warning communication and decision making. The study also revealed that data quality control is a main challenge for citizen science. Despite having limitations, the findings have shown that citizen science can be a platform for increasing awareness and creating a sense of community that adds value and helps bridge gaps in the warning value chain.

KEYWORDS

warning value chain, citizen science, high impact weather, warning, warning design

Introduction

Disasters are unexpected events that collectively threaten to disrupt the lives of a populace (Olsson, 2014). Disaster situations come in varying scales and predictabilities and are set within complex contexts where management decisions lead to broad societal consequences (Liu, 2014). The Hyogo Framework for Action (UNISDR., 2005) and the Sendai Framework (UNDRR., 2015) have encouraged the development of Early Warning Systems (EWS) as an integral part of disaster risk reduction. People-centered EWS look to improve disaster management through four key elements: (1) disaster risk knowledge, (2) detection, monitoring, and warning for hazards, (3) dissemination and communication of warnings, and (4) preparedness capabilities to respond to warnings (WMO, 2018). This multifaceted warning process spans many different systems, organizations and stakeholders.

Communication between numerous interlinked people and agencies is complex and can become more challenging during disasters when time is constrained and demand for information grows (Quarantelli, 1997; Andersen and Spitzberg, 2009). Communication gaps in the warning chain can be exacerbated during severe events and have costly impacts. Some case examples of communication failure include the public's underestimation of the warnings provided by authorities during the 2013 super typhoon Haiyan in the Philippines (Otto et al., 2018) and the communication breakdown between the National Weather Service and core partners during the tornadoes in 2011 and 2013 in Oklahoma, USA (Ernst et al., 2018). Conversely, good relationships and strong communication links between warning stakeholders, such as between a national weather service and emergency managers, improve their capacity to respond to disasters (Ernst et al., 2018). These interconnections are crucial; it is important to understand that the warning message from an EWS is only one part of larger mechanisms of information processing and decision making (Otto et al., 2018).

Golding et al. (2019) introduced a value chain approach to understanding the inputs, data, processes, stakeholders, contexts, outcomes, and various relationships to deliver effective high-impact weather warnings. The warning value chain includes observations, weather forecasting, hazard forecasting, impact prediction, warning generation, and decision making (Zhang et al., 2019; Golding, 2022). In its simplest form, this can be thought of as a sequential process; in reality, connections occur between many elements of the warning chain. The warning value chain also reveals the gaps that need to be bridged to deliver more effective warnings. Therefore, the value chain approach facilitates the assessment of the service design and delivery process and identifies options for improvement as part of an ongoing value cycle (Golding et al., 2019; Golding, 2022).

Many sources of data and information are valuable and applicable for use in the warning value chain by different sectors for various purposes. For example, hydrometeorological observations and measurements can come from instruments such as rain and river gauges, satellite and radar imagery, and weather databases and may be collected by official bodies such as meteorological and hydrological services and institutions. However, public surveys, historical records, eyewitness accounts, photos and videos from citizens, among others, can provide data, and these can come from alternate and unofficial data sources such as social media, online databases, and citizen science projects (Harrison et al., 2021).

Citizen science is valuable in contributing local and on-the-ground data for research (Shirk et al., 2012; Haklay et al., 2018; WMO, 2021). It has been beneficial in various research fields as it can provide information for hard-to-access or remote locations (Stevens et al., 2014). Individuals and communities can also gather and share rapidly perishable data (Wartman et al., 2020). However, there is limited understanding of how citizen science can contribute to bridging the communication gaps in the warning value chain. Marchezini et al. (2018) literature search found that only 15% of articles on citizen science and disaster management linked participatory early warning systems with citizen science. Our study explores this gap by asking: How can citizen science contribute to the warning value chain? The topic is investigated from a *high impact weather* perspective. This paper is an exploratory study of the potential role of citizen science in the warning value chain, and it is not an extensive review of existing citizen science projects in the high impact weather space.

The paper first provides a brief background on the high impact weather context, warning value chain, and citizen science. The paper then outlines the method of using a joint workshop to bring together citizen science and warning value chain experts to explore the question. The findings and discussion sections follow, highlighting the role of citizen science in the warning value chain.

Background

The term *high impact weather* puts emphasis on the consequences of severe weather (Taylor et al., 2018). High impact weather events include flooding, drought, severe wind, thunderstorms, hailstorms, heat waves, blizzards, tornadoes, and cyclones (Vinnell et al., 2021). In 2016, the World Meteorological Organization (WMO) and the World Weather Research Programme (WWRP) established the 10-year High Impact Weather (HIWeather) Project "to promote cooperative international research to achieve a dramatic increase in resilience to high impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications" (Murray, 2021). The HIWeather Project uses the warning value chain concept to understand and improve the elements involved in successful warnings (Zhang et al., 2019; Vinnell et al., 2021).

Warning value chain

The value chain concept finds its origin in economics. It characterizes the full range of activities involved in product conceptualization, production, and delivery to its final customers (Kaplinsky and Morris, 2000). The chain describes linked processes and connections between them where value is added at each step to make an initially seemingly unusable product (e.g., timber) valuable for the customer (e.g., table), resulting in optimized cost and efficiency.

The generation of weather warnings and climate services is complex, both technically and organizationally. The value chain concept has become a popular tool for describing and assessing the production, use and benefits of such services that are often established through co-design, co-creation and co-provision with the common goal of enabling timely action to reduce risks (WMO, 2015). This basic idea of generating value along an interconnected chain of processes can be translated into a hydrometeorological context (Lazo et al., 2008; Lazo and Mills, 2021). In this case, the value is in the information created and transmitted through the chain, leading to better decisions and, ultimately, user benefit through (primarily) reduced damage and losses from hazards through warnings.

For describing the co-production of warnings before and during an event, the warning value chain can be visualized as a sequence of peaks and valleys where the peaks represent expertise, and the valleys represent communication gulfs between different areas of expertise (Figure 1, adapted from Golding et al., 2019). Each part of the chain, such as hazard monitoring, modeling and forecasting, risk assessment, communication and preparedness activities, is typically associated with an expert community that delivers that function. However, communication between those communities comes with many challenges. The challenges may at times seem like roadblocks, so communication (represented by the bridges in Figure 1) is vital to link the expert communities and enhance the flow of information and data to inform models and decision processes.

Value is added when data and expertise are combined to generate new information. This information is edited and disseminated through various channels and used for informed decision-making, e.g., by the public or civil protection (Perrels et al., 2012). The warning value chain has multiple associated data inputs and outputs for each component where hazard, vulnerability, and exposure data are needed in the various stages of the warning chain to ensure it operates effectively (Harrison et al., 2022). Further value can be added by improving the tools and communication used by weather services and their partners, leading to increased lead-time, confidence, local accuracy, and engagement.

Value can also decrease since each stakeholder in the chain has its own set of objectives, resources, and constraints and, therefore, may not use all available information (Golding et al., 2019). Challenges include lack of data availability, access, and limited data processing and management capabilities, which can become roadblocks in the warning value chain (Potter et al., 2021; Harrison et al., 2022). As experience is gained, new knowledge is produced and incorporated, and more people contribute to the design and operation of the system, these improvements constitute the value cycle. These reviews and design/revision activities mainly occur before and after high impact events and on slower timescales than warning timescales.

The representation of high impact weather warnings as an end-to-end value chain reflects the traditional top-down view in place in most countries, which emphasizes providing services by authorities to stakeholders. Improvements tend to be technology-focused, usually on the left-hand side of Figure 1, while communication and response capability (the right-hand side) are the weaker links (Garcia and Fearnley, 2012; Baudoin et al., 2016). On the other hand, people-centered early warning systems take a bottom-up approach, starting with the needs of the users (UNISDR., 2005; UNDRR., 2015). Multiple stakeholders are involved in all stages of the design and operation of warning systems that consider the many social dimensions, vulnerabilities, and capabilities of the people (UNDRR., 2015; Baudoin et al., 2016). Improvements in people-centered early warning systems generally focus on the right-hand side of Figure 1.

All parts of the value chain need to operate well to get the full benefit of early warnings. Ideally, the value cycle addresses gaps in warning systems wherever they may exist, whether in the technology or the people aspects. This paper shows that citizen involvement can provide valuable contributions to all parts of the warning value chain and value cycle, especially through citizen science projects and activities.

Citizen science

Citizen science is defined as a "type of science in which the general public contributes to the production of scientific knowledge, either alone, or more often in collaboration with professional scientists and scientific institutions (Strasser and Haklay, 2018, p. 32)". Citizen science may also be known under different names, such as community science, participatory assessment, community-based monitoring, volunteer monitoring, and others (Shirk et al., 2012). The key importance of citizen science is that the public participates in one or all of the various stages of the scientific process, including but not limited to collecting, categorizing, transcribing, and analyzing data (WMO, 2021). Moreover, citizen science projects have a relational aspect between citizens' and scientists', and their roles are supplementary to each

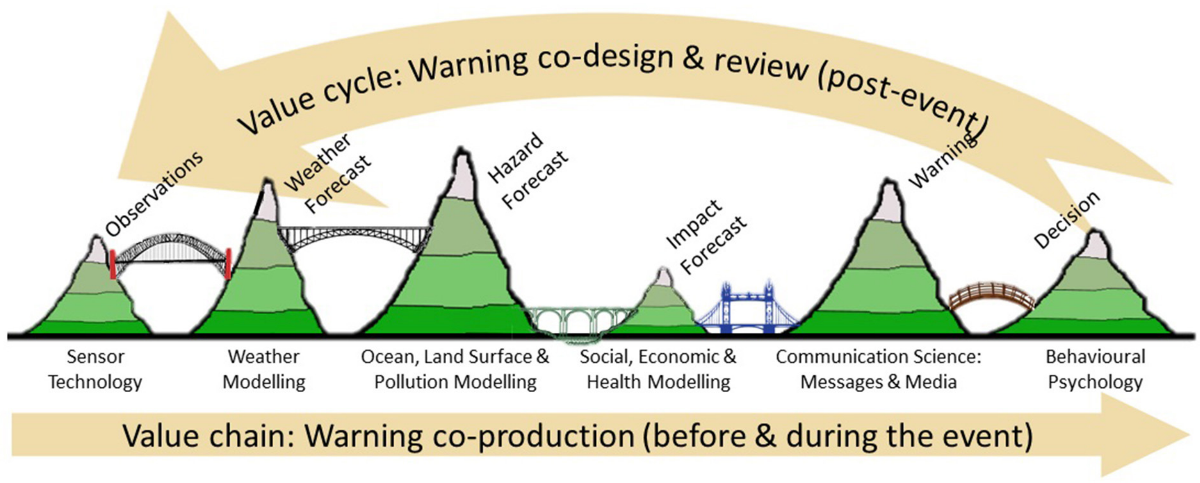

FIGURE 1
The warning value chain concept proposed by Golding et al. (2019), adapted.

other, contributing to the project dynamics. A recent Citizen Science Guidance Note by the WMO (2021) summarizes both the influence of citizens (as sensors, interpreters, engagers and collaborators) and scientists (instructing, collaborating, or co-creating) on different types of citizen science projects (Figure 2).

Citizens can act as sensors to observe and gather data for the projects; citizens can also be interpreters and take a more active role from data collection to analysis; citizens can be engagers in the problem development and design; and citizens can be collaborators, taking a co-production role with scientists to tackle questions (WMO, 2021). Similarly, scientists also can have varying influences on citizen science projects. Scientists can take a more instructive role and primarily lead the project, which may be designed top-down but integrated with citizens' participation, or have a more shared role where projects are co-created with citizens (WMO, 2021). The project design depends on the citizens' and scientists' level of engagement. Citizen science has contributed to various scientific disciplines and has been proven to be a valuable tool in ecology, water, air quality and conservation. Examples can be seen in roadkill studies (Périquet et al., 2018), ecological monitoring of mammals (Parsons et al., 2018), ecology and conservation (Kobori et al., 2016; Harebottle, 2020), drinking water research (Brouwer et al., 2018), and earth observations in general (Fritz et al., 2017; Rubio-Iglesias et al., 2020). As seen in examples from these different research fields, citizen science projects yield many benefits, including financial, social capital, reciprocity, and increase in trust. Studies have investigated the financial value of citizen science in environmental sciences and found significant contributions, for example, US$2.5 billion in biodiversity-related projects (Theobald et al., 2015).

Citizen science for weather hazards and warnings

Citizen science is also present in natural hazards and disaster research (Marchezini et al., 2018; Hicks et al., 2019; Vinnell et al., 2021). Several citizen science projects have contributed explicitly to weather hazards-related research. For example, a citizen science project in the United Kingdom aimed to understand how weather affects pain; it utilized a smartphone app to get 2,658 residents to report their pain symptoms over various weather conditions (Dixon et al., 2019). The German National Meteorological Service also uses apps to engage with the German populace; through its WarnWetter app[1], citizens contributed approximately 660,000 observations from July to November 2020 (Kempf, 2021). Other citizen science projects engage students and schools. Another German project got students from two high schools in the Bavarian Prealps to build weather stations to collect data and weather impacts (Kox et al., 2021). A citizen science initiative in Hong Kong engaged with over a hundred schools to set up weather stations and investigated the urban heat island effect (Lam et al., 2021). Citizen science can also be used beyond data collection. OpenIFS@home engaged with volunteers to run weather and climate modeling experiments[2], where volunteers across the world ran simulations using their computers at home. These simulations were combined into large forecast ensembles (Sparrow et al., 2021).

Citizen science also has a potential role in providing authorities and scientists with additional observations and

1 https://www.warnwetterapp.de/

2 https://confluence.ecmwf.int/pages/viewpage.action?pageId=212456886

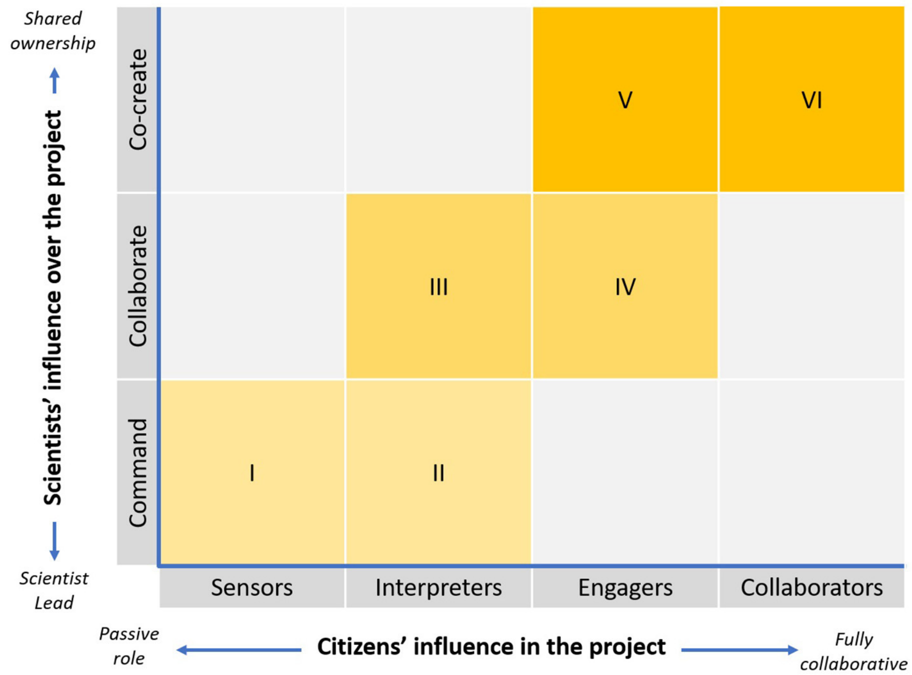

FIGURE 2
Typology of citizen science projects based on citizens' and scientists' level of influence (WMO, 2021).

ground truth to evaluate warnings, especially in hazard-prone situations like high-impact weather events. Citizen science can have a role in the rapid generation and sharing of information (Hicks et al., 2019). OpenStreetMap is a popular online platform for the public and researchers to record and map observations, monitor hazards, and share early warnings (Hicks et al., 2019)[3]. These examples show that citizen science is effectively used in natural hazards research and potentially has a role in enhancing the connections in the various stages of the weather warning value chain.

Members of the public are not merely passive recipients of information but can play active roles in communicating and responding to warnings in times of danger (Schulze et al., 2015; Tan et al., 2017). People look for warning verification and environmental cues from people who are known to them. Even when authorities issue warnings, some people may not fully appreciate the danger unless reinforced by someone known and trusted, such as a family member or friend (Wood et al., 2018). Even when the warning is understood, and people take action, some may require assistance from friends and neighbors to move to a safe location or take other protective action (Boulianne et al., 2018). Furthermore, engaging communities in discussing hazards, whether in person (Abunyewah et al., 2020) or through online channels and social media (Kankanamge et al., 2020), helps to enhance community awareness and preparedness.

The public consumes weather observations and forecasts for decision-making, both for day-to-day activities (Phan et al., 2018) and when threatening weather is imminent (Kox and Thieken, 2017). But citizens also use information from other parts of the value chain, not just the warning. For example, weather enthusiasts take their weather readings and share them with national weather services and volunteer networks (Gharesifard et al., 2017; Krennert et al., 2018). Individuals sensitive to temperature, humidity, and air pollution may need to protect themselves from adverse health impacts even before a warning is issued (Campbell et al., 2020).

Limitations and challenges for citizen science

A researcher or group of researchers, either amateur or professional, can start a citizen science project as long as they have enough motivation to investigate a question (Pettibone et al., 2016). However, researchers should also consider the limitations and challenges of citizen science projects. Lee et al. (2020) and Walker et al. (2021) discuss the benefits but also the issues and challenges of citizen science. Limitations can include costs and negative social impacts, among others. Costs of conducting projects may vary when factoring in the overall project, including the level of training and management and

3 https://www.openstreetmap.org/

control of data quality (Gardiner et al., 2012). Depending on the type of data to be collected or analyzed, some level of expertise may be needed and may require some extent of training and quality monitoring to ensure citizen science data is fit for research purposes (Conrad and Hilchey, 2011). Citizen participation and interests may also change or decline as the project progresses (Sauermann and Franzoni, 2015). It requires time and effort commitment from the public for the benefit of science, which may potentially cause burdening of the citizens, disempowerment, conflict creation, and new forms of inequality (Lee et al., 2020; Walker et al., 2021).

These studies illustrate that citizen science has both benefits and challenges, as with other methodologies and research engagements. Researchers should be mindful of these challenges. Many tools and strategies are available to help citizen science projects acknowledge and navigate the limitations (e.g. Freitag et al., 2016; Pettibone et al., 2016). This study recognizes the limitations of citizen science as it explores how existing or potential citizen science research projects and initiatives can add value to enhance the warning value chain.

A joint workshop

HIWeather is aimed at improving the effectiveness of weather-related hazard warnings. Two of the flagship components of the HIWeather program are the warning value chain project and the citizen science project. The warning value chain project aims to review the practices used to describe weather, warning and climate services to assess and provide guidance on applying value chains in a weather warning context involving multiple users and partnerships. The citizen science project is designed to share information and provide tools to help groups and agencies develop pathways of engagement with the public to undertake scientific research. Each of these flagship projects has expert members on the topics. A joint workshop was conducted to create a dialogue between the two groups to converge on the topics and interact and share their expertise.

The workshop was held with 29 subject matter experts on citizen science and the warning value chain in July 2021 to explore the intersection of the two topics. Few were experts in both topics. This joint workshop pioneers the collective exploration of the warning value chain and citizen science together in the context of high impact weather. The joint workshop received peer-reviewed approval under the Massey University code of ethical conduct for "low risk" research involving human participants (Application ID 400024723).

Participant recruitment

Purposive recruitment was done by inviting the HIWeather flagship project members. The 29 subject matter experts came from different sectors, including meteorological services, research institutions, universities, and commercial weather forecasting services from various counties in both hemispheres, including Argentina (2), Australia (4), Austria (1), Canada (1), China (1), France (1), Germany (2), Ghana (1), Mexico (1), New Zealand (2), Switzerland (1), the United Kingdom (3), and the United States (9). The limitation to this recruitment method is that most participants are from established scientific institutions, and none of the participants is from the public. Therefore, the views provided herein may reflect a top-down institutional perspective rather than a ground-up viewpoint from citizens.

Workshop structure and guide questions

In preparation for the online workshops, the participants were asked to consider the intersection between the warning value chain and citizen science. They shared their initial thoughts through an online collaborative platform called Jamboard[4]. The platform provided a virtual whiteboard that provided an illustration of the warning value chain (from Golding et al., 2019) and a workspace where participants could add notes anonymously at any time before the workshops (Figure 3).

Two online sessions were held (at 0700 and 1900 UTC), so members from different parts of the world could attend the session that best suited their time zones. The sessions ran for 2 h each. Each session opened with brief presentations on (1) the warning value chain and (2) citizen science. The presentations ensured that everyone would have a brief overview and a common grounding. The workshop activity consisted of facilitated semi-structured discussions with the attendees. The facilitators (i.e. the authors of this paper) discussed the following questions under three topics:

1. Citizens in the warning value chain
    a. Where are citizens involved in the value chain?
    b. How do citizens engage with warnings?
2. Citizen science on the warning value chain
    a. Where in the value chain can citizen science contribute to enhancing warnings?
    b. How can citizen science contribute to the enhancement of warnings?
3. Added value of citizen science
    a. What's the added value of citizen science in the value chain?

4 https://workspace.google.com/products/jamboard/

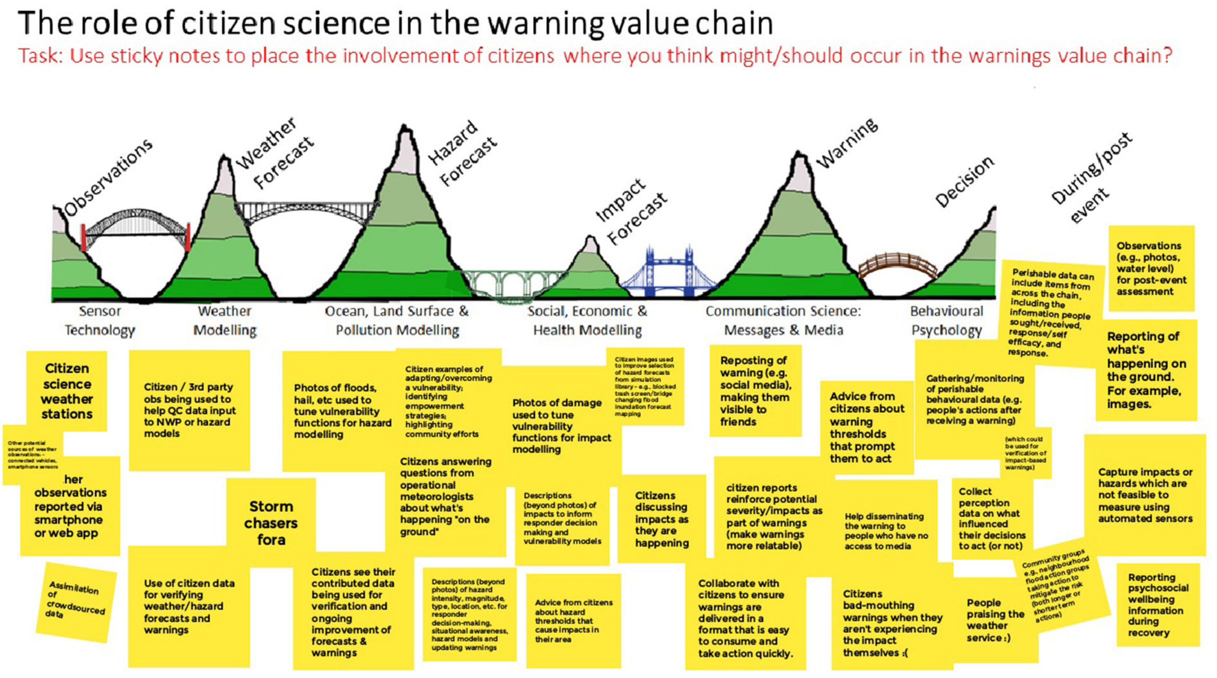

FIGURE 3
Pre-workshop online collaborative board with yellow sticky notes showing the responses provided by participants.

Jamboard was also used to help facilitate the conversation during the online sessions. One board per topic was used. The participants were given a few minutes to post notes anonymously on the board before starting the discussion. As the format was semi-structured, the flow of the discussion was dictated by the participants, and follow-up questions were prompted when necessary.

Data analysis

The discussion method was semi-structured based on the topics and sub-questions. The primary data source for analysis was the seven online collaborative boards (one pre-workshop board and three workshop boards per session), with the participants' responses captured *via* online "sticky notes". During the workshop, notes were taken, and each online session was recorded digitally. The sticky notes from the sessions were extracted, compiled, and organized to a table using Microsoft Excel. This allowed for easy reference back to the notes and recordings to capture the participant's insights. The short quotes presented in this paper are gathered from the participants' sticky notes.

A qualitative thematic analysis was conducted from the insights gained from the workshop, where the main process for analyzing the qualitative data was through naming and classifying (Flick, 2007). This study follows the thematic analysis approach by Braun and Clarke (2006, 2012) to identify, analyze and report themes from gathered data. For the initial coding process, the responses from both sessions were collated and mapped using the Golding et al. (2019) warning value chain. Then the codes were reviewed to identify underlying patterns to form themes. A 'theme' for this study reflects a pattern of shared meaning – a core concept (Braun and Clarke, 2012). Where necessary, the responses were aggregated by collapsing and combining the themes and then the various themes were defined and named. Using the themes, the research team then built a visual summary of the insights on the potential role of citizens and citizen science in the warning value chain.

Findings

The participants of the joint workshop had different expertise and came from various institutions. Through the workshop, they shared their experience and knowledge on citizen science, participatory engagement, science outreach, warning value chain, warnings, communication, meteorological research, and others. Given the range of expertise, the workshop provided a successful platform for shared learning on the topics where participants were able to ask questions and provide their perspectives on citizen science and the warning value chain. The analysis of the workshop shows two broad themes on citizen science and the warning value chain: (1) citizen involvement and (2) citizen science contributions.

Citizen involvement in the value chain

Consistent throughout the workshop is the theme that citizens are involved throughout the warning value chain. Figure 4 is a visual summary of the findings from the workshop on citizens' involvement in the value chain during high impact weather events. The involvement of citizens does not necessarily follow a linear sequence; findings from the workshop show that citizens' involvement can happen at any time, either pre, during, or post high impact weather events. The warning value chain itself does not follow the temporal chronology of an event but rather is presented as a succession of expertise that supports the delivery of the warning, with citizens interacting with various parts of the warning chain at different times. Figure 4 reimagines a condensed warning value chain portrayed in a cyclical process moving between expertise in (1) observations, (2) weather, hazards, and impacts, including their forecasts, (3) warning communication, and (4) decision making and response. The cyclical representation shows that each part of the warning value chain affects the other parts. For example, the upper right quadrant indicates that as citizens experience weather and the associated hazards during an event, such information from citizens can potentially contribute to the forecasting of weather, hazards, and impacts.

Snippets gathered from participants' sticky notes in the workshop showed opportunities for citizens' contributions:

> *"photos of flood, hail, [and others] to tune vulnerability functions to hazard modeling."*
>
> *"descriptions (beyond photos) of impacts to inform decision making and vulnerability models."*
>
> *"Citizen/3rd party observations [can be] used to help quality control data input to numerical weather prediction or hazard models."*
>
> *"citizens [can answer] questions from operational meteorologists about what's happening on the ground."*
>
> *"gathering/monitoring of perishable behavioral data (e.g. people's actions after receiving a warning) – which could be used for verification of impact-based warnings."*

Through the workshop discussion, participants also identified several ways citizens could participate and provide observations on the warning value chain. Weather observations from home or school-based weather stations can provide valuable data streams to national weather services to enhance the situational awareness of forecasters and emergency managers. Observations can also be shared online with the broader public through the Weather Observations Website (WOW)[5], Weather Underground[6], or other websites. Aside from weather stations, other mechanisms may be able to capture data, such as devices like smartphones and connected vehicles. People could also manually report weather observations using dedicated apps. App examples given in the workshop were MPing in the United States of America[7], WeatheX App in Australia[8], and WarnWetter App in Germany[9]. Other citizen observations were mentioned, including photos and videos of weather and hazard phenomena by storm chasers, for example, who are rich sources of intelligence in severe weather. Crowdsourced data through social media can also provide on-the-ground, real-time observations of hazards and their impacts.

Citizens' involvement can range from a personal level (e.g., experiencing an event) to community interaction (e.g., sharing warnings to friends); this is also highlighted in Figure 4. For example, in an individual capacity, citizens can act on warnings to protect themselves and their loved ones, and they can contribute data by submitting images and other types of data and information. Citizens can also interact collectively in engaging with the warning chain as a community; for example, by interacting with each other to help disseminate, interpret, and reinforce warnings.

Citizen science contributions to the warning chain

The second theme highlighted by the workshop was that citizen science (research) could contribute to the different parts of the warning value chain and enhance the value chain for warnings, as illustrated in Figure 5. The public can participate in these citizen science projects in varying ways, ranging from passive contributions (e.g., sending images from an event) to more active roles (e.g., co-designing warning approaches).

The cyclical representation in Figure 5 shows that each part of the warning value chain affects the other parts. Consequently, contributions of a citizen science project on one part of the chain may influence other parts and the warning value chain as a whole. For example, a project involving community engagement activities (e.g., hazard observation with citizens) may help develop public awareness and build relationships between citizens, authorities, and the warnings; processes which can then help citizens with decision-making when warnings are issued. Citizen science can engage people to become interested, support science, and make *'warning ready citizens.'*

5 https://wow.metoffice.gov.uk/
6 https://www.wunderground.com/
7 https://www.citizenscience.gov/mping-weather-reports/
8 https://weathex.app/
9 https://www.warnwetterapp.de/

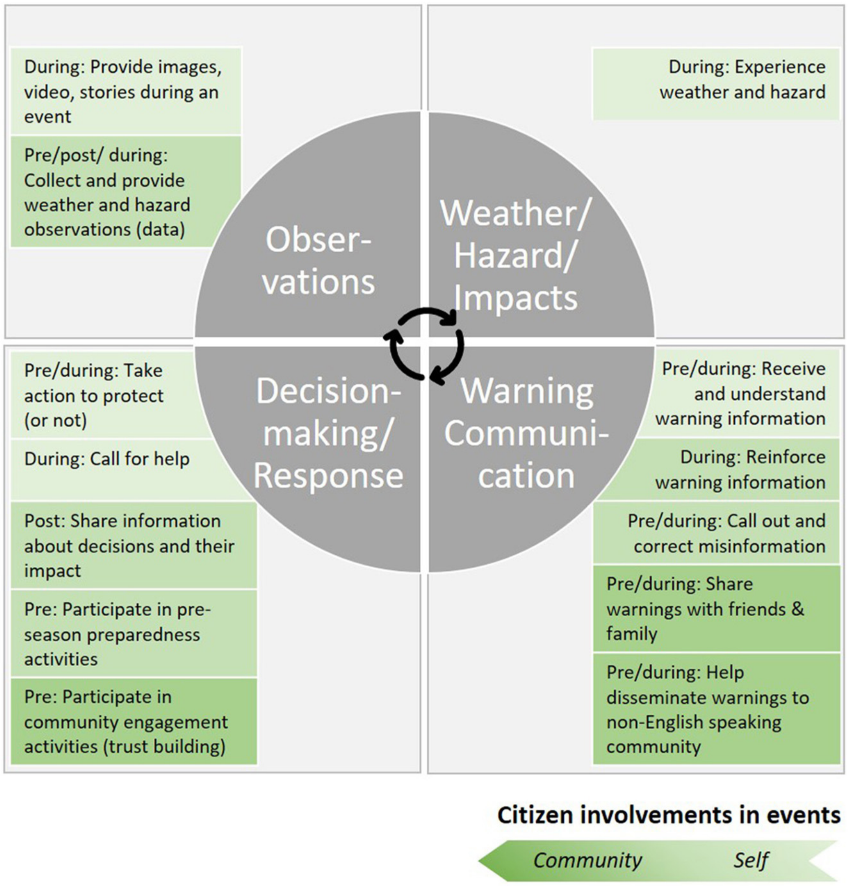

FIGURE 4
A visual summary of findings on citizens' involvement in the warning value chain.

Snippets from participants' sticky notes highlight some example outcomes of engaging in citizen science in the warning chain:

> *"School science projects" and "Involving younger people - raising awareness/understanding of weather [and hazard] topics (e.g. schools)."*
>
> *"collaborat[ion] with citizens to ensure warnings are delivered in a format that is easy to consume and take action quickly."*
>
> *"community groups, e.g. neighborhood flood action groups taking action to mitigate the risk (both longer- or shorter-term actions)."*

Citizen science projects can offer a way for communication and knowledge exchange between various parties (e.g., between weather agencies and the people). Citizen science projects can facilitate the exchange so that the communication could become two-way. For example, citizen science projects can be designed to help identify and correct misinformation in real-time to communicate warnings better. Citizen science projects are not just about citizens passively contributing data (with no reward for effort), but citizen projects can be a platform for agencies or authorities to acknowledge the value of the citizens' contributions and participation. Citizen science projects can also be designed to evaluate the effectiveness of warning communications and people's responses to warnings. Snippets from participants' sticky notes present some ideas on how projects can enable public participation and input in enhancing the warning value chain

> [citizen projects can help] in *"calling out and correcting misinformation."*
>
> *"citizens to see their contributed data being used for verification and ongoing improvement of forecasts & warnings."*
>
> *"a post-event [study] where citizens [share] about how they were warned, [...] how they were affected, or how they responded."*
>
> [agencies can] *"find out who is not receiving warnings and what communication medium would reach [the public]."*

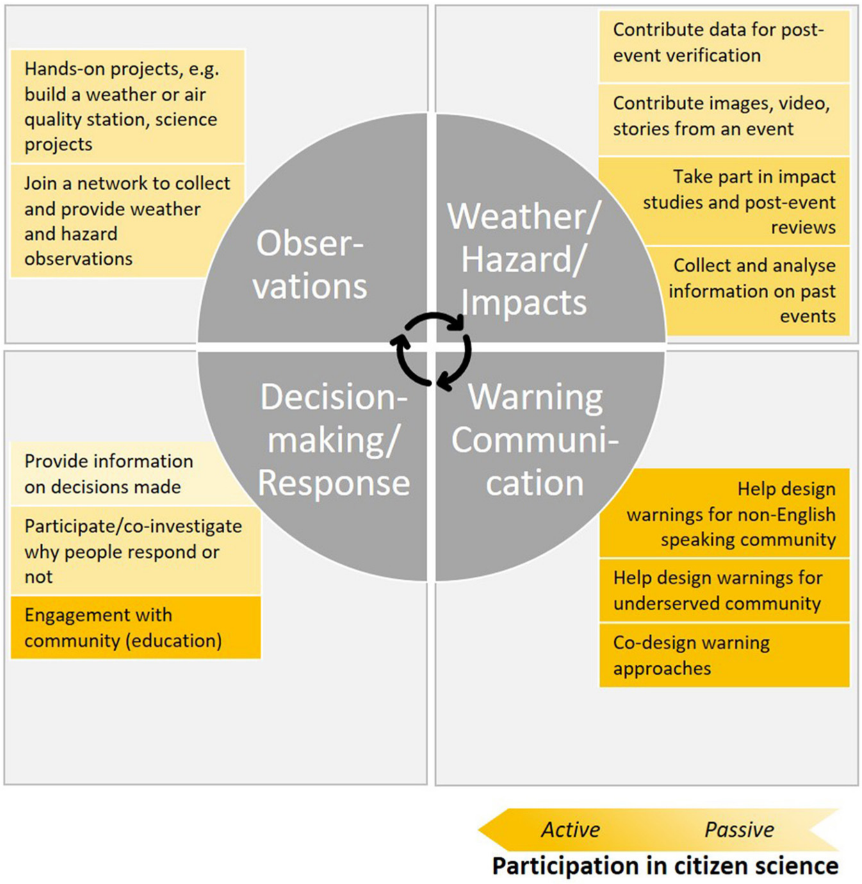

FIGURE 5
A visual summary of findings on citizen science contribution to the warning value chain.

The findings also pointed out opportunities for projects that engage with communities where current warning communication strategies are not as effective, e.g., minorities, differently-abled communities, and those with limited or no access to media. Citizen science research can help warning services become more accessible. Snippets from participants' sticky notes highlight the issue of accessibility of warnings and the potential for citizen science to enhance this space:

> *"warning communication that might differ according to their technology and information accessibility."*
> *"Help disseminating the warning to people who have no access to media."*
> *"include citizens from marginalized groups in warning product development and dissemination."*
> *"Helping with language interpretation."*

As identified in the findings, project opportunities include co-designing improvements in the warning system, such as translations for non-local languages and integrating assistive mechanisms for the hearing or sight impaired. Such projects can improve engagement, enhance people's understanding of warnings, and lead to specialized services that current warning systems may not yet capture. Citizen science projects can potentially improve the gap between warning communication by building engagement and trust between authorities and the people.

Discussion

As seen in the literature and the workshop findings, citizens are involved throughout the warning value chain. Given the citizens' presence throughout the chain, there is also potential to engage in citizen science projects and initiatives that enhance parts and subsequently the whole warning value chain, thus helping warnings achieve their goals to reduce impacts and improve safety.

Value of citizen science for bridging communication gaps

Examination of the warning value chain has identified communication gaps between expertise areas, such as between warning providers, decision-makers and responders (Golding et al., 2019). Findings from the workshops have shown that citizens are involved in various parts of the warning value chain, which opens a clear opportunity for citizens and citizen science research to help bridge gaps and design systems to meet the needs of all concerned. A study on coastal residents' decision-making during a typhoon identified that "during impending severe weather, residents may receive information about the storm from various resources including state and local government officials, news media, and their community contacts, including neighbors and civic organization." (Pan, 2020, p. 6). Different factors and contexts are involved in the official messaging and people's decision-making, which could create communication gaps in translating warnings into an appropriate response. Trusting the official information source is an essential criterion for making decisions (Pan, 2020).

A potential opportunity for citizen science is to aid the handling of misinformation during events. Multiple channels may improve people's decision-making when communicating risks (Pan, 2020). However, the diversity of information can also cause confusion, especially in the era of social media, where misinformation can proliferate. Individuals, after all, are influenced by their social networks, both online and offline, during decision-making when risks are communicated during extreme weather events (Sadri et al., 2021). Unlike traditional hierarchical communication through weather services and emergency management agencies, decentralized communication may be prone to misinformation and bad-mouthing. Weather and emergency services and some avid citizens might call out and correct misinformation. Still, quality control for warning information shared *via* social media and word-of-mouth remains a challenging task. Citizen science projects can have some mechanisms or processes to get citizen scientists to help in quality checking and verification to help identify and correct misinformation in real-time during events.

Citizens may often be considered the endpoint of warnings, where they interpret and act on information and warnings provided by authorities (Kox et al., 2018; Taylor et al., 2019). However, actively involving citizens in collecting, verifying, and sharing information before, during, and after an event can lead to better outcomes for the community (Kaewkitipong et al., 2016). Citizens' ground observations can be used to see whether forecasts match actual events. For example, during or after events, people can share (e.g., images, videos, and stories) and verify with their experiences whether the weather, hazard and impacts were more or less extreme than predicted and whether or not they received warnings. Citizen science can facilitate two-way communication between citizens and authorities and improve public awareness of hazards (Ferri et al., 2020).

Research on warnings also has tended to treat the general public as homogenous, but the push toward people-centered warning systems has emphasized the need to recognize diverse groups and how differently they may respond to warnings (Tan et al., 2020). The findings point to the need to collaborate with underrepresented communities, e.g., minorities, elderly, differently-abled communities, and those with limited or no access to media. Citizen science has an important role in co-designing more diverse and accessible warning services.

As technology advances, so does the digital divide (Schulze et al., 2015; Lorini et al., 2019). The digital divide is a product of many factors, including social and economic status and accessibility to the internet, and it has introduced problems in engagement and information dissemination (Harrison and Johnson, 2019). Authorities and researchers, including those involved in citizen science, must ensure that those underrepresented in the digital world are included and do not miss opportunities to receive life-saving information (Anderson et al., 2016; Tan et al., 2020).

Similarly, citizen science in the warning chain can bring a risk of increasing the digital divide or isolating communities, but it also provides an opportunity to bridge gaps. The WMO (2021) guidance note on high impact weather citizen science encourages project leaders to consider such ethical issues. This includes asking questions such as: "are there steps in place to ensure equal and meaningful opportunities for different groups (e.g., gender and marginalized groups)" WMO, 2021, p. 8)?

Enriching warnings with citizen science data

The World Meteorological Organization encourages citizen science to enhance the global weather enterprise (WMO, 2021). National weather services have started to recognize the role of citizen science as a source of weather intelligence to better observe, predict, and understand the environment by harnessing the power of the crowd (NOAA., 2021). Citizen science can add value by enabling citizens to collect data that may be difficult or expensive to collect using traditional science methods (e.g., observations from remote locations or perishable impact data). New citizen science projects could set up observation stations with communities in remote places and could also enable the rapid collection of impact information.

Citizen science can employ crowdsourcing, where members of the public act as sensors, and it can provide information by using readily accessible instruments (Kankanamge et al., 2019). Citizens can record information on the impacts of hazards through sharing locations, messages, images, and videos of damaged properties, data that is often difficult to obtain and access using other means (Kankanamge et al., 2019). The benefits of citizen science for collecting data could outweigh the cost of preparation, post-processing and quality control (Lee et al., 2020). If conducted successfully, scientists receive significant contributions of crucial data and knowledge for their studies (Lee et al., 2020). There is also an opportunity to advance citizen science in managing data quality by tying in with social sensing—the science of extracting crowdsourced information for routine warning and analysis (Arthur et al., 2018; Spruce et al., 2021; Weaver et al., 2021). Social sensing is an emerging field that explores new data collection paradigms and reliability problems from data collected from humans and their devices (Wang et al., 2015).

More robust engagement in citizen science projects inevitably creates intangible and social benefits for citizens (Haywood, 2014), such as increased awareness and understanding of the citizens in topics such as weather, hazards, and warnings. The value will be realized for citizen science projects related to hazards when the benefits (e.g., minimizing impacts and protecting life and property) manifest during hazardous events. Ferri et al. (2020) showed through a cost-benefit analysis of a citizen observatory in a catchment that citizen science coupled with citizen observatories with hydrological modeling can reduce damage by 45% for different flood scenarios. Liu et al. (2020) also describe the role of citizen weather spotters in enhancing public safety in Nashville, Tennessee. Citizen weather spotters supply ground information from vital locations, providing quick severe weather information that can be acted upon, thereby saving life and property (Liu et al., 2020). Sharpened perspectives, attitudes, and behaviors about weather, hazards and warnings would significantly increase community resilience (Ferri et al., 2020) and, as such, a merit consideration to continue the discourse on how citizen science can contribute to the warning value chain.

Limitations of this study

To the best of the authors' knowledge, the joint workshop described in this paper is the first to collectively explore citizen science and warning value chain together in the context of high impact weather. Through this workshop, we were able to bring together 29 experts from around the globe to explore the topic. However, as purposive recruitment was conducted with a focus on experts, the participants came from research institutions which would have provided perspectives from a scientist or researcher perspective. Future research on the intersection of citizen science in the warning value chain should include perspectives from citizens.

In this exploratory study, thematic mapping (see Figures 4, 5) was conducted, reflecting the participants' knowledge, highlighting where citizens interact with the warning chain and identifying areas where citizen science can potentially contribute. Although the participants provided many citizen science examples, this study was not intended to document an exhaustive list of citizen science projects in the high impact weather space. It would be worthwhile for future studies to survey citizen science projects to investigate and create a representative mapping of citizen science projects in the warning value chain.

This paper is of exploratory nature and does not detail how all communication gaps between expertise areas will be addressed by citizen science. However, the paper has illustrated instances of how gaps can be filled. For example, the gap between official warnings and the public's decision-making can be partly bridged by engagement through citizen science projects. Future research can investigate in detail the gaps in the warning value chain. Furthermore, prospective citizen science projects in the high impact weather space can use the warning value chain as a guiding tool to identify where the project's contributions lie in improving data and communication through the chain.

Conclusion

At the beginning of this paper, we raised the research question: How can citizen science contribute to the warning value chain? This study has shown that citizens, at individual or collective capacity, interact throughout the chain, and there are many prospects for citizen science projects that can be conducted throughout the chain. Both the literature and the findings highlight the potential usefulness of citizen science for data collection. Best practices from other areas, such as social sensing, can help with advancing citizen science, especially in managing data quality for use in warnings research. Organizations such as WMO and NOAA have recognized the crowd's potential "power" in enhancing the weather enterprise. The call for more people-centered early warning systems in the Sendai Framework (UNDRR., 2015) implies an important role for citizen science in their design, operation and improvement. Citizen science can be used as an engagement tool to bridge gaps and enhance communication between authorities and the public. It can be a platform for awareness and inclusivity for disadvantaged groups in the warnings space. The levels of engagement in citizen science projects create social benefits for citizens, such as increasing awareness and creating a sense of community that eventually translates to warning-ready citizens.

The beauty of citizen science is that anyone can do it, regardless of location, qualification or expertise. As highlighted in this paper, citizen science projects have potential value for enhancing the warning value chain. However, as there are benefits, there are also costs and considerations involved in conducting citizen science projects. The WMO guidance note 2021 is designed as a starting reference for groups and agencies considering citizen science; the guide raises key questions for project leaders to consider for citizen science projects. The joint workshop from this study is just the beginning of exploring the intersection of citizen science in enhancing warnings. Researchers and institutions are encouraged to explore further how citizen science projects can be used to bridge communication gaps in the warning value chain.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The project, however, received peer-reviewed approval under the Massey University code of ethical conduct for low risk research involving human participants (Application ID 400024723). Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

Conceptualization, methodology, investigation, and writing—review and editing: MT, DH, EE, DJ, and AC. Formal analysis: DH, MT, EE, and AC. Writing—original draft preparation: MT, DH, and EE. Visualization: DH. Project administration: MT, AC, DH, and EE. Funding acquisition: DJ, EE, MT, and DH. All authors have read the manuscript and agreed to be accountable for the content of the work.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Public earthquake communication in Italy through a multi-source social media platform: The INGVterremoti experience (2010–2022)

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Communicating scientific information about earthquakes is an important and delicate issue in countries like Italy, where seismic risk is high. Furthermore, continuous and scientifically sound communication is needed, especially in recent times when social media have amplified the risk of being biased by misinformation, fake news and conspiracy theories. For this reason, we have developed a communication strategy for earthquake science and risk in Italy, mostly based on social media. The INGVterremoti platform was born between 2010 and 2012 with the goal of increasing scientific information released to the public, and also establishing a two-way communication channel between scientists and citizens. In the past 12 years, the INGVterremoti platform has gained trust and popularity, increasing the number of involved people, which amounts today to several hundred thousand. The platform consists of a coordinated suite of social media channels and a blog-magazine, where updates on ongoing earthquake sequences and posts on scientific topics are continuously published. Our end users are mostly citizens, but also authorities and media. Special attention has been given to interactions with the public, especially on our Facebook page, in order to understand their information needs, identify rumors and fake news, particularly in areas affected by seismic sequences, and address the most pressing requests. In this paper we describe the INGVterremoti strategy, the different media that we use, focusing on their strengths and weaknesses. We concentrate on the experience, carried out in the last few years, of the publication of provisional information on ongoing earthquakes, a long-standing issue strongly requested by our followers. The INGVterremoti platform has played a fundamental role in many seismic sequences of the past 12 years in Italy, starting from the Emilia sequence in 2012, to the central Italy one, started with the deadly earthquake of 24 August 2016 and still ongoing. Besides the periods of high attention after strong earthquakes, we used the INGVterremoti social media as a tool for releasing continuous and sound information to the public, and as a way to involve citizens in the communication arena.

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1 Introduction

According to some studies (Eraybar et al., 2010; Crescimbene et al., 2014), people's perception of seismic risk is generally low in countries, like Italy or Turkey for instance, where earthquakes or seismic sequences are frequent; therefore, communicating scientific information on earthquakes is very important. After the 2009 deadly earthquake in L'Aquila (Abruzzo) and the long series of social and judicial events that followed it (Amato et al., 2015; Cocco et al., 2015), the involvement of scientists in the communication arena was thought to be at risk. Indeed, the fear of being misunderstood or even caught in legal actions, as happened in the L'Aquila case, could have been a deterrent to scientific and risk communication during seismic crises or even before they occurred. It is known that the earthquake's unpredictability makes it very difficult to have correct, balanced communication to media and to the public, especially when people's fear increases, as after a felt earthquake, and even more during a long sequence of shocks affecting a region. An effective strategy for dealing with such a delicate issue cannot be limited to emergency communication but must include a long-term communication plan during "peaceful" periods, to build trust and possibly establish a two-way communication channel between scientific institutions and citizens. For this reason, after the L'Aquila case, the efforts of scientists have multiplied, both in quantity and in the diversification of tools and strategies, also thanks to the wide diffusion of social media. The potential of social media for managing emergency communication and actions and for disaster preparedness and response, has been widely demonstrated since the early phase of the first social media such as Twitter and Facebook (Peary et al., 2012).

The INGVterremoti communication platform was born in 2010 with the main goal of getting closer to citizens, providing them updated and reliable scientific information on earthquakes, understanding their needs, and giving voice to their questions and fears. During the past 12 years, the INGVterremoti team has been working to diversify the information offer and broaden the audience using different social media channels (Youtube, Twitter, apps for mobile phones, Facebook, a blog and a suite of story maps) and adapting the information to the channel used. Moreover, we have been able to maintain a high publication rate during the whole period 2012–2022, as described in the following sections. This allowed the platform to gain trust and popularity, both on the web and on social media, increasing the number of involved people, which amounts today to several hundred thousand. Our end users are mostly citizens, but also authorities and media: the INGVterremoti tweets on earthquake activity appear often in the first pages of web and TV news magazines a few minutes after an event. Special attention has been given to interactions with the public, especially on our Facebook page, in order to understand their information needs, identify rumors and fake news, particularly in areas affected by seismic sequences, and address the most pressing requests. Among these, a special attention has been given to the rapid release of automatic locations/magnitudes for earthquakes in Italy, that from 2018 are released after a couple of minutes from the earthquake occurrence. The INGVterremoti platform played a fundamental role in many seismic sequences of the past 12 years in Italy, including the seismic sequence that began with the 20 May 2012, Emilia earthquake, and the one in central Italy that started with the deadly earthquake of 24 August 2016 (Pignone et al., 2016).

2 The INGVterremoti activities

In 2010, INGVterremoti team started to reorganize its communication strategy, thanks to a cooperation with Sissa Medialab, a company specialized in science communication. After a series of courses, attended by several tens of INGV researchers, a communication strategy was outlined (Cerrato et al., 2011). In the following 2 years, the cooperation between INGV and Sissa Medialab continued with a thorough analysis of strengths, weaknesses, opportunities and threats of the current communication activities at INGV, leading to a well structured proposal for a communication plan for the Earthquakes Department, in particular for INGVterremoti. (Balli et al., 2013).

The basic points outlined in the report were 1) the definition of the brand identity for INGVterremoti, 2) the objectives (which should be well defined according to the INGV mission), 3) the key themes to specific target audiences, and 4) the vehicle through which delivering the messages (different media for different audiences), and lastly, 5) the budget. Although not all the possible activities and channels could be implemented in the following years, the main idea of having a coordinated suite of web and social media channel for INGVterremoti was pursued, trying to follow the basic literature of science and risk communication (e.g., Renn, 2009, and references therein).

During 2010–2013 the social channels of the INGVterremoti platform were launched in succession (Figure 1). At national level, some of these experiences were pioneering in the area of communication of a scientific institution connected with civil protection, but even at the international level there were not many reference seismological experiences to draw from. At that time, all scientific institutions tried to exploit social channels to bring research closer to the public by skipping the interpretation of traditional media. A temptation that over time proved

	YOUTUBE	TWITTER	MOBILE APPS	BLOG	FACEBOOK	STORY MAPS
STARTING	February 2010	March 2010	March 2011	May 2012	May 2013	May 2013
OBJECTIVE Increasing the level of information about earthquakes in Italy, a basic step for seismic risk reduction.	**Visual** seismic and tsunami information, bringing INGV as close as possible to citizens.	**Fast** communication of seismic and tsunami information.	Fast communication of seismic information tailored for **mobile** device.	Provide quick updates and **in-depth** scientific information (special reports during seismic sequences and emergencies).	Fast communication of seismic and tsunami information; **interaction** with public.	Use of interactive **maps** and geographic information for seismic and tsunami **storytelling**
TARGET	General public	General public, media professionals	General public	General public	General public	General public
CONTENT	In-house short video, including animations and interviews with INGV researchers	Automatic and revised earthquake parameters (location and magnitude), blog post, quick comment	Automatic and revised earthquake parameters (location and magnitude), blog post, maps, mobile interface for content of INGV website	Articles about Italian and global seismicity, activities of INGV researchers, photonews, real time in-depth information during seismic sequence.	revised earthquake parameters (location and magnitude), blog post, quick comment, replay to user comment	Cloud-GIS applications that integrate digital maps, related content and interaction features on INGVterremoti gallery
POPULARITY	13,300+ subscribers	285,000+ followers	2,000,000 downloads	8,000,000 unique visitors	235,000+ followers	100,000+ views
TOTAL ACTIVITY	122 videos	26,000+ tweets	3 release for IOS and Android; the last in 2022	~1,000 posts	20,000+ posts	25+ story maps and dashboards
NOTE	6,200,000+ total views	Awarded the most useful Twitter account in Italy (2012)	Current rating 4+	23,400,000+ total views	Average daily post coverage 10,000+	Integration in INGVterremoti channels

FIGURE 1
The INGVterremoti platform: a coordinated suite of social media channels, including YouTube, Twitter, apps for iOS and Android mobile phones, a blog-magazine on WordPress, Facebook and a gallery of story maps.

simplistic and gave way to a more complex integration. Also Twitter was rising in that period, with major scientific institutions, - for example, U.S. Geological Survey (USGS), Geological hazard information for New Zealand (Geonet) and Euro-Mediterranean Seismological Center (EMSC) - opening their own channels (@Geonet, the Geonet account, joined on January 2009; @USGSted, the USGS account on June 2009; @INGVterremoti, the INGV account, on March 2010; @LastQuake, the EMSC account on October 2010) not only to communicate earthquake locations quickly, but, in some cases, also to use the information produced online by citizens to develop a crowd-sourced earthquake detection algorithms. This integration underlies the work of LastQuake (i.e. Bossu and Earle, 2011; Bossu et al., 2018), a multichannel rapid information system by EMSC, comprising websites, a Twitter quakebot, and a smartphone app for global earthquake eyewitnesses.

After 2013, INGVterremoti activity has grown, both in the number of posts, tweets, *etc.*, and in the variety of topics, researchers involved, and so on. Several choices have been made always looking at similar experiences carried out by similar agencies' best practice, including USGS, New Zealand Institute of Geological and Nuclear Science (GNS Science), and EMSC. Both USGS and GNS Science have a section of their websites dedicated to analyses and insights on specific themes (not only on earthquakes), although the number of posts dedicated to seismological topics is much more limited than what is done by INGVterremoti. Most efforts of USGS, GNS Science, and EMSC experts are devoted to post-event assessment and seismic sequence communication management and problems (Wein et al., 2015; Bossu et al., 2018; Becker et al., 2019; Wald, 2020; Ruan et al., 2022). An interesting analysis on the impact of INGV communication on the media comparing the two main seismic sequences of the last decade (the 2012 Emilia earthquake, the 2016 central Italy seismic sequence) has been carried out by Cerase (2017). A specific attention has been devoted in past years to the issue of contrasting misinformation on earthquake science (see, among many others, Kwanda and Lin, 2020; Dallo et al., 2022, for a recent review and references therein): some of the posts that have been published are related to unreliable or controversial information circulating on the web (e.g., swarms of small earthquakes inhibit the occurrence of large ones, confusing magnitude and intensity scales, induced seismicity, *etc.*). Moreover, the publication of automatic and provisional solutions described in Section 4 had among its goals that of limiting the spreading of false news about earthquakes in the minutes preceding the publication of revised solutions (wrong magnitudes, locations, *etc.*).

Today, INGVterremoti communication moves on two main lines: 1) "peacetime" activities: in the absence of seismic crises, INGVterremoti team operates to promote a better scientific culture, also in view of the Italian people's inevitable coexistence with natural hazards; 2) "times of emergency", i.e., in the presence of damaging earthquake sequences going on, or even in case of attention by the media due to fear and anxiety in the population, as often happens during long seismic sequences, INGVterremoti responds to the citizens' information needs. Through the years, we succeeded in maintaining a continuous and high level of published contents, spread on the different channels of the platform. This has contributed to increase people's trust in our communication. Italy is a country where a large percentage of the population lives in regions with many natural hazards and related risks, therefore the relevance and the social impact of the research carried out by INGV are very high. Its institutional mission - stated in the INGV statute - includes constant and conscious communication, aimed at spreading a scientific culture of the territory and its characteristics, and the risks associated with them, including seismic, tsunami, volcanic, and environmental risks. The main objective of INGVterremoti towards the public is communication and information on issues related to earthquakes and tsunamis through all communication channels developed, also in case of seismic and tsunami emergencies. Since July 2018, the INGVterremoti on-call service has been activated to manage communication in case of emergencies and to provide 24/7 operation when a magnitude $M \geq 4.0$ seismic event happens in the national territory, as well as for other relevant emergencies.

3 The INGVterremoti platform

The INGVterremoti platform consists of a coordinated suite of social media channels, including Twitter, Facebook, YouTube, apps for iOS and Android mobile phones, some story maps and a blog-magazine on WordPress (Figure 1) where updates on ongoing earthquake sequences and posts on scientific topics are continuously published (Amato et al., 2012; Nostro et al., 2012; Pignone et al., 2016). In the first years of activities, each social channel has had its own history and specific development, until a general coordination among the different channels has been completed. In the following sections, we describe the evolution and the performance of the different social media; afterwards we discuss the main issues of the platform, with a specific focus on the interaction with citizens.

3.1 YouTube

YouTube was the first open social channel of the INGVterremoti platform and was inaugurated in February 2010, with the goal of increasing the level of information about earthquakes in Italy, which represents a basic step for seismic risk reduction (Amato et al., 2012). The main objectives of this initiative, which started a few months after the 2009 L'Aquila earthquake, were to inform the public about the seismic activity in Italy, in the Euro-Mediterranean area and in the world, to communicate the results of scientific research in seismology, and to increase the knowledge of the seismic hazard. The choice was to publish short films (lasting less than 5 min) intended for the general public, including interviews with INGV researchers using simple and immediate language with the goal of bringing the INGV as close as possible to citizens. Over 120 videos have been posted to date, most of which have been produced with "in-house" resources and non-professional equipment and software. Although this sometimes results in low-quality technical content (e.g. audio, lights), we have preferred to focus on the scientific content rather than spending too much time on the various aspects of film-making. The videos published on the channel are organized in 16 different thematic playlists on earthquakes in Italy, seismic hazard in Italy, seismic monitoring, world earthquakes, tsunamis, and some relevant seismic sequences (the 2016 central Italy seismic sequence, the 2012 Emilia earthquake, the 2009 L'Aquila earthquake).

The YouTube/INGVterremoti channel has been integrated into the INGVterremoti blog since its publication in 2012. As described in Section 3.4, in the first months of the blog's activity, during the seismic sequence in Emilia in 2012, we have introduced the videos within the posts in order to get a better dissemination and understanding of the message. An emblematic example is the video "the Po Plain Seismic Sequence on May 2012 - The Buried Faults", published on 8 June 2012 and inserted in the post published the same day. This video was seen by more than 72,000 people, about one-half of which has reached it from the blog post, demonstrating a proficuous interaction of the two communication tools. Also in the following periods, the YouTube/INGVterremoti channel published many new videos, integrating them all with posts and some static pages of the blog. The development of the blog, the YouTube channel, and the sharing of content on the various social channels was useful for strengthening the dissemination of authoritative information, both during small and large seismic emergencies, and to narrate the research activity on earthquakes and tsunamis. Even during the 2016 emergency in central Italy, the constant presence of timely information through the INGVterremoti blog and social media has favored the release of a correct information on national media, reducing the need of looking for alternative sources by TV and newspapers.

The YouTube/INGVterremoti channel has been very important as the main information hub during the information crisis following the fake prediction of a destructive earthquake that was supposed to hit Rome on 11 May 2011. The story of the prediction and of the countermeasures taken by INGVterremoti is described in Nostro et al. (2012), whereas the long series of videos published before, during, and after that long day is still visible in a specific playlist.

In 2013, one of the videos on the INGV-Rome Control Room was selected by AGU for the session "AGU Cinema 2013" and projected during the whole duration of the fall Meeting. From February 2010 to April 2022, all the videos posted on the channel had a total of more than 6,260,000 views and the video "Tsunami" (in English), the most watched since the opening of the channel, had about 2,740,000 views. Several videos were seen by more than 100,000 people worldwide, with a majority in Italy (most of the videos are in Italian). The audience numbers described in this study are encouraging and confirm a growing interest, as evidenced by the number of shared videos and the comments of the 13,300 subscribers. Between the 10 most viewed videos, five places are occupied by shakemovie animations, the visualizations of 3D high-resolution simulations of seismic wave propagation for earthquakes in the Italian region with magnitude $M_w \geq 5$, nearly automatically generated within a few hours of their occurrence (Casarotti et al., 2016). Each video has hundreds of thousands of views and has been picked up not only by social media but also by more traditional systems such as news broadcasts. The reason for this large audience is to be found in the readiness with which these videos are released. Our motivation for creating a quasi-automatic system for generating these animations is to meet the demand for rapid scientific information but also to help the visualization of a natural phenomenon that we only visually perceive for its catastrophic aftermath.

3.2 Twitter

The INGVterremoti account on Twitter started its activity in March 2010 to provide constant and timely messages about seismic events localized by the seismologists working at the INGV-Rome Control Room which provides seismic surveillance and tsunami alert services (Amato et al., 2021; Margheriti et al., 2021): earthquakes in Italy with magnitude equal to or greater than 2.5 (M2.5+), in the Euro-Mediterranean area with magnitude equal to or larger than 5.0 (M5.0+) and in the world (M6.0+). Most of the tweets are basic data on ongoing seismicity (events' location, origin time, magnitude, affected areas), but in the last few years more general information has also been published, including links to articles published on the INGVterremoti blog-magazine, *etc.*

In the period 2010–2018, the INGVterremoti account on Twitter provided only tweets with locations and magnitudes after the manual revision by seismologists on duty at the INGV Control Rooms in Rome, Naples and Catania, available within 30 min of the earthquake occurrence (most often within 20 min). This procedure was adopted because it warrants the production of only official and validated information about an earthquake, thereby helping stem potential rumors or misinformation related, for instance, to the earthquake's magnitude, in case of initial under- or over-estimation. However, timing has always been a critical element for this communication, particularly in the past few years due to the diffusion and speed of social networks (Figure 2) In fact, revision of a seismic event by on-duty seismologists includes waveforms' re-picking for P and S-waves identification at several seismic stations, computing hypocentral parameters and local magnitude, checking of the results, *etc.*, an operation that generally takes several minutes, typically 8 to 20, with more time needed for large earthquakes. Undeniably, mobile internet, social network sites, and Twitter in particular require a more rapid and "real-time" reaction, due to a large number of comments and questions coming out in the immediate wake of a felt earthquake. So in the following years (2012–2018) we have worked for the release of provisional but rapid information and thanks to a specific study (see Section 4) we have identified the necessary conditions to limit the diffusion of false or wrong seismic event locations and, also, to define the correct syntax of the tweet text with the provisional location. In Section 4, we describe in detail how we faced this problem, moving to the publication of fast, preliminary, unrevised information with locations/magnitudes for earthquakes in Italy with magnitude larger than 3.0, released after a couple of minutes, initially only on Twitter @INGVterremoti, later also on the INGV earthquake list web page and also on the iOS/Android apps.

Among the followers, besides citizens, students, teachers, scientists, and journalists, there are several media agencies at national and local levels, including mainstream TV channels that publish the tweets as soon as they are available online. In 2012, after the Emilia seismic sequence, this account was voted as the Italian "Most useful Twitter account" at the "Macchianera" social media national award. In the period March 2010 - October 2022, @INGVterremoti has issued about 27,000 tweets (about 2,000/year) increasing its followers to more than 292,000. For comparison, the @USGS_Quakes account has 248,800 followers and the EMSC @LastQuake account has 225,100 followers (both on 18 October 2022).

3.3 Mobile apps

Since 10 March 2011 (1 day before the 2011 Tōhoku earthquake), the INGVterremoti app for iOS has been distributed in the App Store. It was the first native seismological app released by a scientific institution. The goal was to provide fast communication about seismic information tailored to mobile users, an audience that was beginning to be dominant. This app shows data on the most recent earthquakes occurring on Italian territory and, is limited to the strongest events, in the rest of the world. They also make it possible to view Italian seismicity from 2005 onwards, *via* the Search section. Special attention has been paid to scientific information

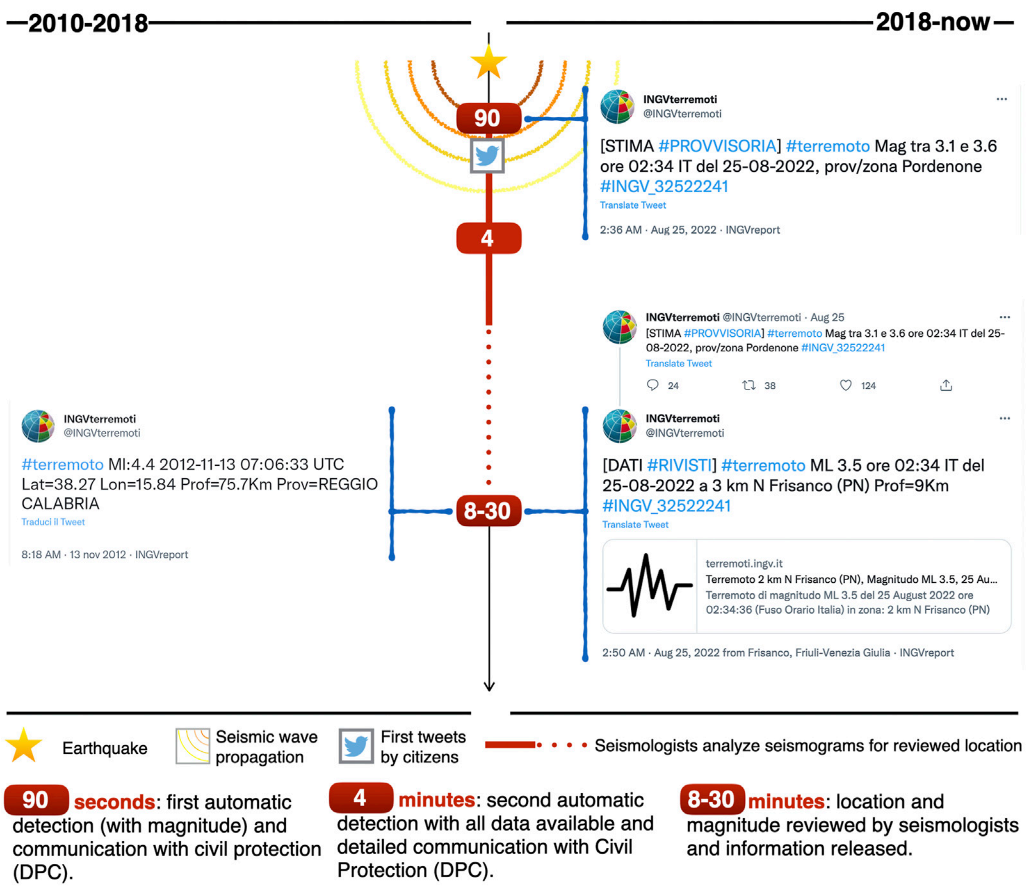

FIGURE 2
Timing of the localization of an earthquake with the systems of the INGV-Rome Control Room; the temporal sequences described above are pre-2018 on the left and the current one on the right, after the publication of the automatic solutions starting on September 2018. Seismologists can review preliminary data strictly within 30 min of the event. In 95% of cases, communications of revised data are made between 8 and 20 min after the earthquake. In addition, the figure shows some examples of tweets according to the sintax and the rules valid before 2018 (left side) and now (right side).

regarding earthquakes with sections linked to the INGVterremoti blog-magazine. When the app was first released, the mobile app market was in its infancy, at least in Italy. Therefore, due to the novelty and the efficiency of a product released by a renowned scientific institution, during the seismic crises ranging between March 2011 and July 2013 the INGVterremoti app repeatedly ranked in the top 10 positions among the most downloaded apps in the Apple App Store (Italy). This app has been constantly updated (3 main releases) both due to the evolution of the technological platforms in which they operate, and due to the changes of the INGV seismicity information service of which they are an integral part. In 2011, the main feature of the original release was that the entire Italian seismic INGV catalog since 2005 was downloaded to the device during the installation to allow the app to function without data connection (e.g., in remote areas or during an earthquake emergency). The improvement of the mobile data coverage in Italy and the creation of APIs to programmatically access the INGV earthquake database have made the presence of the entire catalog within the app a feature no longer necessary in the following releases of the app. Therefore, in 2016 a completely new version of INGVterremoti app has been developed and distributed, not only for iOS but also for Android. Since 2021, the apps show even the provisional earthquake location with the features and limitations described in Section 4. In 2022, the iOS version has been completely rewritten, deeply graphical renovated and released in the App Store. The main feature requested by users but still missing is the presence of a push notification service. This feature has not yet been implemented due to concerns about releasing a notification service that is impeccable in timeliness and robustness, linked directly to INGV, which is the authoritative institution for seismicity for the Italian government. However, the next version of the app will have this feature and is at an advanced stage of testing.

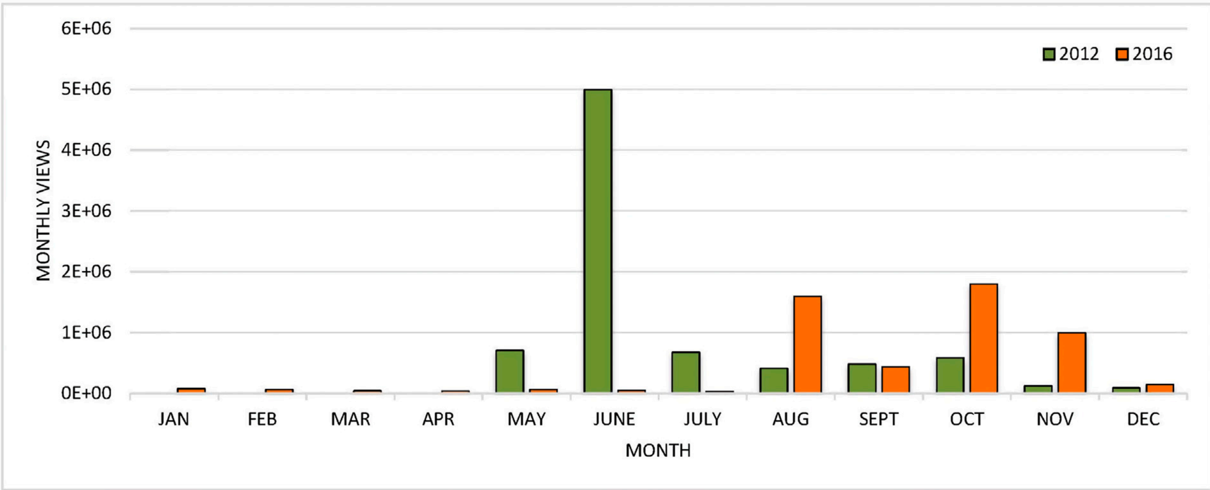

FIGURE 3
Number of the INGVterremoti blog monthly views in 2012 and 2016.

3.4 Blog-magazine

Even if the INGV websites for many years have provided information in quasi real-time about all the earthquakes in Italy, the strongest events in the Mediterranean and in the world, we know that this is not enough. Soon after an earthquake, people look for more news, more specific and detailed information on the region, on previous earthquakes, on the seismic hazard, and on the evolution of the seismic sequence, on the web and social media. For this reason, in the days after the 20 May 2012, Emilia main shock (M_w 5.8), we opened a new blog on WordPress, also called INGVterremoti, to provide quick updates and in-depth scientific information (Pignone et al., 2012). Providing continuous and timely information is particularly important when seismic sequences last for several weeks or months and are characterized by several felt earthquakes, also to counter the bad information, and to fight rumors and fake news that always arise during seismic crises. All the information published on the blog is shared on the other INGVterremoti social media (Twitter and Facebook) and also through the iOS/Android apps.

The blog has continuously released information with three different types of posts:updates on seismic activity; information on the activities carried out by INGV groups in the epicentral area; insights with an increasingly accurate analysis of the available data and the specific results obtained.

In the first 8 months of activity (May - December 2012) 92 out of the 132 articles published on the INGVterremoti blog were dedicated to the Emilia seismic sequence.

The INGVterremoti blog played a central role in the communication also during the long 2016–2017 seismic sequence in central Italy. This seismic sequence began on 24 August 2016 with the deadly M_w 6.0 earthquake affecting the town of Amatrice and other towns and villages of the Rieti province. 109 posts were published in the first 24 months of the sequence. In particular, of the 119 posts published in 2016, 83 are related to the seismic sequence in central Italy and stand out among the most viewed articles in 2016. All blog posts were shared in real-time on the other social media of the INGVterremoti platform (Facebook, Twitter, and iOS/Android apps) and also on the INGV main home page. Even the INGV real-time data portal has published the contents of the blog on dedicated pages that have been automatically fed. The day-to-day work carried out on the INGVterremoti blog during the emergency in central Italy was shared with the INGV Press Office which drafted several press releases based on the contents of the blog.

If we compare statistics of the monthly views in 2012 and 2016 (Figure 3), we note that the blog had the peak of monthly views (5 million) in June 2012 due to the Emilia, 3 June 2012 earthquake (magnitude M_L 5.1). Thanks to the 83 articles published on the seismic sequence in central Italy, in 2016 the blog had a total of more than 5.4 million views and 2.9 million visitors (Figure 4). The peak in the number of views, which was over 830,000 in a single day, was recorded on 24 August 2016, after the M_w 6.0 earthquake that started the sequence.

The INGVterremoti blog has maintained the 2012 original setting until March 2020, where the home page had the timeline of the latest articles and some static pages on general topics: Earthquake in Italy, Seismic Risk, Seismic monitoring, FAQs and Glossary, Story Maps. From May 2012 to March 2020, we published 685 articles, about 85/year on average, 1.6/week, highlighting one of the key performance indicators regarding perseverance. Most of the post are in the “Earthquakes in Italy”

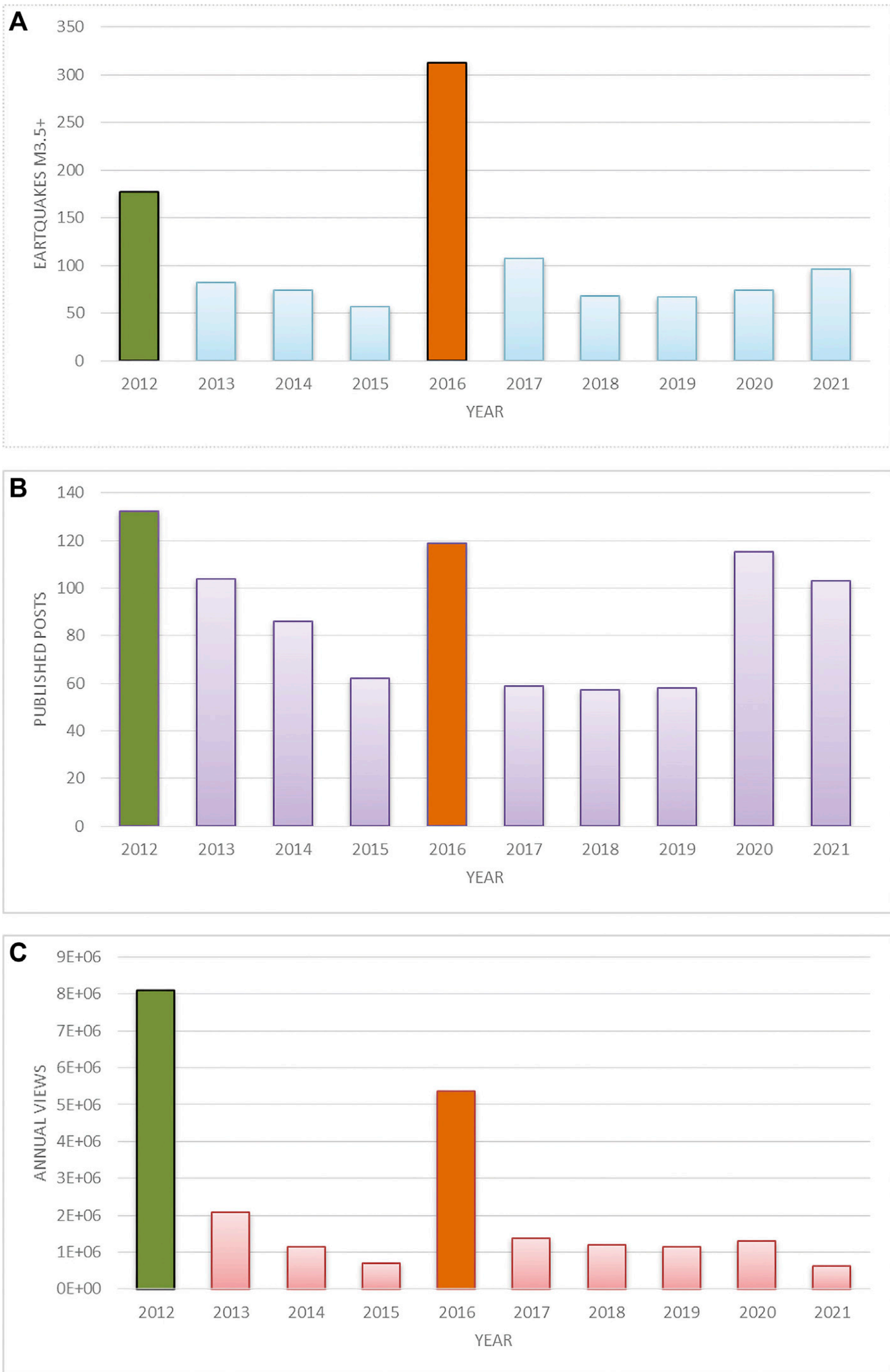

FIGURE 4
Comparison between: **(A)** annual number of earthquakes with magnitude M3.5+ in the area that also includes Italy (lat. 35–49; long. 5–20); these are events that also occur outside the national territory; **(B)** annual number of articles published on the blog; **(C)** annual number of blog views. We note that the blog had the peak of monthly views (5 million) in June 2012 for the Emilia, 3 June 2012 earthquake (magnitude M_L 5.1). This is probably due to the fact that INGV websites in 2012 had many difficulties in being reached by a huge number of users such as those involved in the Po Valley area. The reachability problem of INGV websites was solved in the following years, and the sharing of earthquake data on different INGVterremoti social media was implemented considerably, so the blog in 2016 had a lower views number than in 2012, even if still relevant: 1.6 million in August 2016, 1.8 million in October 2016 e 1.0 million in November 2016.

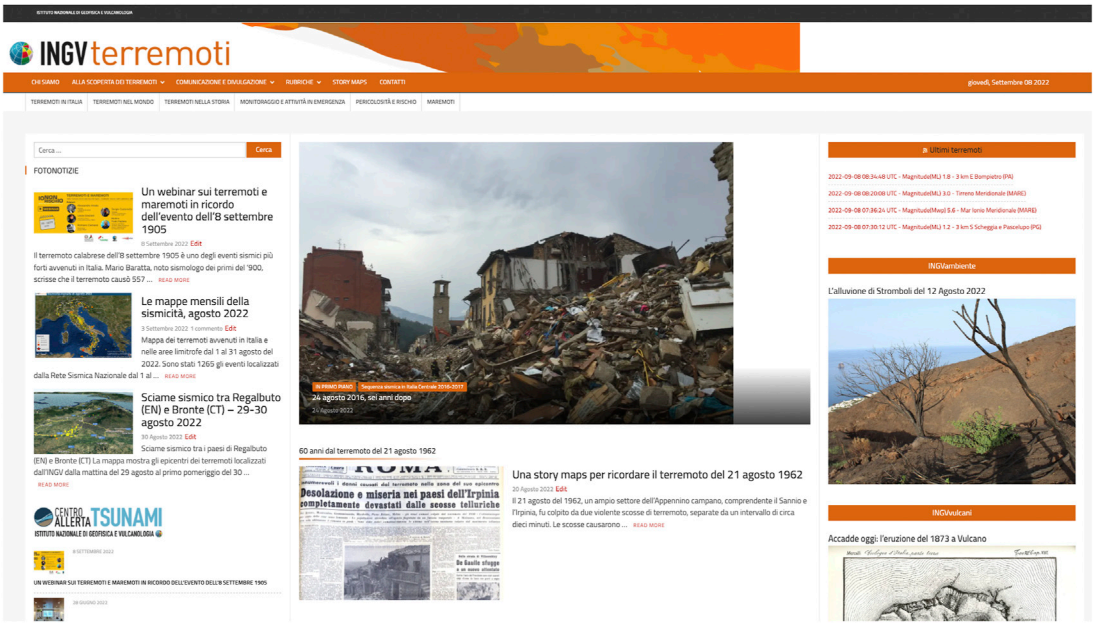

FIGURE 5
Home page of the blog-magazine INGVterremoti in 2022. The INGVterremoti blog menu reflects the new organization of static content and article categories.

category and therefore related to the seismic activity in Italy. In particular, 15 main seismic sequences have occurred from 2012 to 2020 in different regions of Italy (Campania, Toscana, Abruzzo, Umbria, Molise, Lazio, Calabria).

In March 2020 the new INGVterremoti blog-magazine was published, after a 1-year long phase in which a new interface was designed, in coordination with the three INGV departmental blogs (INGVterremoti, INGVvulcani and INGVambiente). A huge work has also been done to achieve a common reorganization of the contents for the three INGV departmental blogs in collaboration with a specialized company through specific on-the-job training. The following points were addressed:

- the analysis of the communication of the three blogs,
- the evolution of communication from blog to e-magazine,
- choice of a new theme, migration from the old to the new one.

A new theme, common to the three blogs, was chosen in order to move from a traditional communication format of blogs (a single chronological time-line for articles) to an interface closer to an e-magazine with a multi-home content management and a greater integration with the social channels of the INGV departmental platforms (Pignone et al., 2020). The new theme allowed blog managers to create various "thematic" time-lines of articles on the INGVterremoti.com homepage, choosing from the various Categories. The new Home page (Figure 5) is much more complex than the previous one and places a slider with the most recent article in the center at the top, immediately below the double menu of the static pages and categories, which reflects the new content organization. On the side, there are the timelines of the articles of the category Photonews ("Fotonotizie"). Photonews is a novelty of this theme, "mini" articles structured with an image and a dozen lines of comment: a faster way to update the magazine with more dynamic and lighter content.

In the vertical development, the structure accepts different timelines to be assigned to a specific theme by selecting the articles of some Categories or Subcategories. Some widgets have been inserted on the right bar: among them there is a link to the last article of the other two INGV departmental blogs. The result of the restructuring perfectly reflects the original idea that prompted the revision and reorganization of the three blog-magazines that today have the same interface and structure. The new version of the INGVterremoti blog-magazine was online at the beginning of March 2020 with the new web address: http://ingvterremoti.com.

This new web page structure facilitated the creation of contents: 115 (68 articles and 47 photonews) and 103 (55 articles and 48 photonews) posts were published in 2020 and 2021, respectively, numbers very similar to those of the years with large seismic sequences. In 2020 there were 1,3 million page views and in 2021 about 623,000. It is

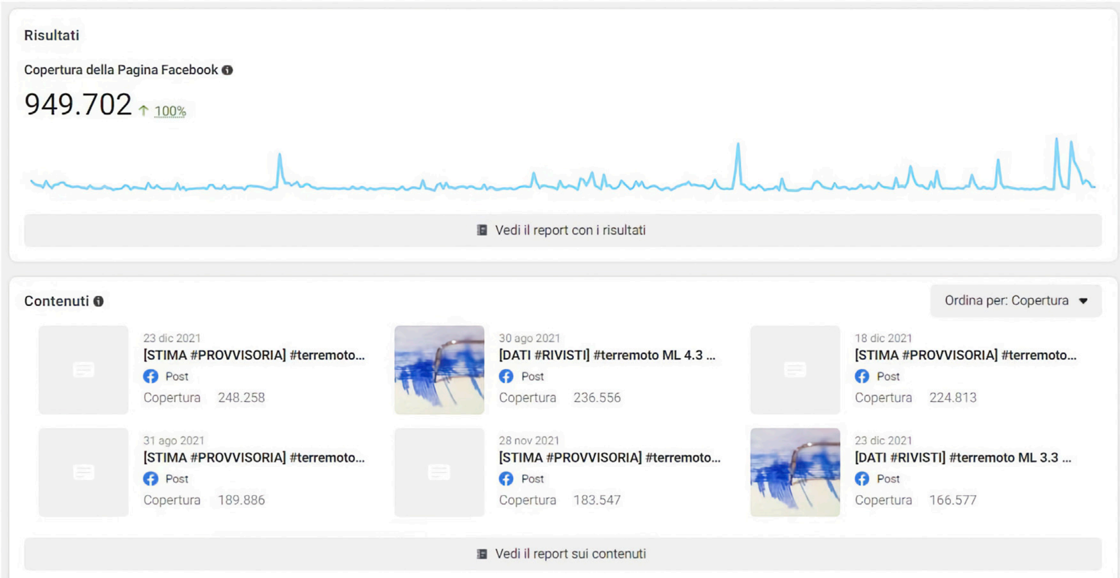

FIGURE 6
The 2021 statistics for INGVterremoti Facebook page, where "Copertura" is Post reach.

important to note the larger number of articles compared to previous years, also considering that no major seismic emergencies occurred. Coherently, among the most viewed articles of the last 2 years, there are not only those related to ongoing seismicity but also in-depth articles (such as, for example, one on the 1908 tsunami and some of those published for the 40th anniversary of the 1980 earthquake in Irpinia-Basilicata, as well as others on the seismic surveillance and monitoring activities during the lockdown due to the COVID-19 health emergency.

In 2022, the blog's homepage was lightened to facilitate consultation from the mobile phone. Indeed, the analysis of accesses to the blog-magazine revealed that mobile phones represent 80% of the devices through which the blog is viewed.

3.5 Facebook

After the 2012 Emilia earthquakes, in 2013 we opened the INGVterremoti page on Facebook to publish, in a similar way to what was already happening on the Twitter channel, data about seismic events in Italy with magnitude equal to or greater than 2.5, quick updates on seismic sequences and to open two-way communications with users. In addition to locations of the M2.5+ events in Italy, M5+ earthquakes in the Euro-Mediterranean area and M6+ global events are automatically published on the Facebook page. The aim is to reach the broad public using Facebook as its only or preferred social media. Furthermore, all the posts that come out on the INGVterremoti blog-magazine (Section 3.4) are published automatically on Facebook page. On the occasion of some of the most significant earthquakes, provisional estimates of the locations of the INGV-Rome Control Room have been published since August 2018, with manual intervention by the page managers (who are part of the INGVterremoti team), to respond to users' requests to know where a felt earthquake has occurred, and how strong it was. In these cases, it has been observed that the post with the provisional estimate ([STIMA #PROVVISORIA]) has great resonance, far superior to that of the post with the revised location. If we look at the 2021 statistics (Figure 6), the posts with the largest coverage are those related to preliminary locations. The post related to the provisional estimate of the 23 December 2021, M_w 4.3 earthquake in the province of Catania (Sicily) had over 263,000 impressions, 248,000 reach, 475 shares (see Facebook notes), while the one with the revised data of the same earthquake had over 27,000 impressions, 26,000 reach, 26 shares (Figure 7).

Since 2013, more than 20,000 posts have been published (including location revised by seismologists, preliminary locations/magnitudes and blog articles), with average daily post coverage close to 10,000–15,000 people and peaks over 100,000 during a seismic sequence or when a relevant earthquake occurs. Currently, the INGVterremoti Facebook page has more than 235,000 followers and is the only social network that provides two-way communication with our users. In Section 5 we describe the interactions with followers, a very heterogeneous audience that includes people of all ages and education levels. In the coming months, provisional estimates

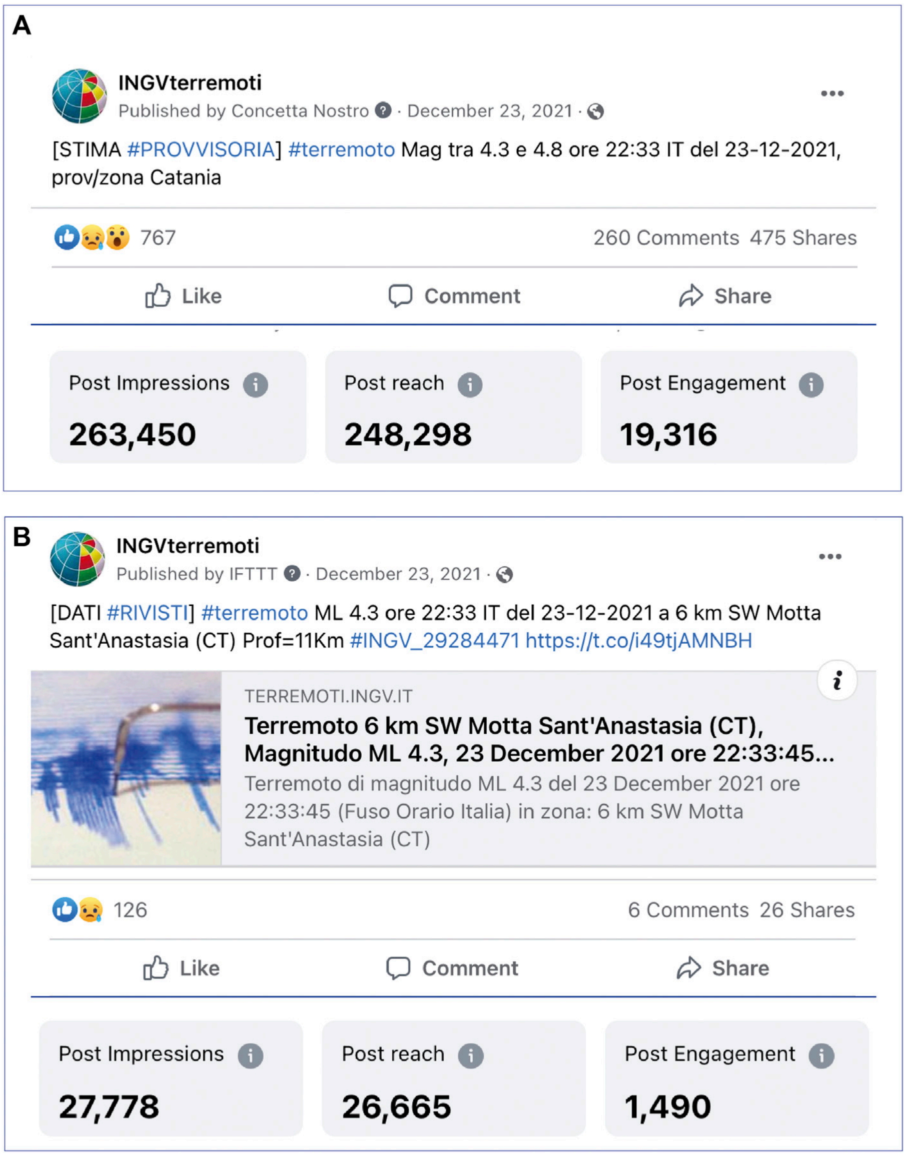

FIGURE 7
The post with the greatest coverage in 2021 is the one related to the preliminary location **(A)** of the 23 December 2021, M_w 4.3 earthquake in the province of Catania (Sicily). **(B)** Post with the manual revision by seismologists on duty at the ONT-Rome control room.

will also be published on the Facebook page with a procedure linked directly to the notification systems of seismic events, in a similar way to what already happens for Twitter.

3.6 Story maps

Since 2013, INGVterremoti has used story maps as a new communication and information channel on seismicity and seismic risk of the national territory. Numerous story maps have been developed to tell the various aspects of the earthquakes that have struck in the past, and in recent years, our country by integrating descriptive, photographic and multimedia information with georeferenced data from the INGV seismological and seismotectonic databases (Pignone, 2015). A story maps is an integrated set of digital maps, related content (legend, text, photos, videos, *etc.*) and interaction features (pan/zoom, pop-up, query, select, *etc.*) that make it an easily understandable and an immediate information and communication product. For this reason they have also

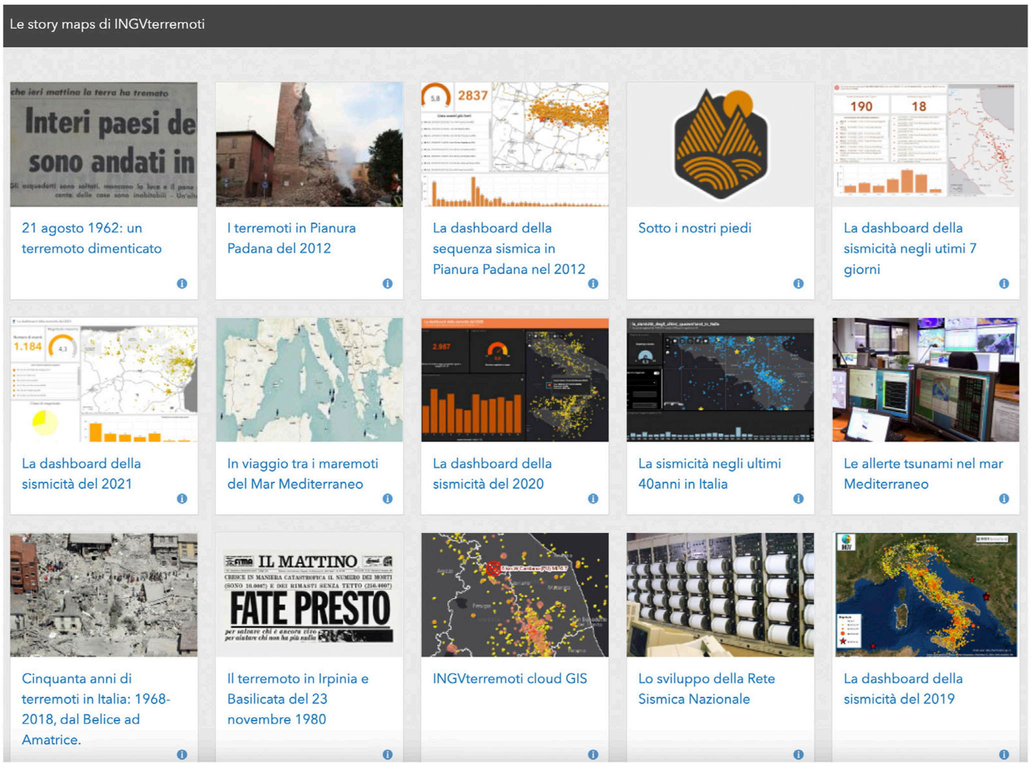

FIGURE 8
ESRI ArcGIS online gallery with the latest published INGVterremoti story maps and dashboards.

become a very valid tool in the outreach public events that INGVterremoti promotes through the use of touch screens that allow you to create real exhibits with which to interact with the public, demonstrating the potential of geographic information in risk communication. After the creation of the story maps, it was decided to also use the web applications of the dashboards type that allow you to make various tools for viewing the datasets and related attributes available, in order to create simple info-graphics, very effective for communication and information for inexperienced users. From 2013 to today, over 25 story maps and dashboards (Figure 8) have been created to describe some of the most important earthquakes and tsunamis of the past in Italy and in the Mediterranean area, and to analyze some of the recent seismic sequences that have affected the Italian territory. There were overall about 110,000 views of the published story maps and dashboards.

Story maps and dashboards are published in a thematic gallery available on ESRI-ARCGIS.com and have been easily integrated into the INGVterremoti web and social communication channels. These web applications represent a useful tool for information on seismicity in progress, on the most important seismic sequences in Italy, on the earthquakes and tsunamis of the past. A section is available on the INGVterremoti blog-magazine which collects the main story maps and dashboards published in recent years.

4 From “slow” revised information to fast automatic data

As a result of the “real-time” nature of social network sites, the time gap between the immediate conversations about an earthquake that takes place on social media, and the official INGV communication, was causing public dissatisfaction, failing to fulfill the need for timely information. Nevertheless, in Italy, the communication of automatic detections, including hypocentral locations and magnitudes, as done by other seismological agencies (e.g. CSEM, Geonet) raised doubts not only from emergency communication experts and civil protection workers but also among INGV seismologists. Among the issues raised was that the public would not understand the provisional nature of this communication. Monitoring the conversation on social networks showed that “evolving” values of earthquake parameters could be seen as: “errors due to ineptitude”, “you are hiding the truth”, and “conspiracy”. Tweeting the automatic detection could increase the risk of unfruitful debates around magnitude or conspiracy theory (e.g. the history of the fake news of the magnitude of the M_w 6.5 30 October 2016 Norcia earthquake documented by valigiablu. it).

It is important to consider that the issue of misinformation is critical in Italy. Differently from other countries, such as New Zealand (see, for instance, (Wein et al., 2015); (Becker et al., 2019)) where the public acceptance of uncertainties and revised estimates seems to be higher, a change in seismic parameters, as, for example, a revision bringing to a magnitude lower than the initial one, is immediately interpreted by many as a fraudulent attempt of minimizing the risk. It happened that after the 2009 L'Aquila earthquake, for which the magnitude Mw was estimated between 6.1 and 6.3, but the Richter magnitude was calculated as 5.9, that this latter value (still present in the INGV website) was criticized because it was erroneously confused with the threshold of the Mercalli (MCS) scale according to which only municipalities with observed degree six or above had the right to be refunded by the State. This and other similar issues still happening today after any relevant earthquake often hold the stage for a long time after an earthquake even on national TV channels and newspapers.

For this reason, INGVterremoti always tries to be fast in releasing earthquake information, but at the same time takes particular attention to the accuracy. To address this issue, the INGV planned the communication of the provisional locations and magnitudes *via* Twitter after a quantitative assessment of user understanding - through an online survey - also exposing the degree of uncertainty of the automatic estimates (Comunello et al., 2015). This assessment is the result of collaboration between domain scientists and communication experts through the PRIN Shakenetworks project led by CORIS (Department of Communication and Social Research, Sapienza University of Rome) (Comunello and Mulargia, 2018). In particular, during the summer of 2014, INGV carried out a quali-quantitative study (through in-depth interviews and a 51-question web survey) in order to evaluate the best format to deliver automatic information involving the Twitter followers and citizens in general. The goal was to improve the comprehension of @INGVterremoti tweets and timeline, focusing on selecting words, structure, and information of automatic detection tweets. This survey is the first experiment to involve citizens and the media to consider earthquake parameters as evolving estimates as long as new data become available and analyses results become more reliable. The survey obtained 1,224 completed responses and the results are detailed in Comunello et al. (2015). Here we highlight that respondents place great importance on official information within 2 min of a seismic event. Respondents' preferences on the information they value most drove both syntax and wording, as well as the order of topics within the tweet, with the most relevant information at the beginning of the text. Local time was inserted, substituting the previously used UTC time; the label [STIMA #PROVVISORIA] ("provisional estimate") was chosen. We valued the concept of provisional estimate as the most important information to be conveyed, in order to avoid misunderstandings in case of differences between the automatic and the reviewed parameters. The automated tweet is always followed by a second tweet as a reply to it, containing the parameters reviewed by the seismologist, in order to show the evolution of the estimates. The quantitative analysis of user comprehension has laid a solid foundation both for reducing misunderstandings and to face possible criticisms. In order to satisfy the need to communicate "provisional estimate" within 2 min of a seismic event, we explored a set of parameters to define the reliability of automatic detections, balancing timeliness with the robustness of information. The goal is to communicate provisional estimates for as many events as possible, avoid false alarms (events that are reported but did not actually occur) and reduce cases where automatic parameters differ substantially from those reviewed by seismologists. Thus, analyzing the solutions provided by the seismic monitoring room for the Italian territory, four reliability thresholds were defined. Automatic localization of a seismic event is then considered for open communication only if all the following conditions are true: 1) magnitude M greater than or equal to three calculated on a number of channels greater than 10·M; 2) more than six observations; 3) root mean square $<$ 1.5 and error in depth $<$ 10.0 km; 4) azimuthal gap between seismic stations $<$ 180°, distance from first station $<$ 100.0 km. Thus, applying the previous conditions to the seismicity that occurred in the Italian territory from 1 January 2013, to 1 September 2018, we found that 78% 1,432) of earthquakes with a magnitude greater than three were judged reliable (Figure 9). In contrast, there would have been six false alarms (0.3%), in general, due to temporary technical problems or simultaneous events or deep events.

Based on these results and supported by the user comprehension survey, we decided to provide the provisional magnitude estimate as a range of values (precisely -0.3 and +0.2 from the central value). Considering this range of values for reliable earthquakes, we observe that 5% of these have revised parameters that visibly deviated from the provisional magnitude range (Figure 10) or from the spatial location by more than 20 km. Expressing a range of values in which the magnitude is included is a choice that highlights the associated uncertainty.

These analyses were adequate to allow Dipartimento della Protezione Civile (DPC) and INGV representatives to shift the communication paradigm from immutable over time, monolithic localization parameters, to prompt estimates including uncertainties, that evolve with improved analysis and new data availability. Since September 2018, first on the Twitter account, then on the INGV earthquake list website and on the iOS and Android apps, automatic solutions are posted through the syntax shown in Figure 2. In Figure 11 we show the geographical distribution of earthquakes (since September 2018)

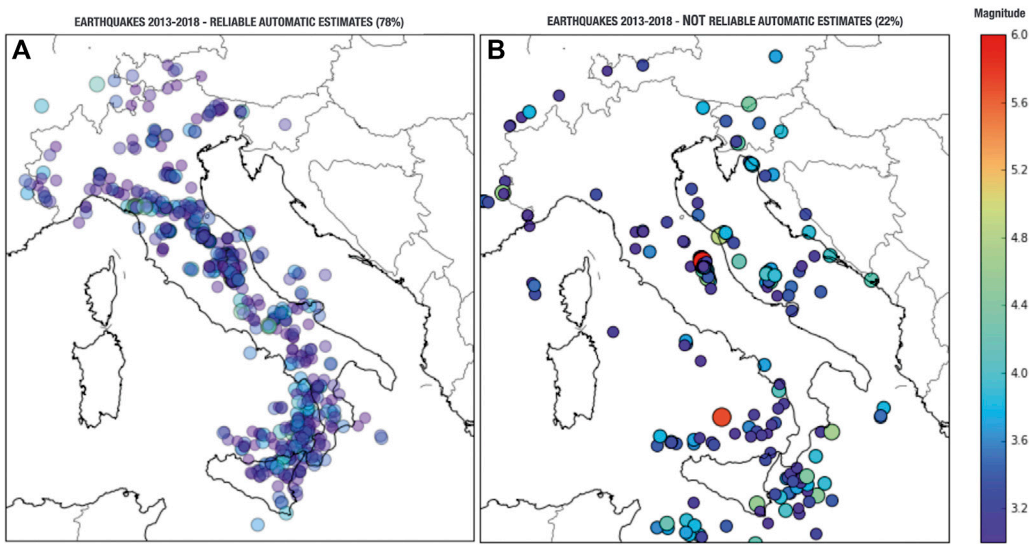

FIGURE 9
Earthquakes with M ≥ 3 recorded from 1 January 2013 to 1 September 2018 in Italy and surrounding regions **(A)** reliable automatic estimates (78% of all the events with M ≥ 3) that satisfy all the following conditions: a) magnitude M ≥ 3 calculated on a number of channels greater than 10·M; b) more than six observations; c) root mean square < 1.5 and error in depth < 10.0 km; d) azimuthal gap between seismic stations < 180°, distance from first station < 100.0 km **(B)** automatic estimates that don't satisfy the conditions of reliability The unreliability of the automatic solutions increases during important seismic sequences (i.e., the 2016 central Italy sequence) since waveforms from several earthquakes could be overlapping.

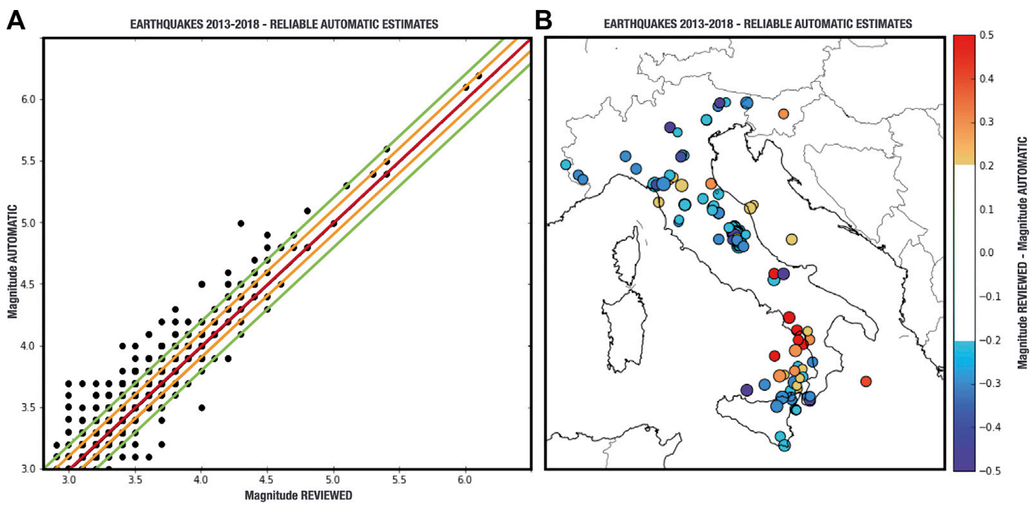

FIGURE 10
Analysis of the difference between automatic and manually revised magnitude for reliable automatic estimates **(A)** Distribution of reviewed magnitude of reviewed M_L vs. automatic M_L, the lines highlights difference with 0.1 step **(B)** map of automatic reliable estimates with difference in magnitude greater than 0.2, higher differences correspond to deep events located on the subduction of the Calabrian Arc that usually shows higher error in the automatic location.

for which provisional parameter estimates were reported, together with those that failed the reliability thresholds.

As can be seen, comparing Figure 9 and Figure 11, earthquakes located in the Adriatic Sea and at the edge of the national seismic network have increased during these years, thanks to the improved station coverage and network sensitivity. However, given the unfavorable station geometry, the manual revised solutions with at least one parameter outside

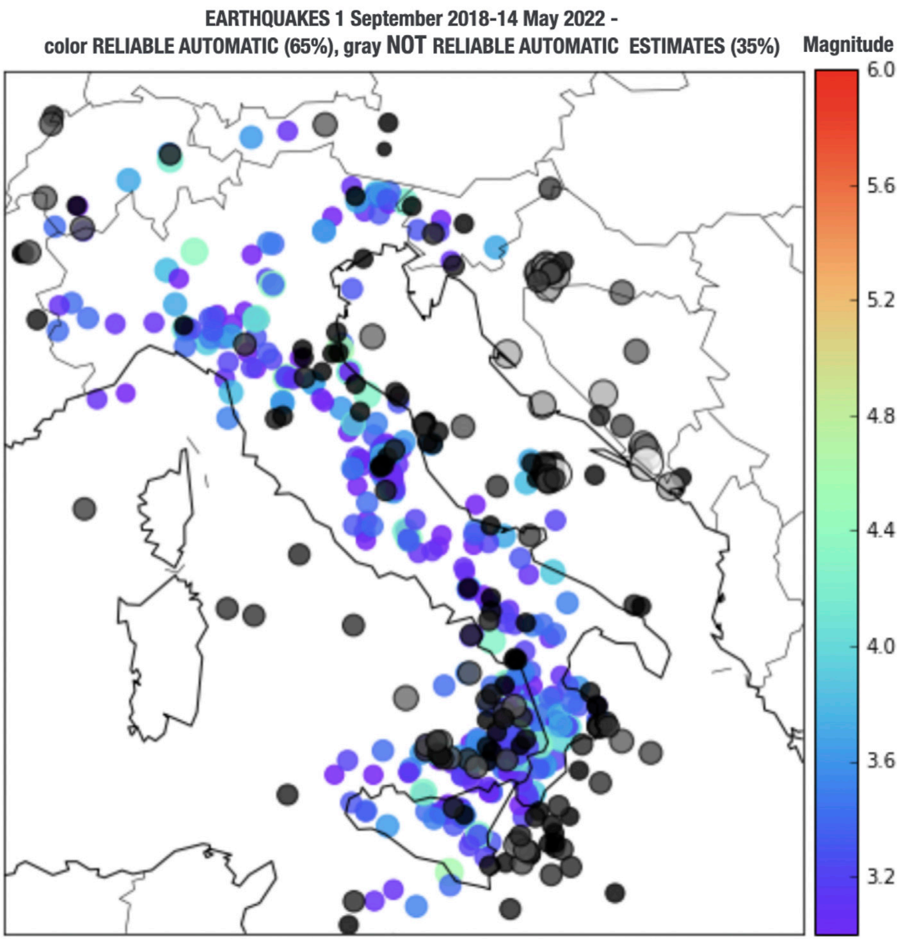

FIGURE 11
Geographical distribution of earthquakes (1 September 2018–14 May 2022) for which provisional parameter estimates were reported (color), together with those that failed the reliability thresholds (gray).

the reliable provisional estimates (magnitude out of the uncertainty range and epicenter coordinates different more than 20 km) are increased with respect to the previous period (7% vs. 5%). In Figure 12 we report such events, highlighting that the revised parameters differed from those of the provisional estimate in a way that made the communication "wrong".

A first and relevant communicative effect of this paradigm shift was the reduction of controversy after an earthquake. Unfortunately, this remains when reliability criteria are not fulfilled and the only official communication remains the one related to seismologist-revised parameters, that is released some minutes later. It is remarkable that the most relevant national online media, such as Repubblica. it or Corriere. it, in the commitment to reducing fake news and unreliable information, have started to embed our automatic tweets directly on their page, confirming that it is an important and awaited tool for journalists and citizens. According to Twitter analytics, the statistics of the automatic tweet scales significantly fast (Bossu et al., 2015) after events that are felt in densely populated areas, reaching tens of thousands of impressions in less than 5 min. The information included in the automatic tweet, if timely provided (i.e., within 2–3 min from the earthquake origin time), is enough to meet the demand of citizens: in fact, the statistics for tweets with the revised parameters are substantially lower (fewer retweets, fewer likes, fewer comments), even when they are available a few minutes after the one with the automatic estimates. This lower popularity of the tweet with the most reliable information could also be due to Twitter's algorithms that display more frequently in user timelines tweets that quickly become popular. Obviously, we observe a proportional relationship between the number of impressions and the earthquakes' magnitude, modulated by the population density of the impact areas. We underline that the tweet issued after the largest Italian event of the last 20 years - the 30 October 2016, M_w 6.5 Norcia earthquake - has got 440,000 impressions (at that time only the revised solution was published). Nevertheless, after the

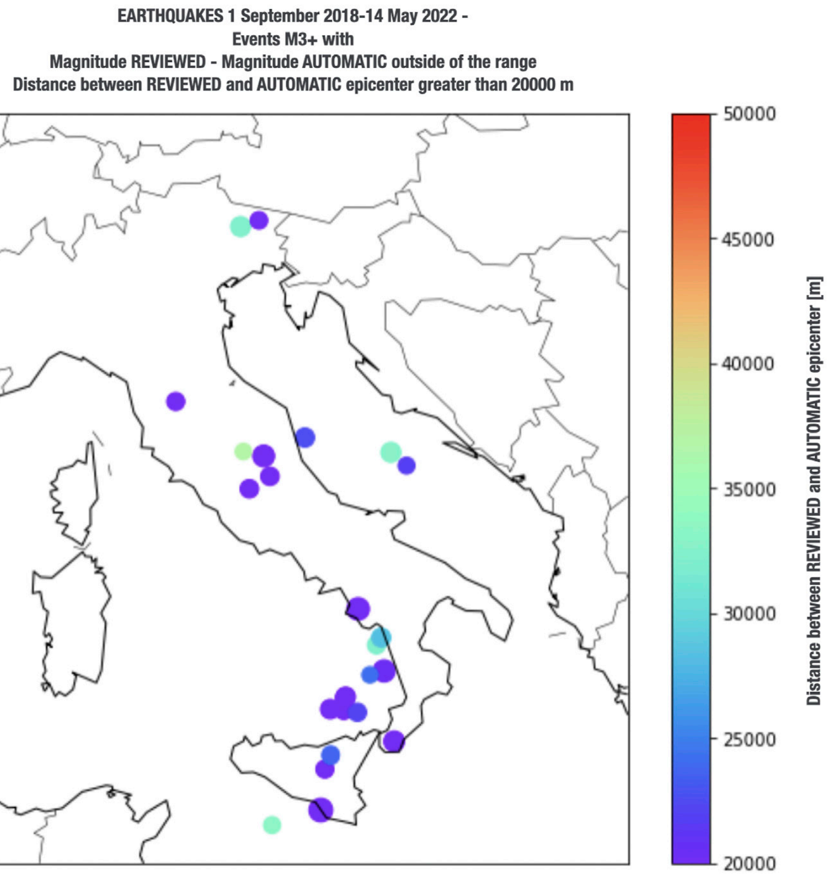

FIGURE 12
Geographical distribution of earthquakes (1 September 2018–14 May 2022) for which the revised parameters differed from those of the provisional estimate in a way that made the communication "wrong" (magnitude out of the uncertainty range and epicenter coordinates different more than 20 km).

introduction of the provisional parameters, Twitter Analytics shows that the most viewed tweet has been the automatic data of the earthquake M_w3.9 occurred on 18 December 2021, 37 km NE to Milan (a very densely populated area) with more than 800,000 impressions, emphasizing the importance of the fast release of information after a felt shock.

5 Interaction with citizens

All our social media are followed by the INGVterremoti team to check the reactions after the publication of the posts, and possibly engage with citizens, providing feedback and answers to specific requests. In general, we observe the greatest number of reactions and comments on the Facebook page, where the number of reactions is directly related to the magnitude of the earthquake and to the population that felt it (with additional secondary factors such as the anxiety level, if a sequence is ongoing, the time of the day). For the earthquakes in central Italy in 2016, there were thousands of comments for each shock of high magnitude. On the contrary, reactions on the Twitter channel are much more limited, although the channel is considered an important source of information, as shown by the automatic locations often published by many newspapers or websites. This is probably due to the type and the attitude of the public participating in the two social media.

For this reason, we have decided to have an active role in the Facebook page only, albeit not an invasive presence. We respond to private messages from individual users, and reply to public comments from the followers of the page that in our opinion require useful clarifications for our audience. It was necessary to explain to users that the page is not followed 24 h a day and therefore it is not always possible to reply quickly.

Through private messages, we receive requests for information on newly felt earthquakes to which we reply with preliminary location information, if available. Many requests are related to seismic sequences in progress. These create apprehension in the population affected and generally the request is something like: "What will happen next?", or "I know that earthquakes cannot be predicted, but should we expect stronger quakes?". We also receive many reports of phenomena for which we are asked for explanations, such as cracks in the ground, gas emissions, variations in some springs' flow rate, *etc.* These messages are always answered, receiving thanks for the work done by INGV.

As for the public comments made to the posts, therefore visible to all, we note different types of comments. In absolute terms, the INGVterremoti posts that receive more comments in a very short time are those related to the provisional locations of earthquakes of magnitude greater than 3. These posts respond to the request for timely information when an earthquake is felt, and many people write indicating where they felt the shaking, how it was, how long it lasted, *etc.* The comments are very numerous when major cities are concerned, especially Rome, Milan, Bologna, Florence, *etc.* We receive many hundreds of comments within minutes. After the first few minutes, we receive other kinds of comments: requests for explanations of the phenomenon, for information on the evolution of seismicity, on the fault that generated the earthquake, *etc.* In this case, we observe that sometimes the answers to these requests are given by our own followers, that include geologists who answer correctly; otherwise, or if there is no answer, we comment directly so as not to leave the questions unanswered or with wrong answers. In all these years, rarely on our Facebook page, there have been exchanges of comments that have turned into insults among users. Only 2–3 times were we forced to remove users' comments. Some of the requests posted during a seismic sequence have been useful to decide the preparation and publication of new posts on some specific topics. A typical example is the explanation of the possible (unknown) evolution of ongoing seismic sequences. In such cases, we try to explain what has happened, providing some information on the possible evolution, based on previous cases and on the statistical assessment of aftershock distribution. An important point we always try to stress is the uncertainty affecting any estimate of possible future evolution. We also take advantage of the high attention raised by a local increase in seismic activity to remind the importance of reducing buildings' vulnerability if one wants to reduce seismic risk.

6 Conclusion

In the past 12 years, the INGVterremoti platform has continuously provided quick updates on the ongoing seismic activity in Italy and worldwide, and scientific insights on several topics regarding earthquake science. These include articles on specific historical earthquakes and tsunamis, on seismic and tsunami hazards, geological interpretations, source models from different types of data, surface effects, and so on. This has been possible thanks to the involvement of more than one hundred colleagues (geologists, seismologists, *etc.*) belonging to the INGV Earthquakes Department and in some cases with contributions from University researchers. The hundreds of articles published in these 12 years are often used and have revealed precious even years after their publication when another earthquake or sequence affects a specific region, and there is the need to explain what is going on, which particular geological phenomenon lies behind that earthquake, and so on. A key issue of our communication strategy through the years is the perseverance of publishing a good number of articles every month (5–10 posts/month on average, except in 2012 when the average was 19 articles). This allowed us to maintain a continuous and active communication with the public, also increasing the number of people interested in earthquake and tsunami science, and in risk reduction.

As far as the rapid information after relevant earthquakes is concerned ($M \geq 4$ in Italy and for large earthquakes worldwide), the INGVterremoti teams is ready to respond 24h7, publishing a first post with the basic information on the ongoing seismicity in less than 1 hour, and then deepening the information publishing additional posts in the following few hours, with the help of specific experts of that area or of that phenomenon. The coordinated use of several social communication channels represents an opportunity to spread information to different segments of the population, both during emergencies and in quiet times. These technologies have the potential to prevent communication breakdown through reliance on just one platform and thereby to reinforce the diffusion of authoritative information. The use of social media channels has allowed us to interact with the public, listen to citizens' curiosity, needs and fears, trying to establish a continuous and virtuous relationship. This has allowed us to respond to people's needs in quasi-real time, answering directly to questions, and doubts, or preparing some specific articles on a debated matter. We have seen several times that the attention of the public on earthquake risk is very high when there is some ongoing activity with felt earthquakes, but it vanishes quite soon when the activity ends. We have tried to use those moments to raise people's awareness and preparedness to future earthquakes, but at the moment we could not evaluate if we succeeded in this, and to what extent.

For the future, we are evaluating how to improve our communication strategy and to increase the quality and quantity of information both on ongoing seismicity and on the hot research topics in earthquake science. We will do this both through the social media already used and by trying to open new ones. Possible developments therefore include the opening of new social media, such as Instagram and possibly TikTok, in order to reach a broader and younger audience and involve them in the scientific dialogue and in risk reduction. Future generations are the main resource for a cultural change in Earth system management, both for climate change countermeasures and for natural risks reduction. More in general, we saw that story maps and storytelling are two important tools to reach more attention from the public and from the media. Another important element to be taken into account is the prevalence of access to our channels from mobile phones (80%) with respect to PCs. This will guide the way in which we will offer contents to the public: we would probably need shorter contents, infographics, and an improved interface more suitable for mobile devices. Other possible improvements include the continuous monitoring and assessment of our communication strategy with specific surveys on targeted audiences.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: http://terremoti.ingv.it/https://ingvterremoti.com/.

Author contributions

MP, AA, CN, EC and CM contributed to conception and design of the work. AA, CN, EC wrote the first draft of the manuscript. MP wrote the section of the manuscript about the blog, CM the section about the Facebook page. All authors contributed to manuscript revision, read, and approved the submitted version. EC performed the statistical analys-is for the communication of automatic earthquake detection. Since the INGVterremoti platform consists of a coordinated suite of social media channels, including Twitter, Facebook, Youtube, iOS/Android apps and a blog-magazine, each author of this work contributes specifically to the different activities that we specify as follows: AA, CN, EC, CM and MP are content creator and manager the whole suite. MP is the blog administrator and web designer and, together with AA, CN, EC and CM, take care of the development. EC and VL are the managers of @INGVterremoti on Twitter. CM, MP, CN and EC are the managers of the Facebook page. EC, MP and VL are the app managers. AA, MP and CN are the YouTube managers. VL and MQ have been working on the technical development of the online publishing of seismic events.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Tsunami risk perception, a state-of-the-art review with a focus in the NEAM region

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Large-scale coastal urban sprawl, development of tourist accommodations and industrial maritime poles have highly increased the tsunami risk to people living and/or traveling along the coasts of our planet. The disastrous tsunamis in the Indian Ocean (2004) and in the Pacific Ocean (2011), as well as a suite of other damaging events worldwide, have encouraged International Institutions, first of all UNESCO Intergovernmental Oceanographic Commission, National Governments and Local Communities to implement Tsunami Warning Systems (TWS), to raise awareness on tsunami risk, and to create a multilevel risk governance. In this framework, research on tsunami risk perception plays a key role. The results of these studies should be taken into account in designing risk mitigation programs and tools (such as drills, activities with local communities, emergency plans, *etc.*). This paper presents a review of such studies, carried out in several countries worldwide through many thousands of interviews performed with different techniques. Most tsunami risk perception studies were carried out in the regions where the Indian Ocean Tsunami Warning System and the Pacific Ocean one (PTWS) operate. In the NEAMTWS (North-East Atlantic, Mediterranean and connected seas Tsunami Warning Systems) region, only few specific studies were conducted, mostly within the EU-funded ASTARTE project (2013–2017) and more recently in a few extensive surveys on tsunami risk perception conducted in Italy between 2019 and 2021. Although the twenty-three studies analyzed in our review show a strong heterogeneity of methodological approaches and population samples, they allow us to outline some general considerations on tsunami risk as perceived by people in the different regions of the world. With the help of a table, we schematically summarized the emerging strengths, weaknesses and lessons learned in the twenty-three papers, noting an increase in the number of such studies in the last 5 years. The surveys were mostly concentrated in high-risk areas and focused on local residents. Some differences emerged depending on the memory of past tsunamis, education level, and local cultures. This provides useful hints for sound citizen-based tsunami risk reduction actions, including improved risk communication aimed at increasing the resilience of tsunami-prone populations. The need for increasing the assessment of tourists' tsunami risk perception, and for a more homogeneous survey strategy also emerge from our analysis.

KEYWORDS
tsunami risk, perception, communication, preparedness, awareness, Europe, neam, social science

1 Introduction

Tsunami risk is one of the most difficult risks to communicate and to deal with, for several reasons. The basic reason is that tsunamis are infrequent phenomena, and therefore citizens, local authorities, journalists, have a very limited knowledge of them. Even in the regions with the highest tsunami hazard worldwide, the recurrence of large, damaging tsunamis is low in comparison to other risks such as those related to extreme weather, forest fires, earthquakes. With a few exceptions, time intervals of damaging tsunamis in a specific coastal region of the world are of several decades, or even centuries. In the NEAM region (North East Atlantic, Mediterranean and connected seas), the occurrence of widely destructive tsunamis is very infrequent, and the latest of them date back to several decades.

Contrary to volcanic eruptions, landslides, earthquakes, storms, which affect mostly local communities, tsunamis can also spread their effects for hundreds to thousands of kilometers, also affecting people and countries very distant from the event origin point, and in areas where limited or no precursory signs of the incoming waves have been observed.

Another reason contributing to underrating the tsunami risk is the general belief that "small" tsunamis are not really dangerous. People often tend to identify the tsunami risk with the huge waves that occurred in Sumatra in 2004 or in Japan in 2011, while the occurrence of less relevant tsunamis (with one–2 m of runup) is neglected, even if these are by far more likely to occur than the abovementioned ones (Alam, 2016; Aytore et al., 2016; Constantin et al., 2017; Goeldner-Gianella et al., 2017; Cerase et al., 2019; Hall et al., 2019).

On the other hand, tsunami risk is also one such risk whose effects can be reduced more easily, at least those related to people's lives. Informed behaviors, like recognizing natural warning signs, knowing inundation areas and escape routes to reach high ground, recognizing official alert signs and sounds, *etc.*, are often sufficient to save lives. The same cannot be said for instance for seismic risk, that needs enforcing proper building codes, long times, and conspicuous funding to be reduced.

For the reasons above, it is extremely important to understand people's level of understanding and awareness of this risk, in order to define the best strategy for communication and prevention campaigns. With this goal, many studies on tsunami risk perception have been carried out in the past in several regions of the world. However, a comprehensive review that could allow a comparative analysis and define some common strategy for risk communication, is still missing.

The Centro Allerta Tsunami of the National Institute of Geophysics and Volcanology (CAT-INGV) operates as Tsunami National Warning Center (TNWC) for Italy, and as Tsunami Service Provider (TSP) within the ICG/NEAMTWS (Intergovernmental Coordination Group for North-Eastern Atlantic, Mediterranean and connected seas Tsunami Warning System), one of the four ICGs coordinated by UNESCO-IOC worldwide (UNESCO-IOC, 2015; UNESCO-IOC, 2017a; UNESCO-IOC, 2017b; Valbonesi et al., 2019; Amato, 2020; UNESCO-IOC, 2020; Amato et al., 2021; Basili et al., 2021). As such, its focus is on the NEAM region, which has similarities with, and differences from the other ICGs. Differently from the Pacific and the Indian oceans, where several countries facing the oceans have been hit by destructive tsunamis in the past few decades (like Japan, Indonesia, Thailand, Chile, United States, India, *etc.*), no large tsunamis have hit the Mediterranean or the Eastern Atlantic countries for more than half a century, and we have to go back to more than a century ago in the historical catalogs to find such a destructive event. In the XX and XXI centuries, the largest tsunami events in the Mediterranean occurred in Italy (Messina–Reggio Calabria, 1908) and in Greece (Amorgos, 1956). For the former event, it seems that its memory is still present among people living in the area, despite the long time elapsed, and this is important for defining a risk communication strategy. For many other regions in Italy, Greece, and other Mediterranean countries, the time distance from past tsunami events is so big that the risk perception is likely very low, and this poses a serious problem for risk communication.

Furthermore, due to the low frequency, scarcity of data, and complexity of the phenomenon, tsunami hazard and risk assessment are affected by a strong component of uncertainty, that also influences people's perception and risk communication (see e.g., Behrens et al., 2021; Lorito et al., 2022; Rafliana et al., 2022).

2 Risk perception, theoretical reference

Risk perception research is based on a multidimensional approach aimed at investigating the way individual and social factors shape intuitive risk judgments on which the majority of citizens rely on (Slovic, 1987; Wildavsky and Dake, 1990; Slovic, 2000; Rippl, 2002; Botterill and Mazur, 2004). This premise makes it clear how difficult and variable a risk perception analysis is. Risk perception studies, dealing with either natural or anthropogenic risks, are based on two main approaches: psychological and socio-cultural.

The psychological approach aims at producing general models of explanation of manifest behavior, attitudes, emotions and beliefs of individuals facing risks, focusing on perceptual processes and how they influence decision-making, attributing a priority value to cognitive processes and individuals' psychological dispositions (Weinstein, 1989; Cerase, 2017; Chionis and Karanikas, 2022).

The sociocultural approach (see, e.g., Douglas and Wildavsky, 1982; Lupton, 1999; Lupton, 2006), highlights the close connection between social structure in which individuals are embedded and their values, attitudes, and worldviews through which (whereby) people define and organize their knowledge of the world (Bradbury, 1989; Renn, 1992; Renn, 1998; Rosa, 1998; Lupton, 1999). Hence, social and institutional factors interacting with each other within a wide set of communication processes which take place through formal and informal channels (Renn, 1990; Renn, 2011). This means that individual risk perception, and hence, response to hazards, are affected by social influence exerted by the individual's surrounding context. The influence of sociocultural contexts on risk perception and disaster response has been stressed in countless anthropological and sociological studies within technological and natural hazard subfields (see, e.g., Krimsky and Golding, 1992; Tansey and O'Riordan, 1999; Boholm, 2003; Casimir, 2008; Tulloch, 2008; Zinn, 2009; Van Loon, 2013).

From here is defined that, risk perception is not a fully objective dimension; instead, risk is also a social construct: "what we measure, identify and manage as risks are always constituted *via* preexisting knowledges and discourses" that are strictly bound to the sociocultural contexts in which these understandings are generated (Lupton, 1999).

The term "risk," in the natural sciences, usually refers to an ontological–observer-independent–reality; a product of probability of an event and the resulting damage.

Therefore, risk perception patterns and the ways in which risks and disasters are managed are the results of social and cultural influences within different groups sharing common cultural values, moral principles and world views. Consequently, risks–and disasters–related notions may vary in time and space: what is considered a risk in a given era and place may no longer be seen so in a later period of time or in a different location (Tulloch, 2008; Field et al., 2012). Therefore, the mechanisms of individual risk elaboration strictly depend on reference social models and context; they are also moderated and filtered by the media that play an active role in the whole process.

As a consequence, while some risks with high probabilities and strong physical impact tend to be downplayed or neglected, some other risks with minor physical consequences may trigger strong public concerns and produce severe social impacts (Kasperson et al., 1998; Kasperson et al., 2003). Risk perception studies are deemed helpful to highlight and clarify what are the psychological conditions and sociocultural processes by which some of these risks are underrated whilst others are overestimated.

Susanna Hertrich's illustration (2008) graphically represents perceived risks as opposed to actual risks (Figure 1). Observing it, one can easily understand that risk perception is an extremely variable dimension influenced by both probability and severity of damages.

Risk perception is definitely a relevant issue for tsunami risk reduction. The way tsunami risk is perceived and understood may explain relevant differences in resilience and preparedness, both factors contributing to the different responsiveness of local communities (UNISDR, 2015).

This review is intended to trace back and analyze, in a simple way, several studies on tsunami risk perception that have been carried out in recent years. According to the very general definition

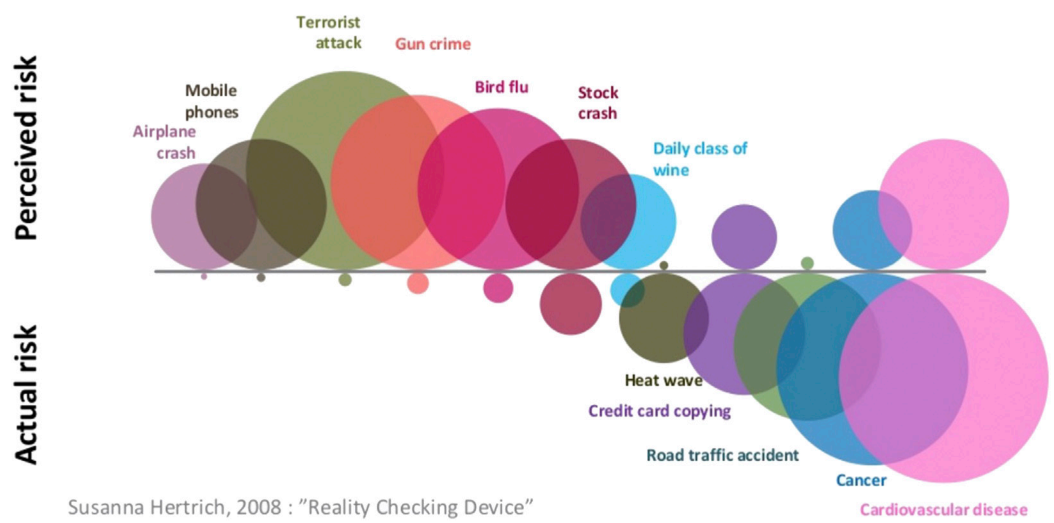

FIGURE 1
Comparison among different estimated vs. perceived risks. The circles' size below and above the horizontal axis are proportional to the "real" risk (estimated on a statistical basis) and the perceived one (estimated from perception studies), respectively. Modified from: *Risk perception and actual risk*. Image by Susanna Hertrich (2008) (based on the work of Dr Peter M. Sandman).

provided by the Royal Society, risk perception "involves people's beliefs, attitudes, judgements and feelings, as well as the wider social or cultural values and dispositions that people adopt, towards hazards and their benefits' where hazards were regarded as "threats to people and the things they value" (Pidgeon et al., 1992). The way risk is perceived by individuals and communities is held to be a relevant explanatory factor to forecast effectiveness of risk mitigation behaviors and possible impacts on a given socio-natural context (Lupton and Tulloch, 2003). "The understanding of risk perception is relevant to hazard prevention, risk management and safety enhancement in several ways" (Renn and Rohrmann, 2000; Rohrmann, 2000). However, risk is a multidimensional concept that cannot be synthesized into a single analysis model and theory (Tulloch, 2008). Hence, different disciplines studying the interaction between people and their context such as psychology, sociology, cultural anthropology and ethics are directly involved in studies on risk perception (Fischhoff et al., 1993).

3 Studies on tsunami risk perception

Tsunamis can cause casualties, along with property, infrastructure, agriculture and the environment destruction at a local, regional or global level. These phenomena are utmost elusive and highly challenging for risk perception scholars due their special characteristic such as low frequency, high uncertainty, non-linearity, extreme variability of impacts and the multiplicity of physical cause that might trigger one or more tsunamis (namely earthquakes, submarine landslide, volcanic eruption and even meteorological phenomena). These variables make it particularly difficult to address the way these phenomena are perceived and understood both at individual and societal level. These characteristics discouraged risk perception studies until the 2004 Sumatra Tsunami, where the unbearable burden of the 250.000 victims sparked a new interest in tsunami risk perception studies, aimed at improving both risk communication and the effectiveness of mitigation measures to reduce tsunami risk.

However, tsunamis' low frequency of occurrence does not reduce their destructive potential. Moreover, how important it is to study people's perceptions of natural hazards (Bonaiuto et al., 2016; Wachinger et al., 2013; Paton et al., 2009; Lindell et al., 2011), particularly tsunami risk perceptions, emerges in various studies conducted in at-risk countries that were affected by tsunamis, such as for example, the 2004 Indian Ocean tsunami or the 2011 Japan tsunami (Kurita et al., 2007; Sugimoto et al., 2010; Alam, 2016; Arias, et al., 2017; Akbar et al., 2020).

The primary goal of multidisciplinary paradigms underpinning risk perception research is to get a comprehensive understanding of the phenomena, also tackling fragmentary explanations and poor assessment of complex interactions between psychological, sociological, cultural and political dimensions of tsunami risk perception.

In this regard, this literature review compares research carried out in different geographical areas (from Oregon to Japan, through New Zealand and from Bangladesh to Australia and Europe) focusing on the population at tsunami risk.

Therefore, although the articles described in this study analyze people's perception of tsunami risk from various perspectives and methodologies, our review does not have an evaluative purpose, rather it aims to possibly provide an overview of the present literature to propose new study insights and data gaps.

Besides the suite of papers focused on the assessment of risk perception that we describe in this review, several other studies were carried out in the last 15 years, that deal with tsunami risk from the perspectives of preparedness, knowledge, awareness, evacuation, local culture traits, attitudes and practices in use in different regions (e.g., Paton et al., 2008; Achuthan, 2009; Paton et al., 2009; Bird et al., 2011; Goto et al., 2012; Esteban et al., 2013; Kanhai et al., 2016; Nakasu et al., 2018; Makinoshima et al., 2020; Martinez and Toulkeridis, 2020; Sutton et al., 2020; Tanner and Reynolds, 2020; Bailey and Mahutonga, 2021; Hawthorn et al., 2021; Lindell et al., 2022). However, we do not include these papers in our analysis as they are out of our review focus.

We have analyzed a total of twenty-three papers published on peer-reviewed scientific journals: seven in the Indian Ocean area, ten in the Pacific Ocean area and six in the Mediterranean area.

All the twenty-three papers analyzed here were published after the 2004 Sumatra tsunami, but mostly appeared in the last 5 years (see Figure 2).

The emerging highlights in the reviewed papers are addressed using a table of analysis which examines *strengths, weaknesses and lessons learned* from past events.

4 A meta-review of tsunami risk perception surveys and studies

As explained in the introduction, this meta-review aims to provide access to recent surveys on tsunami risk perception in several geographical areas that present significant differences (geomorphological, demographic, cultural, political, economic, and consequently have different levels of vulnerability) and to provide some insights on current directions in tsunami risk perception studies and their possible contributions to improve our understanding of social response to tsunami, thus improving risk governance. This required a great synthesis of the surveyed texts and, to facilitate the reading and the purpose of the work, just the core of each survey was extrapolated.

This paper examines twenty-three studies that we describe below, following the IOC-UNESCO worldwide organization of Tsunami Warning System ICGs,:

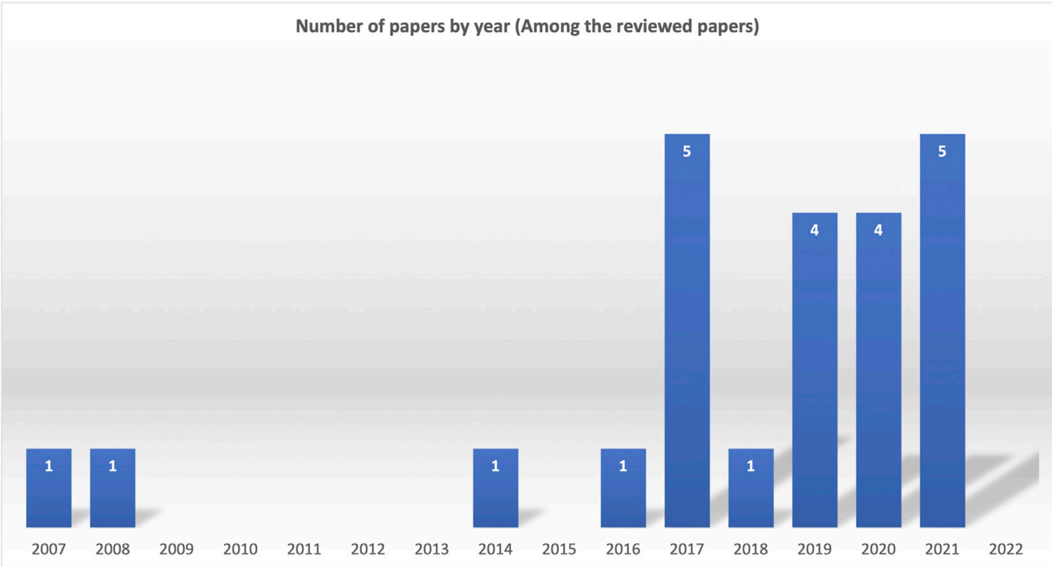

FIGURE 2
Number of reviewed papers by publication year.

- Seven surveys with focus on the Indian Ocean (IOTWS)
- Ten surveys with focus on the Pacific Ocean (PTWS)
- Six surveys with focus on the Mediterranean Sea (NEAMTWS)

The papers were selected by web search keywords by entering: Tsunami Risk Perception + the ICG competence area. The strictness of the search criteria did not allow the introduction of papers addressing perception from a multi-risk perspective or similar. In the following section, for each study we describe the basic elements and the main results, trying to retrieve the most relevant features and to identify common elements and differences.

4.1 Surveys conducted in the Indian Ocean–IOTWS

4.1.1 Regional characteristics of tsunami risk perception among the tsunami affected countries in the Indian Ocean

Study location: This study by Kurita et al. (2007) was conducted in Indonesia, Sri Lanka and the Maldives (Indian Ocean) which in 2004 were catastrophically damaged by the Indian Ocean tsunami (Kurita et al., 2007, Journal of Natural Disaster Science).

Tsunami local history: In Indonesia since 2000 to date (2022), there have been nine disastrous tsunamis that caused more than 173,000 casualties. The major tsunamis that affected Sri Lanka are 4 (1883, 1907, 2004 and 2005) with more than 35,300 casualties. The Maldives was recently affected by the 2004 tsunami that caused 82 fatalities and 24 missing (NCEI/WDS, 2022).

Sample and methods: The survey aims to study the tsunami risk perception among residents, students, teachers and government officials using a structured questionnaire trying to fill the gap in comparative studies among different areas affected by the 2004 tsunami.

The survey was conducted in different months of 2005 and collected around 1,000 interviews in each of the three countries above. The participants were selected by dividing the coastal zones and the questionnaire was randomly administered using an interview-style method. The local surveyors visited people at home, questioned them, and then recorded their answers on questionnaire forms.

Main results:

- A lack of prior knowledge concerning tsunamis among residents was a common trait in all three countries.
- Many residents in Indonesia indicated that the damage would not have been reduced, even had they been equipped with such knowledge in advance due to the extreme proximity to the tsunami source giving residents little time to evacuate.
- Respondents in Indonesia and Maldives answered that they would prefer to receive alerts through TV while in Sri Lanka respondents would like to be directly informed by their families and neighbors.

The paper includes some results from data collected in Simeulue Island where factors such as historical memory and conscious behaviors dramatically helped to reduce tsunami deaths. Reliance on oral transmission among Simeulue Islanders produced a contrasting result: most respondents said there was no need to introduce disaster education in schools. Conversely, in Nias Island, where the loss of life was much greater than in Simeulue, residents preferred that disaster education be introduced in schools.

Brief conclusion: The survey results show that both Indonesia, Sri Lanka residents and the government officials confirm how important it is to improve tsunami knowledge, receive adequate information about tsunamis, and to carry out evacuation activities supported by early warning systems.

4.1.2 Tsunami knowledge, information sources, and evacuation intentions among tourists in Bali, Indonesia

Study location: The survey assesses, through a multidisciplinary approach, the tsunami risk perception, knowledge, and evacuation intentions among tourists in Bali, Indonesia (Hall et al., 2019, Journal of Coastal Conservation).

Tsunami local history: Since 1900, the island of Bali experienced 5 moderate-sized earthquake induced tsunamis (in 1917, 1985, and three in 2018) and two volcanic eruption induced tsunamis (NCEI/WDS, 2022).

Sample and methods: The first part of the paper comprehensively reviews the existing literature on tourism managers' perceptions of natural hazards and tourists' expectations of tour operators. The survey on tourists' assessment of tsunami risk perception, perception of tsunami causes, tsunami knowledge sources, and evacuation intentions was developed with a pen/paper questionnaire.

Main results: Among the survey results, it is worth noting that:

- Most of the respondents reported that they had not learned about tsunamis while traveling to and within Indonesia.
- More than half of the respondents know about tsunamis through the media.
- Three-quarters of the respondents correctly believe earthquakes can cause tsunamis.
- Almost all participants said they would run to higher ground if a tsunami were approaching.

The results also show a higher time expectancy for evacuation. The model considered in the paper (Titov et al., 2011) shows that the time frame for an evacuation would be much shorter than tourists imagine.

Brief conclusion: The authors, concluding their analysis, note the lack of tsunami knowledge on about 3/4 of respondents traveling to Indonesia. Few of them claim to have learned information from the appropriate signs and even less from tour operators, reading material provided in travel, hotels or airports. Results suggest a need for education through channels more used by tourists in which simple explanations on correct behaviors in case of earthquakes should be provided.

4.1.3 Disaster Risk perception and household disaster preparedness: Lessons learned from tsunami in Banten

Study location: The survey has been carried out in the Pandeglang Banten coastal areas, Indonesia, which directly experienced the catastrophic Banten tsunami (Akbar et al., 2020, IOP Conference Series: Earth and Environmental Science).

Tsunami local history: The study area has been affected by many tsunamis throughout history. Most of them, especially recent tsunamis, were generated by volcanic eruptions or landslides (aerial or submarines) as the 2018 tsunami caused by the Anak Krakatau volcano eruption (NCEI/WDS, 2022).

Sample and methods: To develop the questionnaire items, the authors started with the dimensions used in two survey instruments: the Risk Perception Belief for disaster measurement (NSHRP) developed in 2012 by Yong (published in 2017), and disaster preparedness through a survey instrument used by the Indonesian Institute of Sciences (LIPI) and shared by UNESCO.

A structured Likert scale-based questionnaire with six response grades was administered for the survey. The questionnaire was administered to a non-probabilistic sample of 174 people living on the coast of Sumur district.

Main results: Survey results show a positive correlation between disaster risk perception and disaster preparedness. Data analysis also indicates that about three-quarters of households have good disaster preparedness, and the entire sample has a very good perception of risk.

Brief conclusion: The authors conclude their analysis noting that Pandeglang's families have a high perception of natural hazards in their area. This impacts their responsibilities, behavioral control, acceptance of living in an area prone to natural hazards and encourages communities to increase their preparedness and resilience.

4.1.4 Tsunami awareness and evacuation behaviour during the 2018 Sulawesi earthquake tsunami

Study location: The survey was conducted on the coastline of Palu City and Donggala Regency in the Sulawesi district of Indonesia after the 28 September 2018 Sulawesi earthquake and tsunami (Harnantyari et al., 2020, International Journal of Disaster Risk Reduction).

Tsunami local history: Sulawesi district has a long historical background of tsunamis. Since 1900 there have been 10 such events, eight of which were caused by strong earthquakes and two by volcanic eruptions (which occurred in 1918 and 1919). Of these, the 2018 tsunami caused the largest number of casualties and extensive damage (NCEI/WDS, 2022).

Sample and methods: The paper-based questionnaire was administered in the Palu and Donggala Regency residential area about 1 month after the event, between October 27th and 31st, 2018, concentrating interviews on the coastline of Palu City and Donggala Regency. 200 paper/pen questionnaires have been collected, following the same format of Chile and Indonesia research (Esteban et al., 2013).

Main results: All respondents (100%) are aware that they live in a tsunami risk area, this can be associated with recent tsunami experience, particularly the one of the 2004 Indian Ocean tsunami.

- Most respondents know that a strong earthquake could anticipate a tsunami.
- Most respondents answered that during the 2018 tsunami they evacuated because they saw someone else was evacuating.
- A lower percentage say they evacuated after they felt the strong earthquake.

Brief conclusion: The authors conclude their analysis noting that younger people have a lower tsunami risk perception, so education for action during an emergency needs to be increased. They also highlight the key role of social media in accelerating emergency communication. To some extent, this compensated for the lack of rapid official alerting. They also highlight the lack of effective evacuation plans and clear evacuation routes, that created congestion during evacuation.

4.1.5 Earthquake and tsunami knowledge, Risk perception and preparedness in SE Bangladesh

Study location: The study conducted by Alam (2016) explored the perception and preparedness for earthquake and tsunami risk in SE Bangladesh, including Chittagong city, the second largest city in Bangladesh with more than 6 million people.

Tsunami local history: Bangladesh has been affected by two major tsunamis: the 1762 tsunami, due to a strong earthquake in the northern Bay of Bengal, and the 2004 tsunami that caused two fatalities (NCEI/WDS, 2022) (Alam, 2016, Journal of Geography & Natural Disasters).

Sample and methods: The survey was carried out using different tools within a mixed methods approach: questionnaire; Focus Group Discussion (FGDs); informal interview for deeper understanding about general hazard perception and knowledge.

The survey consisted of two phases: the first cognitive phase, in which the lead author informally interviewed residents to structure the second survey phase.

The second survey phase included: twenty-five in-depth household interviews (15 male and 10 female) as they play the main role in economic activities and disaster response processes. Twenty informal interviews were conducted involving people indicated by local people as educated and influential respondents who better know about earthquakes and tsunamis. Five Focus Groups, two in each location with equal numbers of males and females in each group and with age over twenty-five were randomly selected.

Main results: Among the most interesting results are to be noted:

- Respondents show a widespread lack of knowledge about tsunamis. They also do not remember any damage or casualties caused by tsunamis or earthquakes.
- Low perception of risk and subsequent lack of preparedness to deal with these types of events.
- Lack of direct experience with earthquakes and tsunamis and more attitude to face more frequent hazards like tropical cyclones emerges both in focus groups and in the interviews.
- Lack of government and NGOs disaster risk reduction strategies for earthquakes and tsunamis.

Brief conclusion: The survey results show that people are aware of the low frequency of occurrence of earthquakes and tsunamis in their area and they have no recent experience with them. Therefore, they do not consider themselves personally at risk. Their faith in Allah increases fatalism, which leads them to not adopt proactive behaviors.

4.1.6 People's risk perception of tsunami hazard in a developing district of Balochistan, Pakistan: The case of Gwadar

Study location: The survey was conducted in Gwadar, a district of Balochistan in Pakistan (Mengal et al., 2020, Pakistan Geographical Review).

Tsunami local history: Pakistan was affected by strong earthquakes generated along the Makran Subduction Zone, off the southern coasts of Iran and Pakistan. Since 1900, the area has been affected by two strong earthquakes that have generated tsunamis. The largest being the 1945 event that caused about 4,000 casualties by both earthquake and tsunami (NCEI/WDS, 2022).

Sample and methods: The questionnaire used by Mengal is based on approaches adopted in similar studies conducted by Bird and Dominey-Howes (2008). In addition to the socio-demographic section, the questionnaire contains a section to study aspects of tsunami disaster management and to survey the emotional responses of the indigenous population living in Gwadar district. The survey collected 264 questionnaires administered by telephone and e-mail.

Main results:

- The interviewees, on average, show a high tsunami risk perception and are aware of the possibility that Gwadar district may be affected by a tsunami.
- Most of the respondents access disaster information preferably on their mobile phones, secondarily by TV, newspapers, internet, and lastly radio.
- A high percentage of respondents say that an earthquake may be the major cause of a tsunami. Few of them say a tsunami can be generated by landslides or volcanic eruptions.
- Most respondents cite mortality and human injury as among the major effects of a tsunami and imagine that their shores could be hit by tsunami with run-ups greater than 2 m and mostly between 5 and 10 m.

Brief conclusion: Since this is the first study on the topic done in the area, the survey aims to give a broad overview of tsunami risk perception in Gwadar due to the exposure of the area to tsunami hazard. The survey also aims to facilitate the creation of risk mitigation policies and management plans that can be implemented and easily used by the population.

4.1.7 Knowledge, awareness, and attitudes toward tsunamis: A local survey in the southern coast of Iran

Study location: The study carried out by the authors surveys respondents' knowledge, awareness, and attitudes toward a tsunami in four cities located in the Gulf of Oman in southern Iran: Chabahar, Konarak, Tis and Ramin (Salah and Sasaki, 2021, Sustainability).

Tsunami local history: Historically Iran has been affected by tsunamis generated in the Makran subduction zone but in the last 75 years no major events were recorded. Since 1945 there have been four minor events (1945, 1990, 2004 and 2017) the last of which was a meteo-tsunami. For the previous events, no casualties were recorded and damage was contained (NCEI/WDS, 2022).

Sample and methods: The survey uses a mixed method approach consisting of questionnaires, interviews among residents and beach users, and focus groups based on questionnaire results. In Chabahar city, 153 questionnaires were collected using random methodology (in densely populated areas). In Konarak city, 45 questionnaires were collected by locating inhabitants living in the tsunami-prone area by GPS method. In Ramin and Tis cities, 24 face-to-face interviews were surveyed. The 3 focus groups were conducted in fishing ports involving fishermen and beach-users.

Main results: The survey shows widespread low tsunami risk awareness among those who have basic knowledge of tsunamis. Lack of awareness and risk perception are associated by the authors with:

- Lack of information and absence of evacuation maps.
- Citizens did not receive or hear information about tsunamis from local government and other territorial agencies (NGOs, emergency department, local disaster management authority)
- Absence of community education programs.

Brief conclusion: In conclusion, the work shows a lack of trust in institutions, civil protection and warning systems increasing the vulnerability of the areas. According to the authors, such a lack of trust is associated with religious differences.

4.2 Surveys conducted in the Pacific Ocean (PTWS)

4.2.1 Testing the use of a "questionnaire survey instrument" to investigate public perceptions of tsunami hazard and risk in Sydney, Australia

Study location: The questionnaire administration was conducted in Sydney, Australia (Bird and Dominey-Howes, 2008, Natural Hazards).

Tsunami local history: Sydney city and Australia more generally are affected by many seismic sources surrounding it, capable of generating strong earthquakes and tsunamis. From 1900 to the present, Sydney tide gauges detected sea level changes for the 1960 Chile tsunami (for which historical sources report: Slight to moderate damage to boats in harbours at Evans Head, Newcastle, Sydney and Eden) and the 2011 Japan tsunami (for which, unusual currents have been observed in Sydney Harbor and Kembla) (NCEI/WDS, 2022; http://www.bom.gov.au/, last accessed on October 2022).

Sample and methods: The questionnaire was administered face-to-face to 30 participants and was also administered to a "captive group" consisting of environmental experts, engineers and insurers who deal with the risks, in order to have an experienced counterpart. The snowball sampling technique is used to obtain participants through the recommendation of other participants (Atkinson and Flint, 2001), which guarantees that all respondents are interested in the topic. The authors note that the survey tool developed is a baseline that must be implemented as needed, and in the article they suggest useful insights for the proper achievement of survey objectives.

Main results:

- Most respondents have heard about tsunamis before the Indian Ocean event (2004) even if they do not show scientifically in-depth knowledge of the phenomenon.
- All the respondents claim that earthquakes are the major cause of tsunamis followed by underwater volcanic eruptions.
- Most respondents say Sydney could be hit by a tsunami but few remember the last tsunami that affected the city.

Brief conclusion: The questionnaire implemented by the authors to study the tsunami risk perception shows to be an effective survey tool for those who want to deepen their knowledge and perception of tsunami risk perception in a study area. It is also an effective tool for collecting population data before implementing communication strategies and policies for tsunami risk mitigation. Moreover, this survey tool could be adapted to different contexts. They also recommend that the questionnaire should be integrated with in-depth interviews for better information and qualitative opinions from the population.

4.2.2 Tsunami risk perception and preparedness on the east coast of New Zealand during the 2009 Samoan tsunami warning

Study location: The survey was conducted in Tairua and Pauanui, on the east coast of New Zealand (Couling, 2014, Natural Hazards).

Tsunami local history: New Zealand is susceptible to being hit by tsunamis generated in different regions. Since 1900, 15 tsunamis have impacted New Zealand's coastlines. None of these have resulted in casualties but several damages have been recorded (NCEI/WDS, 2022).

Sample and methods: Qualitative data were collected using face-to-face interviews to produce the fullest possible description of evacuated residents. Participants were fifteen, selected using the snowball technique: nine females and six males, with an age ranging from early thirties to the eldest participants who were 95 years old.

Main results:

- Tsunami risk perception is generally very low or nonexistent ("the risk does not exist").
- Lack of knowledge of the natural signs of a tsunami and a lack of communication between the Ministry of Civil Defense and Emergency Management (2010) in New Zealand and citizens are evident.
- The respondents know that they must move to a high place if they receive a tsunami warning, but they do not know the phenomenon.
- Interviews also show that the population would not adopt a rapid evacuation for the reasons written above and because of low tsunami risk perception. Moreover, during the 2009 tsunami alert, there was a lot of traffic on Pauanui's main street, suggesting that residents wrongly thought they would run away with their vehicles.

Brief conclusion: The authors report that good communication between the institutions and the community is needed; in addition, the government must consider the official use of redundant communication methods that reach the population directly.

4.2.3 The low-likelihood challenge: Risk perception and the use of risk modelling for destructive tsunami policy development in New Zealand local government

Study location: The survey was conducted in three New Zealand locations: Gisborne, Hawke's Bay and Wellington (Crawford et al., 2019, Australasian Journal of Disaster and Trauma Studies).

Tsunami local history: The historical local tsunamis have been previously described (see Section 4.2.2).

Sample and methods: Survey methods included analysis of 58 official documents addressing risk management policies with the aim of identifying specific tsunami risk management policies. Twenty-three in-depth interviews, involving people with expertise in this type of risk, were then conducted in the 3 locations surveyed. The interviewees were also asked whether RiskScape risk modeling platform through proper communication was successful in increasing risk perception and stimulating the creation of effective tsunami risk management policies.

Main results: Text analysis reveals a paucity of risk-based policies for tsunami risk management. Out of fifty-eight documents analyzed, only three deal with tsunami risk. In-depth analyses highlight some important aspects including:

- A complex natural hazard management legislative environment.
- The scarcity of available natural hazard data and information and disconnection between science and policy.

Brief conclusion: Interviews also show that respondents trust RiskScape as a useful tool for communicating risk because it facilitates risk communication to a wide public. However, the authors remain uncertain about its usability and how much decision makers accept it among their management choices.

4.2.4 Assessment of households' responses to the tsunami threat: A comparative study of Japan and New Zealand

Study location: This is a comparative analysis between the towns of Christchurch in New Zealand and Hitachi in Japan (Wei et al., 2017 International Journal of Disaster Risk Reduction).

Tsunami local history: One of the countries most affected by tsunamis in its history is Japan. From 2000 to the present (2022), the catalog reports 36 events, of various magnitudes, for which sea level changes were recorded. Among them it is necessary to mention the 2003 tsunami (which caused two casualties) and the 2011 tsunami (which caused 18,428 casualties). Kamakura city was also affected by several historical tsunamis (NCEI/WDS, 2022).

Section 4.2.2 provides historical tsunamis that occurred in New Zealand.

Sample and methods: A total of 589 interviews (257 from Christchurch and 332 from Hitachi) were collected using a random sample. This survey was carried out based on the Protective Action Decision Model (PADM) (Lindell and Perry, 2012).

Main results:

- Several socio-demographic differences are present in the two surveyed communities (Higher average age in Hitachi than in Christchurch; larger families in Hitachi; longer average community tenure in Hitachi; and greater proximity to the coast for the Japanese community).
- Hitachi residents on average show a generally higher tsunami risk perception (tsunami expectation, city damage, city casualties) than Christchurch's ones.
- Significant difference in the arrival times expected by citizens of the two communities for a tsunami. Very short for Hitachi residents and longer for Christchurch.
- A positive correlation emerges between risk perception and evacuation attitude.

Brief conclusion: Risk perception is the best predictor of evacuation. This is positively correlated with hazard awareness, information sources, household size, and home ownership but is negatively correlated with proximity from the coast, income, and education.

4.2.5 Tsunami awareness and preparedness in Aotearoa New Zealand: The evolution of community understanding

Study location: The survey was conducted in Wellington, Wairarapa, Hawke's Bay and Gisborne in New Zealand (Dhellemmes et al., 2021, International Journal of Disaster Risk Reduction).

Tsunami local history: see Section 4.2.2.

Sample and methods: This is an evaluative study of tsunami risk mitigation initiatives carried out by various local agencies between 2003 and 2015. A similar questionnaire was administered, in the same area, before and after the initiatives. The questionnaire consists of 68 mostly closed-ended questions that explore: knowledge of tsunami hazard, risk perception, knowledge of mitigation actions and self-responsibility, preparedness to deal with a tsunami emergency and evacuation intentions. A total of 874 questionnaires, in paper-format, directly sent to households' mailboxes were considered valid.

Main results:

- In the ten Aotearoa communities, between both questionnaire administration phases, the general awareness and tsunami risk perception from 2003 to 2015 has increased.
- Respondents identify among the main risks that could affect the local community in 2015: earthquakes and tsunamis. In a 2003 survey, "coastal erosion" and "storms or cyclones" had a high percentage response rate.
- The three proposed scenarios (local, distant, and regional) show differences in preferred evacuation behaviors. In the local and regional scenarios would be by foot and in the distant tsunami scenario would be by car.
- The population's preferred warning methods include TV, Radio and sirens. "Earthquake" as a natural warning sign also received high response rates, indicating a good knowledge of the natural hazard that can trigger a tsunami.
- The education campaign to acknowledge the natural signs that can anticipate a tsunami's arrival (long strong shaking) positively increases the awareness that it is not necessary to wait for the official warning before starting the evacuation.

Brief conclusion: The survey showed an increase in respondents' risk perception and awareness of people living in a tsunami risk area. The authors encourage the creation of an official warning communication system that would reduce confusion around tsunami warnings.

4.2.6 A low-cost toolbox for high-resolution vulnerability and hazard-perception mapping in view of tsunami risk mitigation: Application to New Caledonia

Study location: The survey was conducted in New Caledonia, an archipelago of islands located in the South Pacific Ocean (Thomas et al., 2021, International Journal of Disaster Risk Reduction).

Tsunami local history: The population living in these islands is exposed to tsunamis threat generated by strong earthquakes, frequently higher than magnitude 7, like the events of 5 December 2018 (Maré, magnitude 7.5) and 10 February 2021 (Matthew Island, magnitude 7.7). From 1900 to date, 17 tsunamis induced by strong earthquakes are mentioned in the catalog. None of them have caused casualties.

Sample and methods: The research follows mixed methodology analysis with the aim of developing a set of quick-use tools named by the authors "low-cost toolbox." The toolbox contains several tsunami hazard assessment methodologies in a bundle, useful for two purposes: first, to facilitate decision makers to identify and quantify the population most exposed to tsunami risk due to living in vulnerable areas (using as few personal data as possible, for privacy reasons), and second, to survey the general public's tsunami risk perception. For this, a structured questionnaire was administered to a sample of 402 respondents. The authors aim to give the toolbox a local reproducibility in similar contexts.

Main results:

- The majority of New Caledonia's population lives between 0 m and 50 m above sea level.
- Mapping population distribution and building use patterns proves essential to develop ad hoc local tsunami risk mitigation policies.
- Many natives believe that tsunamis pose a real hazard to the islands indeed, revealing a higher tsunami risk perception than non-natives.
- Respondents widely believe that coral reefs and mangroves can mitigate the effects of a tsunami.

Brief conclusion: The study shows how important it is to integrate different methodologies into a single "low-cost toolbox" to obtain population mapping in relation to territorial characteristics and, together with population data, activate effective tsunami risk mitigation policies. The data on tsunami risk perception also show how important the historical transmission of past tsunamis is between native and non-native islanders. This has an important influence on tsunami risk perception.

4.2.7 Risk awareness and intended tsunami evacuation behavior of international tourists in Kamakura city, Japan

Study location: The survey was conducted in Kamakura city, Japan (San Carlos Arce et al., 2017; Safety Science).

Tsunami local history: see Section 4.2.4.

Sample and methods: The authors, before interviewing tourists, decided to provide background on the communication strategies implemented by the authorities. The survey design and the non-probability sample did not allow the data to be treated statistically, and consequently the survey results are not generalizable to the general population. The survey is based on a mixed method approach. Key informant interviews, on-site surveys and questionnaire surveys have been used to understand the risk awareness of this target. 163 structured questionnaire surveys were considered valid.

Main results:

- Most respondents know the natural signs that may precede a tsunami and that tsunamis constitute, together with earthquakes, one of the major natural hazards that could affect Kamakura.
- On average, respondents would not evacuate quickly.
- Most respondents said they had not seen or heard any information regarding natural hazards in Kamakura.
- Most respondents, following an earthquake, would evacuate.
- The issue of evacuation means also emerges. Many respondents would evacuate using public transportation, cars, or other means of transportation.

Brief conclusion: The authors report that good communication between the Disaster Prevention Offices and the Tourism organizations, both at the city and prefectural levels is needed. They also highlight the need to place evacuation signs in more visible places and unify the language and format.

4.2.8 Household risk perceptions and evacuation intentions in earthquake and tsunami in a Cascadia Subduction Zone

Study location: The survey was conducted in Seaside, a small town located on the coast of central Oregon (United States) (Buylova et al., 2020, International Journal of Disaster Risk Reduction).

Tsunami local history: North America is exposed to tsunamis generated from nearshore sources such as the Cascadia Subduction Zone (CSZ), as well as to tsunamis generated from very distant sources. The NOAA catalog reports 16 earthquake-induced tsunamis that affected the coastline since 1900 (NCEI/WDS, 2022).

Sample and methods: The research follows the PADM model stages starting from the socio-environmental variables to reach the behavioral intentions, through the psycho-cognitive aspects and the socio-demographic variables. A structured online questionnaire was administered to an initial sample of 944 households, out of which 211 were completed. As a result of factor analysis, two behavioral indexes were created: evacuation behavioral intentions and pre-evacuation behavioral intentions.

Main results:

- People who have participated in tsunami risk mitigation exercises, evacuation simulations or risk planning processes have higher intention to evacuate immediately in case of emergency and low intention to be engaged in pre-evacuation actions.
- Those who have been involved in or have had recent experiences of extreme events show greater risk perception and greater intent to engage in pre-evacuation behaviors and during evacuation.
- The study shows that the evacuation behaviors adopted are directly correlated with the risk perception and self-efficacy.
- The tsunami risk perception is influenced by: a) where respondents live (more or less close to the coast) b) physical preparedness that correlates with better self-efficacy attitudes c) confidence in basic tsunami knowledge.

Brief conclusion: The study shows that the application of the PADM model can provide a framework on pre-evacuation behaviors. The study also shows that there is no linear relationship between hazard knowledge and adopting conscious behaviors especially in an emergency. The study therefore suggests increasing the level of preparedness and self-efficacy as they contribute to increased tsunami response intentions and immediate evacuation.

4.2.9 Tsunami preparedness and resilience in the Cascadia Subduction Zone: A multistage model of expected evacuation decisions and mode choice

Study location: The survey was conducted in Coos Bay, Oregon and Crescent City, California (Chen et al., 2021, International Journal of Disaster Risk Reduction).

Tsunami local history: The historical local tsunamis have been previously described (see Section 4.2.8).

Sample and methods: This survey uses the PADM model to study tsunami hazard perception, tsunami hazard knowledge, effectiveness of evacuation methods and evacuation intentions of the coastal population surveyed. The sample consists of 483 respondents randomly selected: 258 from Coos Bay and 225 from Crescent City.

Main results:

- Almost half of the respondents report a moderate likelihood that a major earthquake (M9) will occur in the next 10 years and that it will cause fatalities and infrastructure damage.
- Respondents are confident in their perceived tsunami hazard knowledge, which is positively influenced by the evacuation drills previously conducted.
- Risk perception, perceived hazard knowledge, and perceived self-efficacy are directly related to some demographic variables and experiences (field experiences, drills).
- Evacuation intention is positively correlated with psychological variables such as: risk perception, self-efficacy, and knowledge of perceived danger; not related to socio-demographic variables and past experiences. This is consistent with the PADM model.
- Higher percentage of Crescent City residents would wait for an official warning and check social media before evacuating.
- Most of the respondents would prefer to evacuate by car. Significantly lower percentage by foot.

Brief conclusion: The study highlights how important it is to integrate different methodologies within a single survey tool to obtain a framework that allows effective tsunami risk mitigation policies to be developed quickly and without significant effort. Moreover, the tool developed by the authors is part of a toolbox that can be applied to other contexts with minor adaptations.

4.2.10 Hazard proximity and risk perception of tsunamis in coastal cities: Are people able to identify their risk?

Study location: The survey data were collected in Iquique, Chile (Arias et al., 2017, PLOS ONE).

Tsunami local history: Since 1900 Chile has been impacted by 25 tsunamis, caused by both local and distant sources (e.g., Japan 2011; Tonga 2022; *etc.*). Among the largest tsunamis that affected Chile it is necessary to mention the 1922 tsunami (which caused about 200 casualties), the 1960 tsunami (which caused over 2,300 casualties and extensive damage), the 2010 tsunami (which caused 229 casualties), and the 2015 tsunami (8 casualties) (NCEI/WDS, 2022).

Sample and methods: 487 interviews on earthquake and tsunami risk perception recorded in Iquique, were extrapolated from the 2,054 interviews collected by Bronfman et al. (2013) in a large face to face survey involving the Chilean population on assessment and perception of natural hazards, and trust in the institutions. The geographic coordinates of each respondent's residence were loaded into ArcGIS software and placed on the map to divide the respondents into 1) those living in the tsunami safe zone, 2) those living in the tsunami inundation zone.

Main results:

- People living in Iquique show a high and widespread tsunami risk perception.
- Data show no differences by gender.
- Among the most significant findings is a higher tsunami risk perception by young people (29 and younger) living in the risk zone than peers living in the safe zone. In general, elderly people have a higher tsunami risk perception.
- The socioeconomic status does not affect tsunami risk perception.

Brief conclusion: The positive correlation between tsunami hazard proximity and relatively high-risk perception emerges concurrently with some relevant factors such as inherited social memory of past events. Therefore, the memory of recent and non-recent events is alive and increases awareness and preparedness. Local authorities and experts play a key role in making people aware, keeping them informed and prepared for a tsunami warning.

4.3 Surveys conducted in the NEAM region

Not many studies on tsunami risk perception have been carried out in the NEAM region.

Most of them have been realized during the EU-funded project ASTARTE (Assessment, STrategy And Risk Reduction for Tsunamis in Europe, 2013–2016 (https://cordis.europa.eu/project/id/603839). We will briefly describe here some studies from this project that have been published either in peer-reviewed journals or in the project final report, available online (https://cordis.europa.eu/project/id/603839). Moreover, a few other analyses carried out in Italy in the last few years are described below.

One of the objectives of ASTARTE, a 3-year European Union-funded project from 2013 to 2016, was the assessment of tsunami risk perception. The goal was to identify key components of tsunami resilience and their implementation in the NEAM region. The study involved ten test sites where tsunamis have occurred one or more times in the past: seven on the Mediterranean coasts (Spain, France, Italy, Greece, Romania, and two in Turkey), two on the Atlantic coast (Portugal and Morocco), and one in Norway. All of these sites are exposed to earthquake-related tsunamis (Álvarez-Gómez et al., 2011) and several to eruptions of submarine and island volcanoes located in Italy, the Canary Islands, and Greece.

Among the surveyed topics, respondents were asked about their source of information (TV, school, newspapers, internet) and if the area where they lived could be affected by a tsunami.

Interviewees were also asked whether the government makes the right information about the tsunami risk and whether the natural hazard preparedness measures are satisfactory. The questionnaire, translated into nine different languages, also discusses evacuation plans and, in addition, respondents are given the opportunity, in a section of the questionnaire, to suggest how they can reduce the tsunami risk.

The project's output, regarding the study on tsunami risk perception and assessment of population preparedness, was published in some papers (Sections 4.3.1–4.3.3 below). whereas other studies are described in a report (http://194.117.20.221/index.php/deliverables.html– *D9.7–Report on preparedness skills, resources and attitudes within the communities*) that includes some unpublished work (Dogulu et al., 2014) and will not be discussed here.

More recently, tsunami risk perception studies have been addressed in Italy, where past tsunamis affected mainly southern Italy (Sicily, Calabria, Apulia, Campania and the islands of the Aeolian arc) but also the Ligurian coasts (in 1887) and the Adriatic (in 1,627, 1743, *etc.*). Given the widely recognized tsunami hazard and given the need to activate tsunami risk mitigation policies in a context of strong urban and coastal settlement development, CAT-INGV and Civil Protection have been supporting this type of community-based studies since 2018.

4.3.1 Perception of the risk of tsunami in a context of high-level risk assessment and management: The case of the fjord Lyngen in Norway

Study location: The survey was conducted in Norway between spring 2014 and autumn 2015 (Goeldner-Gianella et al., 2017, Geoenvironmental Disasters).

Tsunami local history: Norway experienced three major "rockslide tsunamis" in the 20th century (1905, 1934, 1936) causing a total of 174 victims (Harbitz et al., 2014). In the Norwegian county of Troms, the banks of the fjord Lyngen are highly exposed to a rockslide tsunami hazard.

Sample and methods: The survey used the ASTARTE questionnaire, with 99 random interviews collected in different places: 62.5% within Lyngseidet, 21% on the ferry crossing the fjord between Lyngseidet and Olderdalen, and around 17% in the neighboring villages.

The authors note that the small sample size and sampling methodology does not give statistical robustness to the survey to make it representative of the population.

Main results: Data analysis shows a widely high tsunami risk perception (rockslide-induced).

- Respondents associate the term Tsunami with the adjective "big" (40%) and the word "wave" (50%) and prefer to use the word "flodbølge" that translates as "a wave that causes flooding." Moreover they are aware that in their area a tsunami can be caused by a rockslide (55%) or an earthquake (25%).
- TV is the primary medium through which residents get most of their information about tsunamis, followed by school education and general media coverage, especially after the 2004 Indian Ocean tsunami.
- More than 30% of local respondents do not know how much time would be available for evacuation, are unaware that a warning system exists, and do not know how they would evacuate.

Brief conclusion: The warning and evacuation system installed in the past years thus does not appear to be sufficiently well-known and the population is not sufficiently prepared for evacuation. While citizens show a good level of trust in local institutions for how they manage the risk and for the dissemination of information in schools and among the local population. Tourists shows a lack of knowledge of tsunami risk due to a lack of information provided.

4.3.2 Perception and preparedness of the tsunami risk within the Black Sea (Romania) communities

Study location: The research was carried out in 2014 in Eforie Nord, in Romania (Constantin et al., 2017; Section Applied and Environmental Geophysics).

Tsunami local history: The Eastern side of Romania faces the Black Sea and the whole area is at risk of strong earthquakes that could generate tsunamis. Two strong earthquakes and a submarine landslide generated tsunamis that affected the Black Sea coast, including the strong 544 earthquake (M7.5), the 1901 earthquake (M7.2) and the landslide that occurred in 2007. Tsunamis have reached a maximum height of 2–3 m.

Sample and methods: The survey's goal was assessing the tsunami knowledge, the risk perception and the possible attitude to evacuate. The questionnaire was administered to eighty-four respondents of which 17% residents or people working in the area, and 83% tourists on vacation in the area, among whom 48% from Bucharest.

Main results:

- Tsunamis are not considered a major hazard by respondents, compared to earthquakes and storms. The majority of those mentioning tsunamis are tourists, describing the tsunami as a "big wave."
- TV is the major information source through which people get informed about the tsunami phenomenon, then the internet and the other mass media coverage that have spread images and descriptions after the great events of the Indian Ocean and Japan.
- Respondents consider sirens the best warning system and claim that exercises for natural tourihazards are not satisfactory. Moreover, in North Eforie there are no signals, warning systems or evacuation maps.

Brief conclusion: Tsunami risk perception is diffusely low and respondents are not aware of any tsunamis that have affected the area in the past.

4.3.3 La perception du Risque tsunami a sines, Portugal: De L'importance du paysage dans La perception sociale du Risque (in French)

Study location**:** Liotard et al. (2017) conducted a tsunami risk perception study in the city of Sines in Portugal (Liotard et al., 2017, Finisterra - Revista Portuguesa de Geografia).

Tsunami local history: Since 1900, Portugal has been affected by four tsunamis induced by strong earthquakes. These events caused small sea level changes. Although not very frequent, large-scale events have occurred in the past, such as the Lisbon tsunami of 1755.

Sample and methods: In addition to including questions reported in the questionnaire common to ASTARTE test sites, the authors used a photo-elicitation technique, consisting of showing four photographs illustrating different hazards on various coastal areas and asking if they can perceive any risk based on the images. A total of 133 people in Sines were interviewed including residents, workers, and tourists. 77% of the interviewed people work in Sines but do not live there. 86% of the total respondents lived in coastal areas.

Main results:

- The respondents classified the risk of a tsunami on the fifth position, after pollution, earthquake, explosion and storms.
- However, 71% of the respondents proclaim that a tsunami could affect Sines city again.
- The workers and inhabitants associate a tsunami with a destructive phenomenon.
- A significant result is that 51% of the respondents mentioned the school as their source of information about tsunami risk.
- The individuals have a relatively high level of knowledge about the precursory signs of a tsunami: 31% cited a seismic activity, 28.6% the sea retreat, while 17.1% mentioned an unusual animals' behavior. Moreover, 90% of the respondents would evacuate the beach in case of seismic activity.

Brief conclusion: Regarding the photo-elicitation method, the conclusion after analyzing the remarks provided by the respondents is that in general, they underestimate the risk of a tsunami, which are seen as a spectacular phenomenon and compared to typical ocean storms. For the coastline inhabitants, who are familiar with adverse weather phenomena or sea storms, it is problematic to distinguish tsunamis from the other coastal phenomena from the proposed images. The authors encourage increased knowledge that distinguishes the two different events and does not underestimate the tsunami risk.

4.3.4 Tsunami risk perception along the Tyrrhenian coasts of Southern Italy: The case of Marsili volcano

Study location: The survey was done on a non-probability sample of the population living in Campania, Calabria and Sicily (Italy) between 2015 and 2016 (Gravina et al., 2019, Natural Hazards and Earth System Sciences).

Tsunami local history: Southern Italy has been repeatedly hit by tsunamis in the past. The most recent events are the devastating 1908 Messina-Reggio earthquake-induced tsunami, and the damaging tsunami triggered by a volcanic collapse in Stromboli in 2002.

Sample and methods: The survey used a structured questionnaire consisting of five sections with open and closed questions aimed to analyze knowledge, perception, and citizens' opinions about the tsunami phenomena.

The 888 questionnaires collected (regarding respondents' estimate of tsunami arrival times) were compared with a tsunami scenario due to a Marsili seamount flank collapse elaborated by Mari and Gravina (2015).

Main results:

- Respondents show a widespread consciousness that a tsunami may occur.
- However, they also say that in case of a tsunami they would not know how to behave because of a lack of preparedness.
- A comparison of response percentage shows slightly greater preparedness in Campania than in Calabria and Sicily, possibly due to a drill carried out in 2013.

- Questionnaire answers underlined that participants address tsunami risk in the Tyrrhenian Sea as due to both submarine earthquakes and volcanic eruptions.

Brief conclusion: The research emphasizes the importance of designing adequate tsunami risk information campaigns and of helping the population to understand that tsunamis could be triggered not only by earthquakes, but also by landslides or volcano flank collapses, that could not be perceived by the population acting as precursors of tsunamis.

4.3.5 Tsunami risk perception in Southern Italy: First evidence from a sample survey

Study location: Cerase et al. (2019) investigated tsunami risk perception in coastal municipalities of two regions in southern Italy (namely Apulia and Calabria) (Cerase et al., 2019, Natural Hazards and Earth System Sciences).

Tsunami local history: As described in the previous Section 4.3.4, Southern Italy has been affected by several tsunamis in the past. Also Apulia had at least three tsunamis that occurred in the 17th and 18th century.

Sample and methods: The research was based on a stratified sample of 1,021 people, interviewed by telephone (CATI methodology), representative of about a total of three million coastal inhabitants.

The questionnaire consisted of 27 items with closed questions and Likert scales.

Main results:

- In both surveyed regions, tsunami risk is generally perceived as low, despite the high hazard.
- Risk perception appears to be influenced by both socio-demographic variables.
- However, the study highlights a remarkable difference between the two regions, highlighting the importance of the collective memory in risk perception.
- People appear to acknowledge that earthquakes are the most frequent cause of tsunamis, even though they consider volcanoes as another relevant source of tsunamis, possibly underrating landslides.
- An interesting finding is that the interviewed ignore or neglect the risk posed by small tsunamis, whose probability of occurrence is significantly higher than that of large tsunamis.
- Also, according to the respondents the words "tsunami" and "maremoto" refer to different phenomena, the first being associated with the televised imagery of Sumatra 2004 and East Japan 2011 events, whereas the word maremoto is more influenced by the memory of local past events such as the 1908 Reggio Calabria - Messina tsunami.

Brief conclusion: The collective memory is very important and needs to be kept alive. Many people do not understand the physical difference between tsunami waves and those due to normal sea storms, resulting in misleading assumptions about the real hazard posed by (even small) tsunamis. In risk communication, attention must be given to the terms used for describing the phenomena.

4.3.6 Tsunami risk perception in Central and Southern Italy

The detailed analysis of these surveys is ongoing and will be part of a comprehensive study (Cugliari et al., 2022).

Study location: The surveyed regions were Sardinia, Lazio, Molise, Campania, Basilicata and Sicily (Italy). Moreover, a national panel of about 1,500 interviews covering all Italian regions has been surveyed, in order to have a landmark of people representative of the Italian population, therefore including tourists visiting coastal areas for vacation.

Tsunami local history: see previous sections. Among the surveyed regions, there are relevant differences in terms of number and impact of past tsunamis. This is also shown by the tsunami hazard model of TSUMAPS-NEAM (Basili et al., 2021).

Sample and methods: Two surveys were carried out in 2020 and 2021 using the CATI methodology with the same questionnaire used for the study described above (Section 4.3.6), collecting 614 and 4,027 questionnaires, respectively. It was administered to a rigorously selected sample divided by proportional shares taking into account age, gender, education level, and coastal slope.

Main results:

- In general, about 40% of respondents believe that a tsunami can occur in the Mediterranean Sea. This percentage decreases among respondents living along the coast of the Adriatic Sea who for 60% believe that a tsunami cannot occur.
- Comparison of tsunami risk perception in metropolitan cities for the coastal reference side shows a general data alignment. Except for the city of Rome, which has a lower perception of risk than the Tyrrhenian slope on which it is located, and the city of Reggio Calabria, which shows a very high risk perception compared to the Tyrrhenian and Ionian coastal slope.
- The areas affected by tsunamis in the (relatively) recent past (such as the Tyrrhenian and Ionian coasts) still preserve a historical memory, handed down orally and revitalized by both the local and social media.
- Respondents with higher educational degrees would be more conscientious in case of a tsunami. Conversely, a lower educational level corresponds to insecurity and incorrect behaviors.

- Most of the respondents believe that tsunamis are mainly caused by earthquakes. Volcanoes represent the second possible cause of tsunamis. A higher percentage of responses on volcanoes were given by those living on the Thyrrenian coasts, due to the presence of Stromboli and Vulcano islands, and of submarine volcanoes such as Marsili and Palinuro Mts., often mentioned by the media.
- The comparison of tsunami risk perception (likelihood of a tsunami occurring in the Mediterranean Sea) surveyed through the national population sample (national panel) and the coastal sample (CATI) shows that perception is significantly higher among those living on the coast than the national average.

Brief conclusion: The study shows that people in general are aware of the possible effects of a tsunami. However, the knowledge appears to be influenced and distorted by the media. Historical memory of past events plays a key role in developing effective tsunami risk mitigation policies shared by the population. Conversely, the loss of historical memory of past events increases the difficulty of making the community aware of the hazard posed by tsunamis and makes mitigation interventions less effective. The study is also of fundamental importance for the development of the UNESCO Tsunami Ready program in Italy.

5 Comparative analysis of the surveys

In this review we have analyzed several studies dealing with people's knowledge and perception of tsunami risk. The series of papers analyzed in our study covers a period of about 15 years, the two major ICGs (Intergovernmental Coordination Groups) regions coordinated by UNESCO IOC, including the Pacific and the Indian Oceans TWS, and finally the NEAM region (North-East Atlantic, Mediterranean and connected seas). As described above, the twenty-three studies show heterogeneities, both in the methodology used to assess people's perceptions and in the sampled population, number of respondents, *etc.* As a result, survey outputs, being projections of different territories and various socio-cultural contexts, also appear heterogeneous in their different approaches to studying tsunami risk perception.

However, some relevant similarities and differences emerge, and allow us to draw some first conclusions on people's attitudes towards tsunami risk, also suggesting some future directions both for designing similar studies, and for applying the results of the current literature in the definition of communication strategies.

In Table 1. We synthetically resumed the information listed in Section 4, as to provide a quick overall view of the whole considered papers, based on the methodology being used, sample characteristics, past tsunami history at local/regional level, points of strength and *weakness*, and above all the most important *lessons to be learned*.

15 out of the 23 considered papers used only questionnaires as a survey tool (69,6%). The questionnaires–structured, semi-structured, were administered in different modalities (pen/sheet, by mail, by phone, *etc.*). 6 studies out of 23 rely on mixed methods (26,1%) integrating both quantitative and qualitative methods such as surveys with qualitative method such as "in-depth interviews"; "focus groups"; "document analysis"; "GIS data" and so on, whereas strictly qualitative methods such as the semi-structured in-depth interview has been used in only one paper (4,3%).

Most of the papers have dealt with residents, only four surveys involved tourists. 6 out 23 papers (about one-third) rely on a mixed method approach, combining different types of data (both quantitative and qualitative) to throw light on blind spots emerging from the field and to get the best out from the research. Finally just a single paper relies solely on qualitative methods (in-depth interviews).

As mentioned above, the strong heterogeneity of samples and methods prevents a comprehensive evaluation of people's perception of tsunami risk worldwide. However, in order to have a synthetic view of the responses, framing the highlights emerging in the analyzed papers, we chose to employ a table of analysis that allows us to summarize the s*trengths*, the w*eaknesses and* the lessons learned of risk perception studies.

This table is reported here to stimulate future in-depth analysis and surveys on tsunami risk perception (Table 1). The result of the table of analysis in the three outputs, could encourage to use existing survey methods or to create new ones, e.g., it could stimulate the creation and validation of a commonly recognized tsunami risk perception index, or stimulate the creation of a repeatable analysis model that may be used in longitudinal studies. The highlights in the table are simple, concise commonalities noted in the literature review.

Among the *strengths* evidenced in the analyzed papers, we note 1) an increase of risk perception studies over time, starting after the 2004 Indian Ocean tsunami and particularly in the last 5 years; 2) the interest in testing and combining different methodologies to assess tsunami risk knowledge and perception as to get a more comprehensive picture of tsunami risk perception and understanding; 3) the presence of a larger number of studies in high hazard regions, where tsunami events have occurred in a recent past. On the other side, points of *weakness* include 1) the lack of a shared theoretical framework and in turn of repeatable research designs for this kind of study; 2) the lack of a consistent design of the study among different ICGs; 3) some weakness in methodological approach, and 4) some poorly statistically representative samples.

Along with strengths*, opportunities* and *lessons learned,* this review allowed us to point out some relevant points,

TABLE 1 Tsunami risk perception research: Review table.

Reference	Method	Sample	Place	Tsunami history	Strenght	Weakness	Most important lesson to be learned
Kurita et al. (2007)	Survey	3000 interviews	Indian Ocean (Sri Lanka, Maldives, Indonesia)	Since 2000 to date, 9 tsunamis in Indonesia. 4 in Sri Lanka and Maldives was affected by 2004 Indian Ocean Tsunami (IOT)	First large-scale survey; data highlight Simeulue as a relevant matter of interest	Descriptive statistics, does not provide explanatory model	Lack of pre-existing knowledge about tsunami, also from civil protection officers
Hall et al. (2019)	Survey	Stratified sample, 304 interviews (tourist from 40 countries)	Indian Ocean (Bali, Indonesia)	Since 1900, 5 earthquake induced tsunamis and 2 volcanic eruptioninduced tsunamis	Investigates tourist's risk perception and their sources of information andknowledge	Subsamples were too small to have convincing data on single countries	Lack of available information sources on place, prior knowledge in their home country
Akbar et al. (2020)	Survey	174 interviews (victims of 2018 Sunda tsunami in Bantan)	Indian Ocean (Bantan district, Indonesia)	Many historical tsunamis, in 2018 Sunda strait tsunami caused by the Anak Krakatau volcano eruption	Considers people affected by a recent tsunami event	Questionnaire items are neither presented nor discussed, research is only on aggregate indicators	"The higher disaster risk perception of a person, the higher disaster preparedness level"
Harnantyari et al., (2020)	Survey	197 valid interviews	Indian Ocean (Sulawesi, Indonesia)	Since 1900 there have been 10 events (8 caused by strong earthquakes, 2 by volcanic eruptions)	Considers people affected by a recent tsunami event, investigates individual response andmitigation measures	Official tsunami warnings failed to reach residents; road congestion resulted in further difficulties to evacuate (near- field tsunami)	High level of tsunami awareness, sometimes coming with a low understanding of phenomena. For 82.5% evacuation was triggered by witnessing others evacuating (imitation)
Alam (2016)	Mixed methods(quantitative / qualitative)	30 interviews+ in-depth interviews	Indian Ocean (Bangladesh)	1762 earthquakeand tsunami and 2004 IOT	Joint use of different methods	Small, non-probabilistic sample	Low risk perception, religious based fatalism
Mengal et al. (2020)	Survey	264 interviews	Balochistan, Pakistan (Gulf ofOman)	2 strong earthquake and tsunamis. In 1945 the largest	Considers information source and individual ability to address risk	Strong gender polarisation in sample, women were not allowed to participate survey	Strong use of smartphones as information source, individual ability to compare tsunami with other risk sources
Salah and Sasaki (2016)	Mixed method	153questionnaires + in-depth interviews	Southern Iran (Gulf of Oman)	Since 1945 4 minor tsunamis events	First survey in the area; relevance of survivors of past tsunami experience	Sample size (low number of cases)	Lack of awareness, low risk perception, role of religion, low trust in institutions
Bird and Dominey-Howes, (2008)	Survey	30 interviews	Pacific Ocean (Sidney, Australia)	Sea level changes for the 1960 Chilean tsunami and 2011 Japan tsunami	It is focused on the development and improvement of questionnaire surveys on tsunami risk perception	The very small sample can only validate tool, it is not consistent and useful to draw sound conclusions about respondents' risk perception	Low level of risk perception and knowledge on tsunami; most of respondent never heard about it before 2004 event. Authors recommend using also qualitative interviews
Couling (2014)	Semi-structured interviews (qualitative approach)	15 interviews	Pacific Ocean (North Island of New Zealand)	Since 1900, 15 minor tsunamis impacted New Zealand	Author adopts a qualitative approach, thus obtaining a rich figure of people's understanding of tsunami	The low number of respondents is unfit to generalize conclusion, researcher bias can affect results	Very low or non-existent Tsunami risk perception; relevant misbeliefs about tsunami physics an anticipatory sign; low level of preparedness (prompt evacuation); imperative need to improve risk communication and community engagement
Crawford et al., (2017)	Mixed methods (Semi-structured qualitative interviews + document analysis)	23 interviews	Gisborne, Hawke's Bay, and Wellington regions (New Zealand)	Since 1900, 15 minor tsunamis impacted New Zealand	The research is focused on the way tsunami risk is perceived by citizen and on their	Selection criteria being applied to interviewees are not clear	Tsunami risk communication is not able to provide a realistic account of phenomena and its consequence; people are

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TABLE 1 (*Continued*) Tsunami risk perception research: Review table.

Reference	Method	Sample	Place	Tsunami history	Strenght	Weakness	Most important lesson to be learned
					expectations on risk mitigation policies		stressed by long return period and high uncertainty and not motivated to change their way of life; visual risk communication (Risk Scapes) might be very effective
Wei et al., (2017)	Survey	589 valid interviews, 257 in Christchurch city (New Zealand) and 332 from Hitachi city (Japan)	Christchurch (New Zealand) Hitachi city (Japan)	For New Zealand see above. In Japan from 2000 the catalogue reports 36 events. The majors in 2003 and 2011	Comparative approach, rigorous research design and use of statistical methods, including logistic regression	Possible biases in sample composition, data presentation is somewhat redundant and might be not clear for non-specialists	Research is based on a consistent theoretical model; significant differences between Hitachi and Christchurch with
Dhellemmes et al. (2021)	Survey (Comparative approach, panel study)	874 completed questionnaires	Ten different communities in New Zealand East Coast	Since 1900, 15 minor tsunamis impacted New Zealand	Research duplicates previous research to address changes occurred over time	Questionnaires were self- administered thus involving the possibility of condescending and biased responses	Data show a dramatic increase in tsunami risk perception from 2003 to 2015. EQ and tsunamis are recognized as the main risks that could affect the local community in 2015, whereas coastal erosion and storms were most feared in 2003
Thomas et al. (2021)	Mixed methods (GIS data, dasymetric population maps, rapid field interviews	12 interviews	New Caledonia (Pacific Ocean)	From 1900 to date, 17 earthquake- induced tsunami are mentioned in catalogue	Survey is based on seven questions, both closed ended and open ended: risk perception survey is combined with GIS data	The application of the "low- cost toolbox" built upon survey and GIS data appears to be a bit less straightforward than expected	Most people live between 0m and 50m above sea level. Risk perception data and GIS combination can help tailoring ad hoc risk mitigation policies. Natives hold that tsunamis are real threats, also considering reefs and mangroves as natural defence against tsunami effects
San Carlos Arce et al., (2017)	Mixed methods (key informant interviews, field visits, analysis of risk communication strategies and field surveys)	163 valid questionnaires (survey) on tourists	Kamakura City (Sagami Bay, Japan)	In Japan from 2000 the catalogue reports 36 events. The majors in 2003 and 2011	Survey is based on both closed ended and open- ended question, providing a further opportunity to explore emerging qualitative issues; tourists being recognized as a relevant group	Results are not necessarily generalizable to all of Japan, and sample composition could not reflect the actual variability and composition of the reference universe	Increased awareness on tsunamis, just few respondents are able to identify potential tsunami risk and self-evacuate; lack of viable risk information in the city
Buylova et al., (2019)	Survey	211 completed questionnaires	Cascadia Subduction zone (Seaside, Oregon, United States	From 1900 to date the NOAA catalogue reports 16 earthquake- induced tsunamis	Rigorous research design and use of statistical methods, including Ordinary Least Squares (OLS) regression analysis	Possible biases due to small number of responses, survey nonresponse errors, and measurement; data presentation is somewhat redundant and might be not clear for non-specialists	Research is based on a consistent theoretical model. People engaged in risk planning and exercises are more likely to evacuate and less willing to be engaged in pre-evacuation actions. People who experienced extreme events have higher risk perception. Research confirms a significant connection between risk perceptions, self-efficacy, and behavioural outcomes

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TABLE 1 (*Continued*) Tsunami risk perception research: Review table.

Reference	Method	Sample	Place	Tsunami history	Strenght	Weakness	Most important lesson to be learned
Chen et al. (2021)	Survey	483 completed questionnaires (258 from Coos Bay, 225 from Crescent City)	Cascadia Subduction zone (Coos Bay Peninsula, Oregon; Crescent Bay, California, United States)	From 1900 to date the NOAA catalogue reports 16 earthquake- induced tsunamis	Rigorous research design and use of statistical methods, including Ordinary Least Squares (OLS) regression analysis, binary logistic regression analyses	Possible biases due to small number of responses, survey nonresponse errors, and measurement; data presentation is somewhat redundant and might be not clear for non-specialists	Research is based on a consistent theoretical model; survey results show that more than 40% of the sample believes a moderate likelihood that a strong earthquake might occur in the next 10 years. Respondents are confident in their tsunami hazard knowledge, being positively influenced by previous evacuation drills. Risk perception, hazard knowledge, and self-efficacy are affected by bothdemographic variables and past experiences
Arias et al. (2017)	Survey	487 interviews	Pacific Ocean (Iquique, Chile)	Since 1900, Chile has been impacted by 25 tsunamis. The majors were 1922, 1960, 2010 and 2015	Authors consider together several variables, including socio-economic status, inherited social memory of past events, distance from coastal borders	Despite the quality of research design, authors did not manage to find causal relationship between relevant variables	Hazard proximity proved to be a relevant factor in risk perception; memory of past events increases awareness and preparedness
Goeldner-Gianella et al. (2017)	Survey	99 face-to-face interviews	Lyngen Fjiörd (Norway)	Norway's rockslide tsunamis in the 20th century (1905, 1934,1936)	Paper comes from wider research on Natural Hazards (ASTARTE). It tries to integrate quality within a mostly quantitative approach	Small, non -probabilistic sample (respondents were randomly approached in different places)	Local population has clear perception of tsunami hazard, related to rockslides and trust local institutions; lack of available information for tourists
Constantin et al., (2018)	Survey	84 face-to-face interviews	Eforie (Black Sea, Romania)	544, 1901 Shabla EQ and Tsunami, 2017 submarine landslide	Paper comes from wider research on Natural Hazards (ASTARTE)	Small, non -probabilistic sample (respondents were randomly approached in different places)	Preparedness level is average: some are well informed and aware of tsunami hazard, while others know about tsunami only from movies. Locals are less informed about tsunamis in comparison to tourists, regarding some aspects. Lack of knowledge is associated to the low level of education
Liotard et al., (2017)	Mixed methods (Survey + photo elicitation)	84 face-to-face interviews (locals, workers, and tourists)	Sines (Atlantic Ocean, Portugal)	Since 1900, Portugal experienced sea level change by 4 tsunamis. The 1755 Lisbon EQ and Tsunami was the major in itshistory	Paper comes from wider research on Natural Hazards (ASTARTE)	Small, non -probabilistic sample (respondents were randomly approached in different places)	Relatively high level of knowledge about the precursory signs of a tsunami; 9 out of 10 interviewees are likely to evacuate the beach in case of a strong earthquake.Photo-elicitation method suggests that people are uneasy in understanding differences between tsunamis and sea storms
Gravina et al., (2019)	Survey	888 respondents across three Thyrrenian regions	Randomized sample of three Italian Thyrrenian Regions (Campania,Calabria and Sicily)	1783, 1887, 1905 and 1908 Messina Reggio EQ and Tsunami triggered by the volcanic eruption from Hellenic Arc (Stromboli 2002)	Research stress the importance of designing effective tsunami risk communication campaigns to help people population to understand tsunamis	Research considers a hypothetic event which has been subjected to a wide media coverage across the time. This aspect is not discussed	Although respondents are conscious about the probability of a tsunami event only few knew how to neither properly behave in case of an event nor consider themselves prepared to face a tsunami wave

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TABLE 1 (*Continued*) Tsunami risk perception research: Review table.

Reference	Method	Sample	Place	Tsunami history	Strenght	Weakness	Most important lesson to be learned
Cerase et al. (2019)	Survey	1021 respondents	Stratified sample of people living in coastal municipalities of two Southern Italian regions (Apulia and Calabria)	1783, 1887, 1905 and 1908 Messina Reggio EQ and Tsunami triggered by the volcanic eruption from Hellenic Arc (Stromboli 2002)	Paper is based on a large sample research and considers together several variables including socio- demographic, geographic and cultural	Research provides a general descriptive account through mono and bivariate analysis	The paper highlights a generally low tsunami risk perception, and different understanding of the phenomena under the label "Tsunami" and "Maremoto". Relevant differences emerge in risk perception emerge from different coastal areas. Finally, people totally ignore or neglect the risk posed by small tsunamis, supposed to be more frequent in those areas. Television is the main source of information, while scientific sources appear to have a very limited impact
Cugliari et al. (2022)	Survey	5842 respondents	Stratified sample of people living in coastal municipalities of eight Italian coastal regions, representative of more than 12 million people	1783, 1887, 1905 and 1908 Messina Reggio EQ and Tsunami triggered by the volcanic eruption from Hellenic Arc (Stromboli 2002)	Paper is possibly based on the largest sample for this kind of research. It continues the research published by Cerase et al, 2019 extending and widening it with a more stratified sample to increase statistical robustness	Research provides a general descriptive account through mono and bivariate analysis	The paper confirms a low tsunami risk perception as well as a different understanding of the phenomena under the label "Tsunami" and "Maremoto". Coastal areas affected by tsunamis in the recent past preserve a historical memory and have higher level of risk perception. The tsunami risk perception by coastal side in some cases differs from the perception surveyed in metropolitan cities that subsist on the same side (Rome, Reggio Calabria). The tsunami risk perception of the wide national panel (Telepanel) is lower than the perception detected in coastal areas

among which 1) the chance to involve citizens and tourists in areas where recognition programs (such as Tsunami Ready) are going on; 2) the need to increase young generations' awareness on tsunami risk; 3) the opportunity to develop some robust synthetic indexes measuring risk perception.

Finally, it is worth mentioning 1) the widespread lack of correct policies for dealing with tsunami risk; 2) the low trust in public institutions; 3) the presence of a fatalistic attitude, eventually due to religious believes; 4) the low interest of local authorities in facing the tsunami risk, considered as not likely to occur, not important or too difficult/costly to face.

6 Discussion

In order to mitigate the impact from future tsunami events, besides improving monitoring and alerting systems, it is necessary to study the way tsunamis are perceived and to understand the "last mile" segment of the warning chain. A correct response of people to both natural and official warnings is fundamental to reduce the tsunami risk.

The review presented in this paper highlights some relevant points related to people's perception of tsunami risk and the way in which this kind of research can be useful for risk management. First, before planning tsunami risk mitigation actions, governments, stakeholders and local administrations should analyze tsunami risk perception and place it in context by identifying the distinguishing traits of local cultures. In fact, our review shows that tsunami risk is not homogeneously perceived, past experience and cultural aspects playing an essential role in shaping the way tsunamis are perceived and understood. Therefore, studying tsunami risk perception within different geographical, social, political and local contexts is, at the same time, a necessary and indispensable means to achieve an effective implementation of local (and intergovernmental) mitigation actions.

Second, as we have seen in this review, tsunami risk is not homogeneously perceived even within the same community, as it is affected by different socio-demographic variables such as gender, age, education level, average income and presence of children in the household/family (see Alam, 2016; Wei et al., 2017; Akbar et al., 2020; Buylova et al., 2020; Dhellemmes et al., 2021), as well as hazard proximity and social memory of past events (see Fraser et al., 2016; Arias et al., 2017; Cerase et al., 2019; Cugliari et al., 2021; Cugliari et al., 2022). These variables are directly or indirectly related to social stratification (e.g., owning a house close to the coastline) as well as to particular risk cultures or worldviews co-existing in the same society (e.g.: egalitarian, hierarchical, individualists and fatalists) (Mamadouh, 1999; Douglas, 2007) which are likely to result in significant differences within a given population; in general, we can hypothesize that those who feel to have more to lose have a higher risk perception than those who feel to have less, thinking to be safe from tsunamis. Furthermore, these differences could be very difficult to understand by people with limited access to scientific knowledge (Cerase et al., 2019; Cugliari et al., 2021; Cugliari et al., 2022) and by some target populations such as tourists from other countries that have never experienced or even heard about such events and may be totally unaware of tsunami risk in their holiday locations, thus requiring additional resources to develop effective risk mitigation strategies (Arce et al., 2017; Hall et al., 2019).

Third, tsunami risk perception is in part related to psychological features of individuals, and in part to local cultures. Different local cultures may provide both a set of correct information about natural signs that may anticipate the arrival of a tsunami wave, and other cultural artifacts such as legends, stories as well as a set of shared norms about proper conducts to be held, and some criteria to address individuals' responsibility and accountability. Such norms do not lie exclusively on scientific expertise and are always consistent with wider conceptions of social goods, as these always embody somewhat cultural and normative conception of what is held to be considered morally, aesthetically, or logically acceptable/desirable (Kluckhohn, 1951). Consequently, different cultures may develop different ways to represent tsunamis and act accordingly: it can be seen as an inescapable act of God rather than a call for individual action (even in apparently extreme forms such as the Tsunami-tendenko[1] in some coastal areas of Japan, see Yamori, 2014; Nakasu et al., 2018).

In general terms, the cultures which are more likely to face a tsunami event within few generations or those who have experienced large damages, deaths and disruption due to a large event tend to develop stronger and more consistent set of responses, that may involve both spontaneous sharing of knowledge about tsunamis, and institutional responses (e.g., evacuation drills, educational programs and ad-hoc disaster risk mitigation programs to increase awareness and resilience) Rahman et al., 2017. It should be also considered that some physical features of tsunamis (e.g., the hazard posed by small waves) are not understood in the same way and in some cases people are uncomfortable to believe scientists as their understanding of such a physical phenomenon does not match with native explanations, which are often based on analogies (e.g., storm waves/ tsunami waves) or on media portrayals of past big tsunamis such as those of Sumatra 2004 and East Japan 2011.

Finally, some methodological considerations on social research should be kept into account, as sample size, research design, and questions' formulation could heavily affect validity and reliability of data. In general terms, the type and the size of the investigated sample and the research design are very important if one wants to avoid reaching misleading conclusions. As an example, small samples and snowball sampling should be used only to get a first descriptive analysis of risk perception but are unfit to draw causal explanations of key factors and, of course, should not be used to ground disaster risk mitigation measures in larger areas. Furthermore, the way to set up structured surveys and quantitative social research may reflect researchers' approach in setting up the research problem rather than the point of view of people who are asked to respond, thus downplaying or neglecting possible relevant factors (e.g., local culture, familiarity and native knowledge) that may have a pivotal role in drawing a comprehensive and satisfactory description and explanation of the considered phenomena.

1 In Japanese, tsunami-tendenko refers to the "everyone her/himself" mentality, which requires a quick tsunami evacuation without waiting for others, even one's own parents or children.

7 Conclusive remarks

The review presented in this paper reveals many interesting aspects of the tsunami risk perception worldwide. As a general starting point, we can say that most of the cases reported here point out the low consideration of tsunami risk by people living in the coastal areas, independently from the region of the world and from the frequency of past tsunamis. There are some exceptions to this, especially in areas where recent tsunamis have occurred (Arias et al., 2017; Thomas et al., 2021). Also people's recent experience of other extreme events (different from tsunamis) determines a better attitude towards mitigation actions and correct response, particularly when the impact of these events on the interviewees has been strong (Buylova et al., 2020).

In general, it appears that in many regions the risk posed by "small" tsunamis is strongly underrated. It has been observed in many cases that even tsunamis with instrumentally measured runup of less than 1 m could generate important inundation and severe damage, as happened for instance in Turkey and Greece with the Samos-Izmir event of 30 October 2020 (Dogan et al., 2021). It seems that the collective image of tsunamis is dominated by the huge inundations provoked by the 2004 and 2011 tsunamis in Indonesia and Japan and broadcasted worldwide. The impact of small tsunamis (i.e., 1–2 m runup) is certainly lower than the mega-tsunamis just quoted, but it is not negligible. Moreover, these events are certainly more frequent than the giant ones. In Italy, after the surveys conducted by Cerase et al. (2019) and Cugliari et al. (2022) particular attention has been given to this concept in the communication with stakeholders, students, and citizens.

Somehow related to this, another interesting aspect emerging from different studies is the use of the term "tsunami" (as known, a Japanese language term) and of other terms traditionally used in the local language, such as for instance "maremoto" in Italian and Spanish (Cerase et al., 2019), or "flodbølge" in Norwegian (Goeldner-Gianella et al., 2017). Although tsunami scientists prefer to use the word *tsunami* for any type and size of the phenomenon, it seems that people prefer the local term. Also, they tend to associate the word *tsunami* to a giant wave (or series of waves), while the local term is considered more familiar and the phenomenon less dangerous.

Another common aspect emerging from our analysis is the importance of memory in people's perception of tsunami risk (Arias et al., 2017; Wei et al., 2017; Cerase et al., 2019). In this sense, the need for frequent drills has emerged in several areas (Gravina et al., 2019; Buylova et al., 2020; Chen et al., 2021), as important tools for stimulating the response of citizens towards the tsunami risk.

The perception of tsunami risk appears to be modulated depending on several socio-demographic characteristics, but there is not a homogeneous behavior among different countries or even nearby cities (Kurita et al., 2007). Cerase et al. (2019) find a positive correlation between education level, risk perception and adopted behaviors, but other authors in different countries do not (Wei et al., 2017).

Another important matter emerging from some of the analyzed studies is the recognized importance of the so-called "natural warnings" that come before or along tsunami events, and the need to make people aware of them. It is clear to the scientific community that for local tsunami sources, especially for those generated by earthquakes occurring along faults very close to the coasts (near-field tsunamis), the time of response must be very short, less than 5 min. The recent case of the Palu, Sulawesi tsunami in 2018 (Harnantyari et al., 2020) and the Samos, Greece, event of October 2020, as well as other past events, such as the 1908 Messina Strait one, demonstrate the need for a rapid and effective response by the population in the very few minutes after the onset of the seismic event, that should be independent from (or better complimentary to) the response expected in case of official warnings (alerts from civil protection authorities). This can be reached with a correct and continuous education of the population to face the tsunami risk.

Another element emerging from some of the studies analyzed here is the importance of traditional media, mainly TV, as the main source of information for people (New Zealand, Italy, Romania, Norway), and as one of the preferred ways to receive alert messages (Kurita et al., 2007; Cerase et al., 2019; Dhellemmes et al., 2021).

From the methodological point of view, we note the lack of a common strategy for evaluating people's awareness and perception of the risk. The twenty-three papers analyzed in this review use different methodologies and samples, not always representative of the whole population exposed at tsunami risk. The majority of the studies investigate local communities, and only a few papers deal with tourists (Arce et al., 2017; Constantin et al., 2017; Liotard et al., 2017; Hall et al., 2019). This is a drawback of this type of studies, since many of the regions under study are vacation destinations, in which the population increases by an order of magnitude during the summer season. In the Italian case, besides residents, we have also started to sample citizens living in non-coastal regions of Italy by administering the questionnaire (as in Cerase et al., 2019) to a national panel representative of the Italian citizens living all over the Country, thus including tourists traveling to the seaside in the summer (Cugliari et al., 2022). However, more detailed studies with specific target population groups are being planned, especially in complex contexts such as the Stromboli volcano, where both a multi-risk (volcanic explosions, tsunamis) and a multi-source tsunami risk (from flank collapse, landslide, pyroclastic flow) must be faced.

Finally, the analysis presented in this review reveals a strong heterogeneity in the adopted methodological approaches and in the sampled population, making it difficult to compare the results among different regions and situations. A more standardized approach in this type of studies would allow a more comprehensive assessment of tsunami risk perception worldwide.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Fighting misinformation in seismology: Expert opinion on earthquake facts vs. fiction

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Misinformation carries the potential for immense damage to public understanding of science and for evidence-based decision making at an individual and policy level. Our research explores the following questions within seismology: which claims can be considered misinformation, which are supported by a consensus, and which are still under scientific debate? Consensus and debate are important to quantify, because where levels of scientific consensus on an issue are high, communication of this fact may itself serve as a useful tool in combating misinformation. This is a challenge for earthquake science, where certain theories and facts in seismology are still being established. The present study collates a list of common public statements about earthquakes and provides–to the best of our knowledge–the first elicitation of the opinions of 164 earth scientists on the degree of verity of these statements. The results provide important insights for the state of knowledge in the field, helping identify those areas where consensus messaging may aid in the fight against earthquake related misinformation and areas where there is currently lack of consensus opinion. We highlight the necessity of using clear, accessible, jargon-free statements with specified parameters and precise wording when communicating with the public about earthquakes, as well as of transparency about the uncertainties around some issues in seismology.

KEYWORDS
misinformation, Earth science, seismology, earthquakes, risk communication, scientific consensus, expert elicitation, crisis communication

Introduction

Misinformation is considered one of the most pervasive threats to individuals and societies worldwide (Lewandowsky et al., 2017; Lewandowsky and van der Linden, 2021), impacting topics from politics (Allcott and Gentzkow, 2017; Guess et al., 2019; Lee, 2019; Mosleh et al., 2020) to pandemics (e.g. COVID-19) (Jolley and Paterson, 2020; Lobato et al., 2020; Roozenbeek et al., 2020), and seismology is no exception. From false earthquake "predictions" during the L'Aquila (Alexander, 2014) and Christchurch (New Zealand Herald, 2011a; 2011b; Griffin, 2011; Wood and Johnston, 2011; Johnson and Ronan, 2014) sequences, to terrorist plots in the United States (Hernandez, 2016), misinformation about earthquakes has been demonstrated to have severe, real-world consequences.

Several methods of combating misinformation have been proposed, including the use of algorithms to prevent misinformation from appearing on social media platforms (Calfas, 2017; Elgin and Wang, 2018; van der Linden and Roozenbeek, 2020), correcting misinformation *via* fact checking or "debunking" approaches (see Lewandowsky et al. (2020) for a best practice guide), building psychological resilience to misinformation *via* psychological inoculation or "prebunking" (e.g., McGuire, 1970; Compton, 2013; Van der Linden and Roozenbeek, 2020), and legislative approaches that regulate the content that media outlets post online (e.g., United Kingdom's Online Safety Bill (Woodhouse, 2021); Germany's Network Enforcement Act (Bundesministerium, 2017). Further, Dallo et al. (2022) recently published a communication guide on how to fight the most common myths about earthquakes specifically; available in English and Spanish.

Key to being able to implement many of these approaches, however, is an understanding of the types of potentially misinformative statements that are common in public discourse, and a clear scientific consensus (which we define following (Myers et al., 2021) and in line with the Cambridge, Merriam Webster and Oxford dictionaries as 'general agreement') on the state of knowledge regarding the "real" truthfulness or reliability of these statements in the domain in question (Dallo et al., 2022). Indeed, where levels of scientific consensus on an issue are high, communication of this fact may itself serve as a useful tool in combating misinformation. Maibach and van der Linden (2016) write that perceptions of scientific agreement act as an important determinant of public opinion and "communicating the scientific consensus about societally contested issues. Has a powerful effect on realigning public views of the issue with expert opinions." (p. 2).

This is a challenge for earthquake science (e.g., seismology and geology). Some domains have relatively high and, indeed, quantified, degrees of scientific consensus on the likelihood of a hypothesis being true (for example the high scientific consensus that climate change is anthropogenic (Oreskes, 2004; Cook et al., 2013; Maibach et al., 2014; Myers et al., 2021) or that COVID-19 is not caused by 5G phone masts (Grimes, 2021). Earthquake science however, is a fairly young and active field where certain theories and facts are still being established. The opinions amongst scholars on certain aspects of earthquake science are still actively and openly debated. Additionally, different ontologies, paradigms and epistemologies within science itself mean that scholars come to the table with a range of backgrounds and ways of collecting and interpreting data, which ultimately influence the way they communicate their science (McBride, 2017). What complicates earthquake communication further is the diversity of phenomenology and terms used, e.g. tremors, quakes, shocks, seismic events. Further, there are semantic differences between languages. In English for example, prediction is used for precise, deterministic statements and forecast for probabilistic ones. In comparison, in Nepali, only one word exists, and this refers to deterministic predictions (Michael and McBride, 2019). Thus, a precise distinction between deterministic prediction and probabilistic forecast can be made in some languages, but not others.

As such, a key first step to combating misinformation about earthquakes is to understand the range of perceptions scientists have about earthquake science, why they hold these views, and what the level of scientific agreement or consensus on these topics is. The present study collates a list of common publicly-made statements about earthquakes from our daily experiences communicating with the public and workshops with the earth science community [see Dryhurst et al. (2022) for workshop synthesis]. It provides–to the best of our knowledge—the first elicitation of the opinions of 164 earth scientists on the degree of "truthfulness" or otherwise of these. It therefore addresses the research question, "what is the expert consensus regarding 13 common statements about earthquakes?".

Materials and methods

Using a combination of desk research, workshops with the earth scientist community and exchanges on daily communication experiences between the authors [see Dryhurst et al. (2022) for workshop synthesis], we first collated thirteen statements about earthquakes that are commonly queried and/or misunderstood by the public (Figure 1).

Between 15th and 22nd March 2021, we then surveyed 164 earth scientists (n = 75 geophysicists, n = 47 geologists, n = 26 seismologists, n = 13 engineers, n = 1 science communicator, n = 1 physicist) studying earthquakes occurring across six continents. The survey was hosted on Qualtrics (Qualtrics, 2017) and participants were recruited *via* a selective snowball sampling method (Parker et al., 2019); the authors contacted expert colleagues *via* the mailing lists of two European Horizon 2020 projects (RISE and TURNkey) and *via* personal networks in the United States, New Zealand and

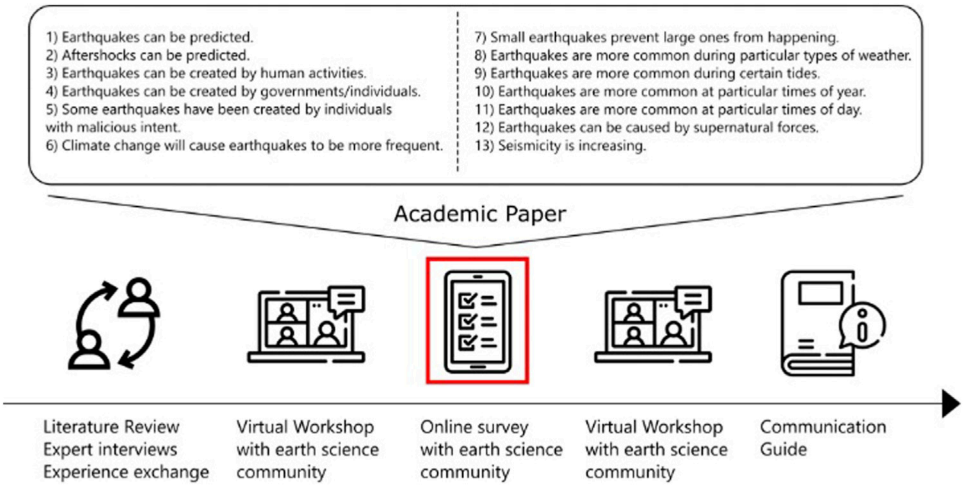

FIGURE 1
Overview of the project activities that the online survey was embedded in, as part of Phase 3 of the project. Includes a literature review, expert interviews (Phase 1), a virtual workshop with earth science community members (Phase 2), an online survey with the earth science community (Phase 3), Virtual Workshop with earth science community (Phase 4), and a communication guide (Phase 5).

Europe, asking if they would fill in an online survey and pass it on to further expert earth scientist colleagues upon completion.

To measure their level of consensus about the truth or falsehood of the thirteen statements, participants were asked to rate each statement on a Likert scale (Joshi et al., 2015) from 1 = Completely true to 7 = Completely false, with an eighth option available for “Undecided”. Percentage consensus ratings of truth or falsehood for each statement were calculated as the proportion of participants choosing each answer option. Mean ratings of truth or falsehood and associated standard deviations for each statement were also calculated, excluding participants who answered “Undecided”.

Several of these statements were purposefully ambiguous in aspects of their phrasing, to keep them true to the way such statements are commonly phrased in public discourse. This allowed us both to garner the responses of earth scientists to misinterpretations that have “real-world” validity, and raise awareness amongst this community of the nature of such misinterpretations.

Participants were also given the option to add written comments about their rating of truth or falsehood for each statement in turn. These qualitative data leant important context to the quantitative ratings, helping identify those statements for which there is a reasonable level of consensus, and the qualifiers and caveats that reveal issues about which there is still open debate and uncertainty amongst the scientific community. The qualitative analysis of these data for the purposes of this paper is based on one round of coding using an emic/inductive process, as outlined by Daymon and Holloway (2002), to which all authors contributed. Statements 1, 2, 4, and 5 were coded in NVIVO (Bazeley and Jackson, 2013; statements 3, 6, 7, 10, 11, 12, and 13 were coded in Excel (Meyer and Avery, 2009); and statements 8 and 9 were coded using QDA Miner (Lewis and Maas, 2007). Different programmes were used because multiple team members undertook the coding, then a master spreadsheet was provided so that all coders could upload their data, cross-check the codes other people were using, and apply those codes to their own coding schedule if applicable.

This project was reviewed by the University of Cambridge Psychology Research Ethics Committee (No: PRE. 2021.018).

Results and discussion

A visual summary of the proportion of participants choosing each rating of truth or falsehood for each statement can be seen in Figure 2.

Statements about earthquake creation

- “Earthquakes can be created by human activities”
- “Earthquakes can be created by governments/individuals”
- “Earthquakes can be created by individuals with malicious intent”

The results relating to the three statements about earthquake “creation” suggest high levels of consensus on the reality of some earthquakes being triggered by human activities such as fracking,

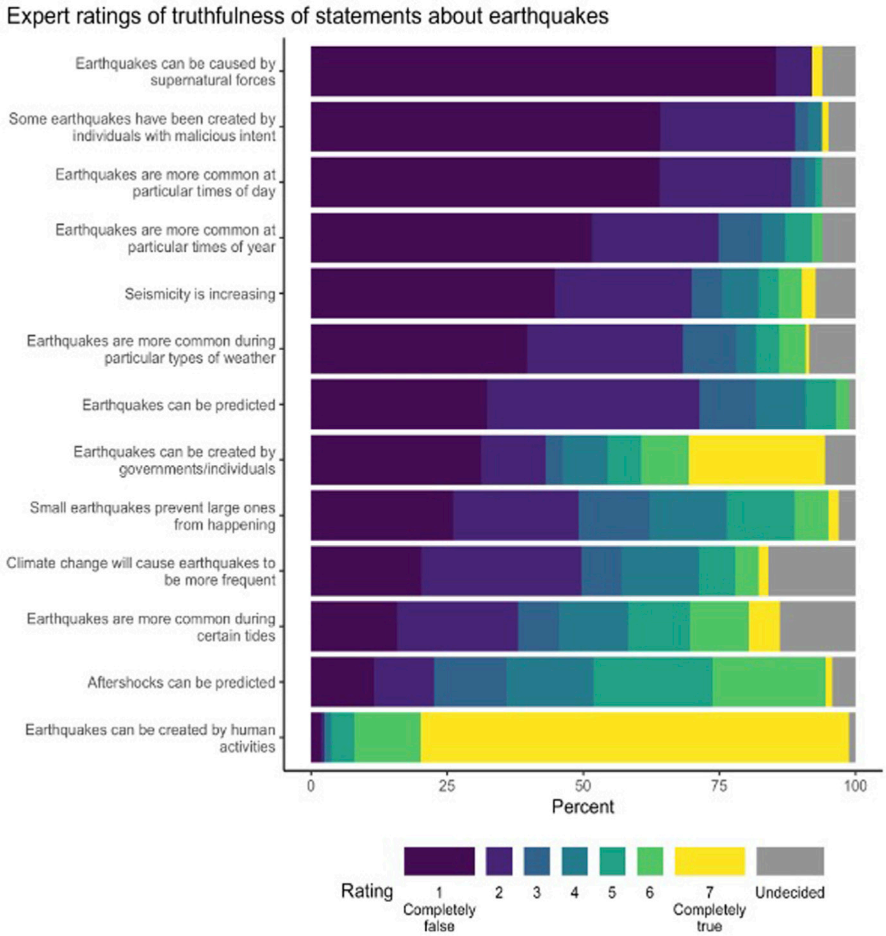

FIGURE 2
Proportion of participants choosing each rating of truth or falsehood for each statement in turn, from 1 = Completely false to 7 = Completely true, including in grey the proportion choosing "Undecided". Statements are ordered by the proportion of participants choosing answer option 1 = Completely false.

waste-water disposal and mining (Ellsworth, 2013) (90.9%, n = 149 chose rating 6 or 7 at the completely true end of the 1–7 rating scale). There was also substantial doubt over the prevalence of such triggering being used with malicious intent. Relatedly, the results highlighted the importance of avoiding intent-based and potentially conspiratorial language such as "created" in communications about human-induced earthquakes and moving towards more neutral wording such as triggered or induced. This would reduce the ambiguity of the statements and consequent variation in their (mis)interpretation. For example, one participant noted "Earthquakes can be induced (directly produced) or triggered by human activities . . . I would not use the word "create" in this context though".

The statement "Earthquakes can be created by governments/ individuals" was particularly ambiguous to participants, as demonstrated by some interpreting it to mean something nefarious (e.g. "I don't think that government or individuals would dare to use seismicity as a kind of weapon, and it would be very hard"), and others simply as another way of saying that human activities, including those that governments can commission, (e.g., wastewater injection) can trigger earthquakes [e.g., "I do not understand the question. It seems to be the same question as the previous question (about human activities)"].

Statements about prevalence and causes of earthquakes

- "Earthquakes can be caused by supernatural forces"
- "Earthquakes are more common at particular times of day"
- "Earthquakes are more common at particular times of year"
- "Earthquakes are more common during particular types of weather"

- "Seismicity is increasing"
- "Small earthquakes prevent larger ones from happening"
- "Earthquakes are more common during certain tides"
- "Climate change will cause earthquakes to be more frequent"

Overall, the perceptions of statements about the prevalence and causes of earthquakes were varied among our participants. There was a high level of consensus that earthquakes are not caused by supernatural forces (92.1%, $n = 151$ chose rating 1 or 2 at the completely false end of the 1–7 scale), although the proportion of participants who were undecided in their rating of this statement was not insubstantial, at 6.1% ($n = 10$). Looking in more depth at the qualitative comments from participants, several (11) found the term "supernatural forces" ambiguous. One wrote, for example, "I do not even know what you are talking about", whilst another wrote "Supernatural forces???? What does it mean?". Another flagged that human activities such as fluid injection might be considered supernatural in that they are "man-made". These comments again highlight the need to be clear in the use of language used in communication.

It is notable that several (7) respondents detailed that the supernatural does not fall within the remit of science. One wrote, for example, "supernatural forces are not within the tools and scope of science. If someone believes in supernatural forces – science cannot overrule his belief". This separation of science from the supernatural may explain why some scientists rated the statement as truthful, or indicated that they were undecided in their response. One participant who rated the statement as completely true explicitly stated their religious beliefs: "As a Christian I believe in a creator who controls the physical laws at all times and in all places". Another participant who recorded their response as undecided also touched on religious ideas, but more as reasoning for why some might invoke supernatural forces such as an act of God in their search for an explanation (evidenced in Joffe et al., 2013), especially during a period of trauma such as loss during an earthquake: "Although seismologists declare knowledge of the inner workings of a quake, it does not change the fact that, for people at the site of a quake, there is a feeling of supernatural power and, arguably, fury and wrath, especially given the destruction and loss of life that quakes are capable of. So, I do not know that you can honestly falsify the statement "earthquakes can be caused by supernatural forces" without simply asserting that there are no supernatural forces, to which someone who just watched their apartment building fall down and crush their whole family is going to say, "Yeah, then who is responsible for that?!" (*who* not *what*)". Another "undecided" participant described how "supernatural forces are unknown unknowns [and] it is unknown how they interact with earthquakes". All these comments suggest that a separation between science and faith in discussions and communications about earthquakes might be useful.

There was also a reasonably high level of consensus in the falsehood of the statement "earthquakes are more common at particular times of day" (88.2%, $n = 142$ chose rating 1 or 2, 6.2%, $n = 10$ were undecided), although some participants did note possible links with tides (see below) and the fact that induced seismicity is more likely to occur during the day. The size of this consensus on falsehood dropped to 74.8% ($n = 122$) as the timeframe over which this statement was expressed increased to a year; whilst the majority still think the statement is false, some acknowledge that the statement is plausible, although several note that if such effects exist, they will be small and not of concern. For example, "I would say this is false for large earthquakes, but seasonal loading from e.g., rain in the monsoon can affect stresses which have been shown to modulate small scale seismicity". This highlights that qualifications, including specifying the parameters of each statement (e.g., timeframe, size of geographic area, size of effect), will be important to lend clarity to communication of earthquake related information, although it is important that such qualifications are in formats that will be interpretable by public audiences without domain expertise.

A similar majority rating of falsehood without a clear consensus also occurred for the statements "earthquakes are more common during particular types of weather" (68.3%, $n = 112$ chose rating 1 or 2, 8.5%, $n = 14$ were undecided) and "seismicity is increasing" (70%, $n = 114$ chose rating 1 or 2, 7.4%, $n = 12$ were undecided). For the latter, qualitative comments suggest some of this variability in expert opinion again comes down to ambiguity in how the statement is phrased. Some participants noted that their answer would be different depending on whether one is talking about shorter timeframes, where there may be increases in seismicity due to periods of heightened seismic activity, or longer timeframes, where there is likely no such pattern (e.g. "In order to define an increase in seismicity one needs to be aware of the relevant time window of analysis."). It was also noted that the answer would differ if talking about human triggered versus "natural" earthquakes, where for the former there may be an increase in local seismicity where activities such as fracking are taking place (e.g. "Natural seismicity varies, but is not increasing. Man-made seismicity has increased significantly due to fracking and geothermal operations."). These are all important parameters to specify in order to improve clarity when communicating to the public about this particular issue (for example that an individual may experience an increase in the number of earthquakes in their location because of an earthquake event "triggering" further events, but that this is not the case on average globally, or over much longer geological timeframes), and again highlights the importance of such precision and specification in the wording of these communications more generally. It is interesting to note that several participants thought that people might perceive that seismicity is increasing due to improved recording of, and communication about, earthquake events in recent years.

There was a low level of consensus about the statement “small earthquakes prevent larger ones from occurring” (49.1%, n = 79 chose rating 1 or 2, 3.1%, n = 5 were undecided), although this may again stem from imprecision in the phrasing of the statement, where no detail on the specifics of what constitutes a “small” earthquake (e.g., magnitude) or on time frames was given. Interestingly, some noted that the word “prevent” regarding the incidence of earthquakes incorrectly implies that it is possible to reduce seismic hazard levels to zero and suggested using terms such as “delay” instead, to reduce the likelihood of such misinterpretation of communications (e.g., “They do not “prevent”. Having frequent small earthquakes may decrease the probability of observing a larger one in certain tectonic settings, but we cannot speak of “preventing”, and speaking of “preventing” gives the public the wrong impression.”).

Arguably, one of the lowest levels of consensus for any of the statements considered was for the statement “earthquakes are more common during certain tides”, where ratings were distributed more evenly across answer choices than for most other statements. This lack of consensus was further evidenced by a substantial minority of participants who were undecided in their rating (13.9%, n = 22). Several qualitative comments suggested that tides can cause stress changes in the earth’s crust, but that would only trigger small events (e.g., “Holds true I think for smaller earthquakes – not large”). Since the statement itself was not specific about the nature of the earthquakes in question (e.g. size), this might have resulted in variation in interpretation of the statement, and thus could explain some of the variation in participant responses. Some comments also suggest that this is a topic still debated within the community and that evidence is contradictory (e.g.“Trick question. This is still being debated in the community. Tides do cause tiny stress changes in the Earth crust, and local variations in earthquake activity have been found that appear to correlate with tidal changes. But does correlation mean causality -- the debate continues!”), which may also help explain the lack of consensus on the statement; openness about this uncertainty in communications with the public on this topic will likely be key, especially where the state of knowledge may be set to change (van der Bles et al., 2020; Batteux et al., 2021; Kerr et al., 2021; Schneider et al., 2021).

Participants appeared most uncertain about the statement “climate change will cause earthquakes to be more frequent”, with 16% (n = 26) remaining undecided in their rating. There was also a low consensus on falsehood (49.6%, n = 81 chose rating 1 or 2). The level of uncertainty about this statement was also apparent through the qualitative comments, where hedge words such as “might” and “can” were used by some [although others were more deterministic in their language (“will”)]. This appears to be an area, that is still actively debated and researched, however there were suggestions in these comments of a variety of indirect links between climate change and earthquakes, such as increased rainfall, changes in lithostatic pressure and an increase in geological pressures from alternative energy use such as geothermal. Nevertheless, many participants suggested that climate change induced earthquakes would relate to local stresses and not larger tectonic processes [e.g., “Not generally. However, some localised consequences (small quakes) associated with isostatic rebound in polar areas (due to large/broad-scale loss of ice cover) could occur.”]. Once again, clarity about parameters, size of effects and transparency about the uncertainty in expert opinion will likely be key to public communication on this issue.

Statements about earthquake prediction

- “Earthquakes can be predicted”
- “Aftershocks can be predicted”

There was a lack of strong consensus on the truth or falsehood of the statement “earthquakes can be predicted”, although the majority of participants did choose ratings 1 and 2 at the “completely false” end of the rating scale (71.3%, n = 117). The statement “aftershocks can be predicted” had lower levels of consensus, with answers distributed more evenly across options than for the former statement. For example, 22.6% (n = 37) chose ratings 1 and 2 at the “completely false” end of the 1–7 scale, whilst 21.9% (n = 36) chose ratings 6 and 7 at the “completely true” end of the scale. In both cases, several qualitative comments highlighted that it is not possible to predict earthquakes or aftershocks in a deterministic way that gives exact information about upcoming earthquake events, but that probabilistic forecasting of such events, notably aftershocks, is possible (e.g., “We can’t currently predict earthquakes but we can forecast earthquakes.”). It should be noted that some participants took issue with the word “aftershock” when it comes to forecasting, since such a determination cannot be attributed *a priori*.

In turn, several comments for both statements highlighted the ambiguity in the meaning of the word “prediction”—whether it was probabilistic or deterministic—which likely explains the variation in quantitative ratings even where qualitative comments seem to imply a reasonable level of agreement (e.g., “I interpreted your use of the term “prediction” as the deterministic establishment before the event actually takes place of its exact place, date and time. If, instead, by “prediction” you meant a probabilistic estimation, then my answers above would have been very different.”). Forecasting versus prediction has a rich and complex history in earthquake science, as explored in Michael and McBride (2019), and our results here underline the necessity of clearly explaining the meaning of such words, and perhaps even avoiding the word “predict” entirely in communication.

Nevertheless, communicating probabilistic information in a comprehensible way is challenging; everyone, whether or not they have high levels of domain expertise, has a propensity towards bias in judgments involving statistical information, that is, presented in certain ways (e.g., Tversky and Kahneman, 1974; Kahneman and Tversky, 1979; Freeman and Parker, 2021). As such, communications of probabilistic information need to be carefully designed, for example making use of formats that aid comprehension in certain circumstances, such as natural frequencies (Gigerenzer and Hoffrage, 1995; Gigerenzer et al., 2007) and risk comparisons (Dryhurst et al., 2021; Freeman and Kerr, 2021). Since different formats help in different circumstances, communications need to be co-designed with their audiences, and evaluated carefully to ensure they support understanding and decision-making (Becker et al., 2019).

Conclusion

Our analysis suggests that some statements commonly seen in the public realm about earthquakes, and which might be considered by some to be "misinformation", are actually still debated within the expert community, and that evidence around them can be contradictory (e.g., "Climate change will cause earthquakes to be more frequent"; "Earthquakes are more common during certain tides"). This active debate helps explain some of the lack of expert consensus on these statements. To ensure that the expert community is trustworthy in its communication with the public, openness about this uncertainty in communication of these topics will likely be key (e.g., Doyle et al., 2019; Padilla, 2021; Schneider et al., 2021).

Our analysis further suggests, however, that some of the uncertainty and overall lack of consensus in experts' ratings of many of the statements put to them may come down to the way these statements were phrased by the researchers and thus to variation in their interpretation. In our survey, we phrased our statements in the way that lay people might, e.g., "earthquakes can be predicted". However, our expert respondents indicated that they needed the statements to be more precise to rate them meaningfully, and in instances where experts agreed with statements we put to them, such agreement was often framed with "it depends"; definitive support for statements without caveats was rare. This may illustrate that while our participants view these statements in complexity, non-experts may perceive these to be yes or no questions.

Several comments from participants indicated that 1) it is necessary to provide clarity on whether statements relating to earthquake prediction refer to deterministic predictions or probabilistic forecasts; 2) the magnitude and other key parameters of the earthquakes the statements relate to (e.g., induced vs. naturally occurring) should be specified; 3) intent-based and potentially conspiratorial language such as "created" in communications about human-induced earthquakes should be avoided and more neutral wording such as "triggered" or "induced" used instead; 4) individual and cultural context may determine belief in information (e.g., more religious people placing greater belief in supernatural forces).

The disconnect between the publics' phrasing of statements about earthquakes and the increased demand for precision and content by experts can be understood *via* the lens of Mental Models (Bostrom et al., 1992), which posits that those with expert knowledge view issues with more complexity and higher risk than those with non-expert knowledge, and can complicate risk communication initiatives and campaigns (Bostrom et al., 1994). This indicates that careful consideration of wording and providing qualifications (e.g., specifying the parameters of each statement) might be necessary when communicating about earthquake related information, both to experts and the public.

This research was intended to be exploratory and informative, rather than conclusive and generalizable. It constitutes an important first step in establishing degrees of consensus within earthquake science, understanding how divergence in consensus might be managed, and opening discussions about the framing of statements about earthquakes in public discourse. The results underline the importance of clarity and precision in communication about earthquakes to both experts and publics, and provide important insights for the state of knowledge in the field. This should aid understanding of what may be classified as earthquake "misinformation", help identify where consensus exists and could be communicated in order to fight such misinformation, and highlight where scientific debate continues and could be openly communicated with the public to aid understanding of where and why, at present, a clear true or false answer cannot be given on certain aspects of earthquake science.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed by the University of Cambridge Psychology Research Ethics Committee (No: PRE. 2021.018). The patients/participants provided their written informed consent to participate in this study.

Author contributions

SD, ID, and LF designed the study. All authors contributed to coding and data analysis. SD wrote the manuscript, with contributions from FM, JK, SM, and ID. All authors edited the manuscript, and read and approved the submitted manuscript.

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Conflict of interest

SD was formerly employed by Frontiers.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Preventing and debunking earthquake misinformation: Insights into EMSC's practices

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Misinformation spreads fast in times of crises, corroding public trust and causing further harm to already vulnerable communities. In earthquake seismology, the most common misinformation and misleading popular beliefs generally relate to earthquake prediction, earthquake genesis, and potential causal relations between climate, weather and earthquake occurrence. As a public earthquake information and dissemination center, the Euro-Mediterranean Seismological Center (EMSC) has been confronted many times with this issue over the years. In this paper we describe several types of earthquake misinformation that the EMSC had to deal with during the 2018 Mayotte earthquake crisis and the 2021 La Palma seismic swarm. We present frequent misinformation topics such as earthquake predictions seen on our communication channels. Finally, we expose how, based on desk studies and users' surveys, the EMSC has progressively improved its communication strategy and tools to fight earthquake misinformation and restore trust in science. In this paper we elaborate on the observed temporality patterns for earthquake misinformation and the implications this may have to limit the magnitude of the phenomenon. We also discuss the importance of social, psychological and cultural factors in the appearance and therefore in the fight against misinformation. Finally, we emphasize the need to constantly adapt to new platforms, new beliefs, and advances in science to stay relevant and not allow misinformation to take hold.

KEYWORDS
misinformation, earthquake, science communication, risk communication, information system, earthquake predictions, people-centered risk communication

1. Introduction

Earthquake predictions, rumors that animals can predict earthquakes, that there is a significant link between weather and seismic activity, or even belief in the ability of some governments to intentionally create earthquakes... earthquake misinformation is numerous and disparate.

Misinformation through gossip and rumors has always existed, including in relation to earthquakes. In 1990 for instance, the self-proclaimed climatologist Iben Browning made the prediction that a major earthquake would occur on the New Madrid

Fault around December 2nd and 3rd. Ignored by the scientists, the information was nonetheless relayed in the media, causing fear and anxiety among the potentially affected residents of the region who had already experienced damaging earthquakes in the past (Gori, 1993). Another well-documented example of misinformation spreading appeared following the 2010 M8.8 Maule earthquake and tsunami in Chile. The earthquake caused more than 500 casualties, and rumors of volcanic activity and of the death of famous people quickly spread on Twitter, adding confusion to the crisis response process (Castillo et al., 2013). Last but not least, Flores-Saviaga and Savage (2021) studied how, after the 2017 M7.1 Puebla earthquake in Mexico, citizens created a specific hashtag on Twitter to make verified information visible.

Earthquake misinformation has taken on larger significance within the last few years because of the rise of social networks and the development of new informational products in seismology. Misinformation is indeed more visible, more numerous, more shared and this has had tangible consequences. While it has been widely demonstrated that social networks can have a positive impact on crisis management (Reuter and Kaufhold, 2018) and on scientific research (Lacassin et al., 2019), their use can present certain pitfalls, including the circulation of false information that can turn viral. With the use of social networks, the false information that already existed before has become more visible and can circulate more quickly (Fallou et al., 2022). In addition, the communication from seismological institutes has expanded and now almost systematically includes a presence on social networks. However, this presence implies greater interaction with individuals on these platforms and the public has developed strong expectations regarding institutional communication through social media (Petersen et al., 2017; Bossu et al., 2020). Because of their growing presence on social media, seismic institutions have increasingly become aware of the misinformation phenomenon to such an extent that they cannot ignore it anymore. Recent developments in seismology research and informational products are the second conducive cause to the flourishing of misinformation. With the current state of knowledge, seismologists are not able to predict earthquakes - that is to say, they cannot say precisely when, where and with what degree of energy an earthquake will occur. Earthquake Early Warning (EEW) is often confused by the public with earthquake predictions, and such a misunderstanding raises doubts about what science can or cannot do (Elizabeth Cochran et al., 2018; Fallou et al., 2021; Dallo et al., 2022). Operational Earthquake Forecast (OEF) – which is communicated through calculated probability for the next tremors- are developing. However, this type of information is complex to communicate and to be understood by the public and the probabilities themselves can evolve rapidly making prior information outdated (Nigg, 1982; Gigerenzer et al., 2005; Marti et al., 2019; Mcbride et al., 2019).

The problem of earthquake misinformation is far from being trivial and has important tangible and intangible consequences. Ill-informed people make decisions that can be dangerous for them or prevent the smooth running of relief activities, jeopardizing preparedness and awareness efforts (Chen et al., 2018; Mero, 2019; Peng, 2020; Zhou et al., 2021). Some of the consequences are more elusive but perhaps even more dangerous in the long term. The dissemination of misinformation can decrease trust in science or in the authorities (Appleby et al., 2019; Fallou et al., 2020; Zhou et al., 2021). Faced with the consequences of misinformation, it is the social and ethical responsibility of seismology institutes to act (Peppoloni and Di Capua, 2012). Yet, they are not the only actors to have a role to play in this fight against earthquake misinformation: researchers, science communicators, political authorities or the media have also their share to do, since their scientific and risk communication actions often place them in the front line in this fight. While research is gradually addressing the issue of misinformation and providing advice and good practices to guide seismological institutes in the fight against misinformation (Dallo et al., 2022; Fallou et al., 2022), there is currently no work that documents the concrete practices of these actors of earthquake science and risk communication.

As a global seismological and public information institution, the Euro-Mediterannean Seismological Center (EMSC) is regularly confronted with earthquake misinformation on social media, mostly on Twitter *via* its @lastQuake account (223 K followers in September 2022). Over the last years the EMSC has therefore gained empiric experience in the field of misinformation, especially on ways to respond to them (debunk) but also to ensure that they don't appear in the first place (prebunk).

The present paper collates EMSC's experiences related to earthquake misinformation and sets up solutions to tackle the issue. By doing so we seek to research what a global seismic institution can do to help fight earthquake misinformation. In order to do so we will first give elements of context regarding the state of the research on combatting earthquake misinformation. We then document the two main categories of earthquake misinformation that the EMSC is regularly facing, namely:

(1) Misconception and misunderstanding of the EMSC information system (e.g., how the EMSC publish information);
(2) Earthquake predictions.

We then expose how, based on desk studies, users' surveys and 10 years' of empirical experience, the EMSC has progressively improved its communication tools and communication strategy to efficiently fight earthquake misinformation and restore trust in science.

2. Earthquake misinformation: A state of the art

2.1. Defining earthquake misinformation

The term "misinformation" sometimes appears as a catch-all (Baines and Elliott, 2020). Here, we define it as any kind of information that is considered false with regard to the knowledge commonly agreed on or known at a given time (Komendantova et al., 2021). Unlike disinformation, which is a deliberate act of spreading false information most often with the aim of causing harm, misinformation is never intentional. It follows that spotting misinformation requires the ability to discern what is true and what is false. Yet, there are cases where true and false information are not obviously separated and assertions are to be nuanced or conditioned. Science, quite surprisingly, is not always able to discriminate what is true or false: as the scientific field is constantly evolving, consensuses are not always established and controversies appear regularly (Dryhurst et al., 2022).

2.2. Why do people believe and share misinformation?

Reasons why individuals believe and share false information relates as much to the socio-technical properties of the technology platforms, as to social and psychological issues of the communities concerned.

Due to their business model (Deibert, 2019), platforms are designed to promote content that has the greatest chance of engaging users, such as sharing, liking or leaving a comment (Marwick, 2018). Content is created and circulates very quickly but is often not moderated, which allows the circulation of unverified content, sometimes in a viral manner. Research has found that, on social media, fake news is about 70% more likely to be shared than real news and it takes on average 6 times longer for real information to reach 1,500 people (Vosoughi et al., 2018).

Crises are a particularly fertile ground for misinformation. The need for information for affected or concerned people is very high and must be satisfied quickly. At the same time, information is rare, sometimes confusing and not always verified (Palen and Hughes, 2018). False information especially propagates when authoritative information is lacking or when it is ambiguous, triggering additional fear and anxiety (Fallou et al., 2020; Peng, 2020; Zhou et al., 2021). Besides, during crises, anxiety and physical or emotional vulnerability reinforce the propensity to believe and share false information (Abdullah et al., 2015). The feeling of certainty conferred by receiving information, albeit false, participates in the collective sense-making process that people affected by a crisis need (Huang et al., 2015; Starbird et al., 2016). Psychological factors are also at play regarding beliefs in earthquake predictions. In their study related to beliefs in the 1990 Iben Browning earthquake prediction, Atwood and Major (2000) show that pessimistic people felt more at risk and were more likely to believe in the prediction. Inversely, optimistic people sought less information about prediction and risk, which led them to a risk denial.

In the case of earthquakes, the lack of scientific literacy increases the risk of misinformation and confusion. Seismology is a relatively young science and is rapidly evolving; conversely the public literacy level for this science is often low. Indeed, interest in seismology grows with experience... and on a lifetime scale, the number of earthquakes typically experienced for which a person feels concerned is relatively small (in regions where the hazard is moderate and outside of aftershock periods). Additionally, even for a given earthquake, the window of interest is often quite short in time (from a few minutes to a few days). For these reasons, communications related to earthquake risk and science only benefit from few and short moments to be efficient and reach their audience (Camilleri et al., 2020). As a result, at an individual scale, people are not often exposed nor attentive to earthquake science messages and therefore may have inaccurate belief about what seismology can and cannot do and about when scientific information is available (Scheufele et al., 2021).

Overall, earthquake misinformation is fueled by uncertainties, misunderstandings, cognitive biases, lack of science literacy or even lack of science consensus (Dryhurst et al., 2022). All of these causes ultimately contribute and reinforce beliefs in misinformation (Dallo et al., 2022).

2.3. What can be done to fight misinformation?

Solutions to fight misinformation in general are traditionally 2 fold according to the literature:

(a) Technical strategies, that use algorithms seek to detect misinformation and limit its spread (Calfas, 2017; Elgin and Wang, 2018; Van der Linden and Roozenbeek, 2020).
(b) Fact-checking methods, also known as debunking (Cook and Lewandowsky, 2020), counteract misinformation by showing how it is false. Although highly necessary, debunking may not be sufficient and, for some, even add to the initial suspicion (Jang et al., 2019).

Research therefore advocates for pre-bunking techniques, which consist in preventing the appearance of false information in advance (Compton, 2013; Van der Linden and Roozenbeek, 2020), including through gamification approach (Roozenbeek and van der Linden, 2019; Basol et al., 2020). States can also intervene by legislating (Koulolias et al., 2018): During crises, citizens themselves can mobilize and contribute to the effort in fighting misinformation by helping to identify, reporting, and labeling false information or even by educating their peers on the subject (Flores-Saviaga and Savage, 2021).

Communicating better is essential for the earthquake misinformation fight. This includes communication on what information is available at what time, with what level of certainty, and what are the risks for the population (Dallo et al., 2022). To be efficient, this information must be tailored to the public in terms of content, format, and medium (Lamontagne and Flynn, 2014). Communication decreases anxiety during crises, while anxiety is an aggravating factor in the spread of misinformation (Fearn-Banks, 2016). Since different types of misinformation can spread at different stage of the earthquake cycle, communicating in order to pre-bunk and debunk is a permanent task in seismology (Fallou et al., 2022).

With the development of new seismic information products, misinformation has become a timely topic. To prepare scientifically based answers to misinformation that could be used by all actors, Dryhurst et al. (2022) evaluated the existence or the absence of scientific consensus among seismologists on a dozen assertions that are controversial or confusing to the public. They also compiled recommendations to better communicate and fight three of the most common types of earthquake misinformation, namely the earthquake prediction, the earthquake creation, and the potential link between earthquakes, climate, and weather. This resulted in a communication guide (Dallo et al., 2022), where the authors underlined the importance of getting to know the audience and establishing with them a trust relationship, to better understand their needs and concerns (Goulet and Lamontagne, 2018).

3. The EMSC and the earthquake misinformation problem

The EMSC operates LastQuake, a multi-component public earthquake information and crowdsourcing system, comprising websites, a mobile application (900 K users in September 2022), and a twitter account (223 K followers in September 2022). It is completed by an online presence on other social media (Facebook, LinkedIn, and Telegram) (Bossu et al., 2015, 2018). LastQuake focuses on felt earthquakes as they are the ones that matter for the public. On the one hand it monitors online reactions of eyewitnesses to detect felt earthquakes (e.g., Bossu et al., 2019) and collects geo-located felt reports, comments, pictures or videos from eyewitnesses. On the other hand it provides earthquake parameters (magnitude, location) and aggregation of citizens' observation such as map of the reported effects (Bossu et al., 2018). Citizens can share their experience, comments and pictures through the app, the mobile website and the desktop website. They can also access all seismic information on these three platforms. The twitter account (@LastQuake) is primarily a bot but also contains manual tweets used to answer users' questions (especially after damaging earthquakes). It is a relay for the three other channels were eyewitnesses can effectively share their experience. LastQuake also includes tools to contribute to risk reduction such as safety tips and safety checks (Fallou et al., 2019). As it targets a global audience, the EMSC makes intensive use of visual communication in order to be universally understandable (Fallou et al., 2019). Yet, the EMSC publications on Twitter are mostly in English, which restricts the audience to English speakers or to those willing to translate the tweets through the integrated translation tool.

Because of its intensive presence on social media and constant communication with the public, the EMSC has been confronted with many cases and types of misinformation. Some of this misinformation occurs occasionally, outside of crisis periods, and thus gets relatively little attention. However, the most frequent type of misinformation occurs right after major earthquakes and is linked primarily to earthquake prediction and, to a lesser extent, to misconceptions about the EMSC system. The fact that certain earthquakes, destructive or shocking for the population, have led to misinformation makes it possible for us to deduce a geographical and a temporal framework of vulnerability of the population toward false information: it is in the few hours to days that follow the earthquake onset that the eyewitnesses, and anyone affected by the seismic event, are vulnerable to misinformation. This spatio-temporal framework allows us to target our action.

In the following sections we present two different categories of misinformation illustrated by examples. Contrary to the classification established by Dallo et al. (2022), the "misinformation categories" we present in our paper are not strictly based on the content of the false information. Rather, our categories sort misinformation by its nature, since it is the nature of the misinformation, not its content, which determines the type of response. The first "misinformation category" brings together misinformation that is linked to a misconception or misunderstanding of the EMSC information system. The second tackles online earthquake predictions.

3.1. First misinformation category: Misconception and misunderstanding of the LastQuake system

The LastQuake information system has been designed to offer easily understandable messages for global eyewitnesses who just felt an earthquake, who may be new to earthquakes and seismology, and who, above everything, may be anxious. The way the information is produced and displayed through LastQuake has nonetheless generated some misunderstandings, which have led to misinformation. We present here two emblematic cases.

The 2018 Mayotte earthquake crisis

On the 10th of May 2018, a series of widely felt earthquakes started to hit Mayotte, a French island located in the Indian Ocean. This earthquake swarm was first left unexplained from a scientific point of view due to a lack of seismic sensors in the area (Lacassin et al., 2019; Lemoine et al., 2020). This information void generated anxiety, frustration, as well as feelings of abandonment and suspicion, which fueled the circulation of false information and even conspiracy theories. For instance, beyond animist and religious beliefs that for some people contributed to account for the phenomenon, rumors attempted to explain the seismic swarm as originating from secret oil drilling. Similarly, rumors that the earthquake magnitudes were systematically being underestimated started circulating. In a second stage of the seismic swarm, when scientific information started being available, the communication, poorly adapted to the expectations of the public and to the socio-cultural context, struggled to achieve its goals. Science communication was not heard, understood, and not even trusted by the public (Fallou et al., 2020; Devès et al., 2021, 2022).

The Mayotte case has been studied in detail in Fallou et al. (2020). Here, we only focus on the aspects of that misinformation and its implications for the EMSC. In a context of general distrust of information, such as the one in Mayotte, the perception of the EMSC and its LastQuake application was ambivalent. On the one hand, LastQuake was very popular and appreciated for the information it could provide. On the other hand, a misunderstanding of the system and the absence of seismic confirmation for certain events generated strong dissatisfaction among users. It also cast doubt on the reliability of the system and on a potential participation of the EMSC in the so-called plot. Originally, the LastQuake information system used to collect felt reports for all the crowdsourced detections that it recorded but published these testimonies only when the seismic activity had actually been confirmed by seismic data from partner institutes. In the case of Mayotte swarm, not enough sensors were there to seismically confirm the information of the system. Despite the testimonies collected, the earthquakes of the Mayotte swarm were not being displayed – a very frustrating user experience! As a matter of fact, earthquake eyewitnesses were able to report their experience for the first 15 min from the shaking and associate it to the crowdsourced detection displayed on the LastQuake app. However, after 15 min, since no seismic confirmation would arrive to the EMSC, the crowdsourced detection disappeared from the app - and the users were not aware of such limits of the system (Fallou et al., 2020). In this specific case, the lack of both the scientific information and the understanding of the system were the driving force behind the dissemination of false information.

The 2021 Las Palmas seismic swarm

On 19 September 2021, the Cumbia Vieja volcano started erupting on La Palma Island. The eruption garnered seismic activity in the form of a swarm, particularly active in October 2021. An interactive map on the EMSC website unintentionally became "evidence" for false information and even conspiracy theories. Indeed, the local seismicity map, when zoomed, displayed a grid shape (Figure 1).

Theories would then explain that these earthquakes were artificial, linked to military activities of the United States of America (including the HAARP system[1]) or heralded a giant tsunami (Figure 2). In reality, this "grid" of earthquake locations was an artifact, due to the fact that the EMSC rounds longitude and latitude coordinates to two decimal points, resulting in a less-granular, less-defined dataset.

This artifact is not unique to La Palma. It may occur on EMSC maps whenever there is a huge zoom on a very small area. In La Palma, the artifact was made visible to many users because of the very small size of the island, which made them zoom in a lot and see the grid shape.

The EMSC only discovered this misinformation after the USGS issued a clarification about the situation[2] and copied it to the EMSC account. The rumor had spread outside our field of vision on these platforms, but as soon as we saw it, we were able to explain the reasons for this artifact through several publications on social networks and the EMSC's forum LastQuakers. The debunking effort became collective with help from news media[3] and other Twitter users even using humor to denounce the incongruity of the theories. The EMSC decided not to change its digit rounding system in order not to fuel conspiracy theories. Indeed, it may have seemed suspicious that we changed the system immediately, and some could have seen it as a proof that we had something to hide. Even though this was a rare case of noticeable grid pattern, and in order to comply with new standard, the EMSC will add a third digit on the new version of its website. After a few days of debunking, believing that those who would like to find the information were able

1 HAARP stands for High-frequency Active Auroral Research Program and relates to a military research program funded by USA to analyze the ionosphere. HAARP is often a mentioned by conspiracy theorists as a tool capable of "weaponizing weather".

2 Available online at: https://twitter.com/USGSVolcanoes/status/1452446024845299712?s=20&t=NWQG3MrQoVuujq3D5faQ4A (accessed May 21, 2022).

3 See for instance USA Today Available online at: https://eu.usatoday.com/story/news/factcheck/2021/11/07/fact-check-la-palma-earthquake-grid-represents-natural-quakes/6186214001/ or https://leadstories.com/hoax-alert/2021/10/fact-check-seismic-activity-grid-pattern-on-map-is-not-evidence-the-lapalma-eruption-and-earthquakes-are-an-artificial-attack.html (accessed May 21, 2022).

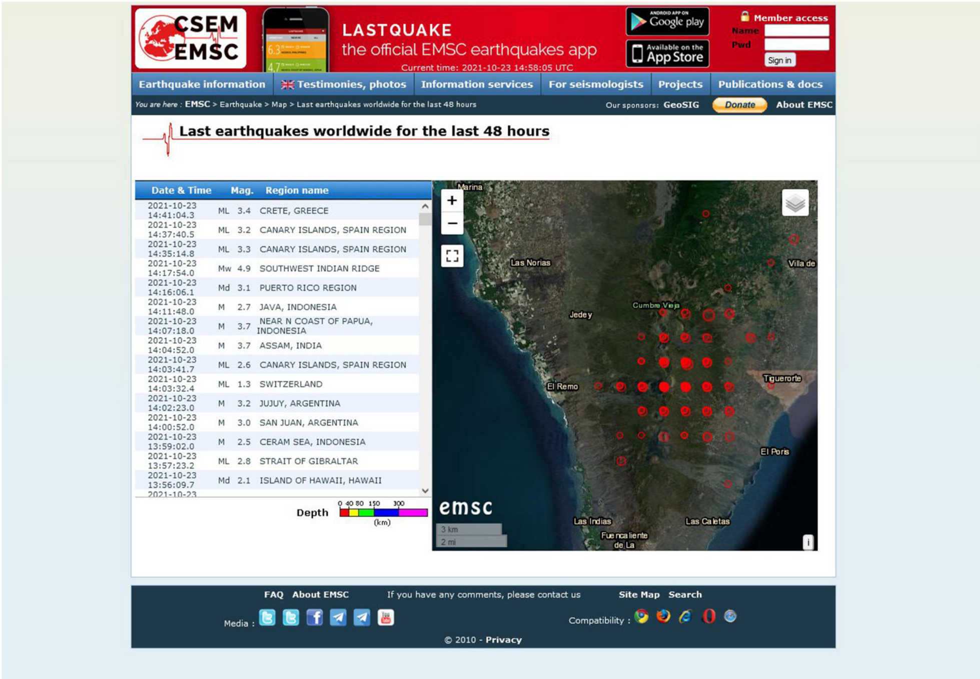

FIGURE 1
Screenshot of the EMSC website displaying the earthquake map with the grid pattern (Screenshot 17 June 2022).

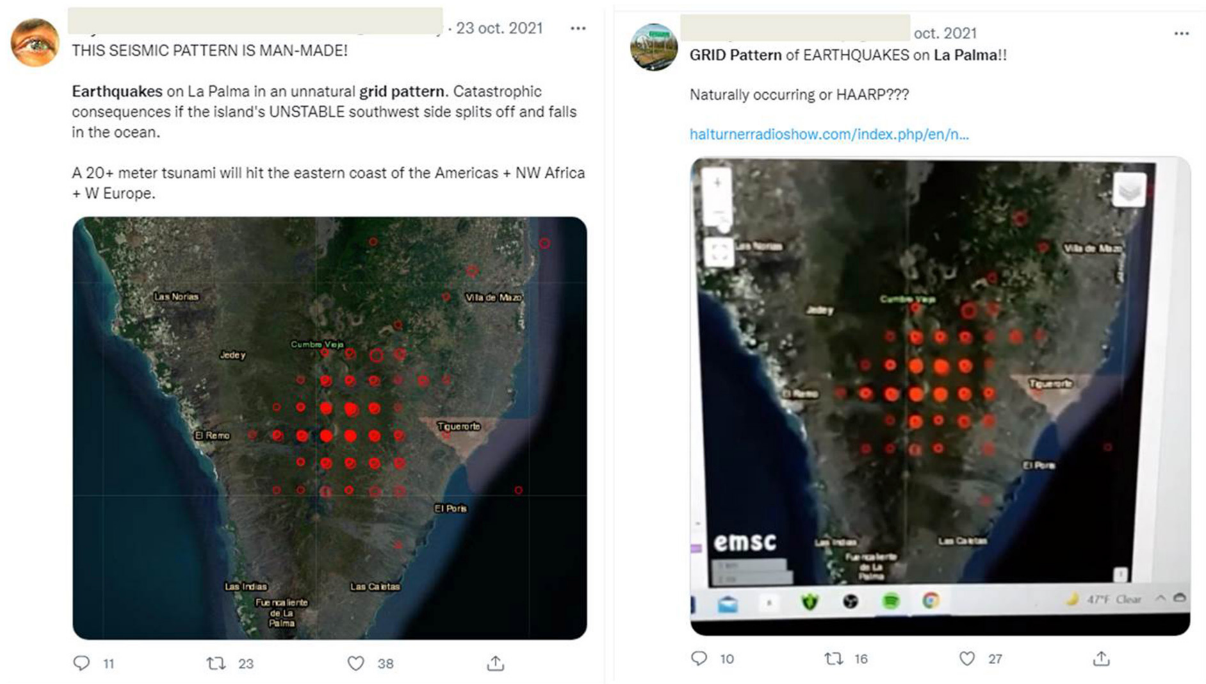

FIGURE 2
Screenshots of Twitter users posting the EMSC map to support misinformation about the earthquake grid pattern (Screenshot 17 June 2022).

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to find it, we stopped broadcasting the explanatory messages. In fact, some were still not convinced and rejected this simple explanation to stick to their more complex and sometimes conspiratorial explanations such as military activity or HAARP. For those, we felt that we would not be able to convince them with our arguments.

In this case study, we observed that conspiracy theories are often not believed by everyone. Yet, here they have set light on a tool (the interactive map) that, because of the incongruity of its visualization, sowed doubt and confusion and raised legitimate questions. This is what made the misinformation visible, and to a certain extent, viral.

Beyond the specific cases of Mayotte and La Palma, the EMSC is confronted with examples of misunderstanding of seismology in general. Among the most recurrent: magnitude discrepancy between agencies, the confusion between magnitude and intensity which leads to people questioning of the magnitude of earthquakes or even the doubt generated by the evolution of a magnitude on a given earthquake. These questions and these doubts coming from the public are not directly linked to our tools or informational products. They are a reflection of (1) the public's lack of knowledge in seismology, (2) a lack of awareness on the mode of production of seismological data, and (3) largely spread scientific misconceptions (Coleman and Soellner, 1995; Francek, 2013).

3.2. Second misinformation category: Earthquake predictions

Contrary to some other natural hazards, earthquakes are unpredictable in the sense that it is not possible to know in advance and with precision, when, where and how strongly earthquakes will happen. Defining the terminology is important here since if it is not possible to predict shaking, products such as OEF and EEW systems can spread semantic and conceptual confusion (Jordan et al., 2011; Dallo et al., 2022). Suffice to say that in some languages the words "prediction" and "forecast" are equivalent or even the same word.

The need and desire for prediction is great among the population (and to a lesser extent among scientists). This desire for prediction is especially high right after an earthquake, when eyewitnesses' first and main question asked on Twitter is "what will happen next?". As legitimate this question may be, scientists are not in a position to provide a precise answer. This leaves eyewitnesses either confused by the sometimes-misinterpreted earthquake forecasts, or vulnerable to unscientific answers that predict the future. In fact, the EMSC is confronted with two types of prediction problems: earthquake predictors and earthquake predictions that arise after significant or damaging earthquakes.

Earthquake predictors

The first type of earthquake predictions occurs regularly and are often produced by seismology enthusiasts or self-proclaimed scientists who often use seismic data produced by the EMSC or other well-known seismic centers to predict earthquakes. Some of them use EMSC's notoriety and audience to give visibility to their predictions by mentioning the EMSC account. For example, a person[4] publishing content on Twitter regularly uses EMSC and USGS data to make videos in which he makes and comments on earthquake predictions. He now has a large community on Twitch (50 K followers) and YouTube (530 K followers). This type of prediction occurs throughout the earthquake cycle since these "experts" constantly monitor the seismic situation on a local or global scale. The number of views generated by these contents suggests that it could be a source of income for their authors (Mathew, 2022).

Earthquake predictions after earthquakes

The second type of prediction faced by the EMSC is more localized and occurs mainly after a significant earthquake (Dallo et al., 2022). The case of the Albania earthquake is particularly interesting here. On September 21, 2019, an earthquake of Mw 5.6 hit Albania and was widely felt in Tirana. The earthquake was followed by numerous aftershocks greatly increasing the level of anxiety among the population. Thanks to the LastQuake system, the EMSC became an important source of information for people affected by the earthquake. The next day, an aftershock hit the town again, but what created panic was a media posting asserting that "A Greek seismographer says stay away from your homes, a major earthquake is expected around 11:30 pm" (Erebara, 2019). This prediction, endowed with great precision and credited with a credibility factor (it quotes a seismologist and the information emanated from journalists) only added anguish. As a consequence, many people decided to share the news with their relatives and to leave the city, creating traffic jams for several hours. Subsequently the journalists who had relayed this prediction were arrested by the police.

Most often, these kinds of predictions do not directly affect the EMSC because we are not the origin or the recipients. They occur after strong earthquakes when the population is anxious and, looking for information. In this case, the EMSC is particularly concerned since the eyewitnesses who use our services are in search of information, in a state of shock and therefore potentially vulnerable to false information. Therefore, educating them on the impossibility of making predictions is essential, as well as not giving them visibility.

4 In order not to give him publicity we will not mention his name here.

4. EMSC's solutions to fight frequent earthquake misinformation

4.1. Fighting the misconception and misunderstanding of the LastQuake system

The EMSC developed two strategies to face the information system misunderstanding problem, a technical one and an informational one.

Technical improvements

After the beginning of the Mayotte crisis, which lasted for several months, the LastQuake system evolved technically to better integrate cases when the information is incomplete. Thanks to a sociological survey (Fallou et al., 2020), we were able to take full measure of the frustration linked to the lack of information. A few months after the beginning of the swarm, we thus modified the system, which now makes it possible to publish the events for which we have collected testimonies but that have not been seismically confirmed to us, normally due to a lack of sensors in the region. We display, in a specific color and without magnitude or location, these particular events (Figure 3). This system developed in 2018, has since proven itself and seems to satisfy users, not only in Mayotte but also in other parts of the world. With this new system we therefore publish, in complete transparency and quickly, all the verified information available to the EMSC.

Informational improvements

The EMSC has become aware of the importance of explaining to the public how the LastQuake information system works in order to limit false information. We created a short explanatory video of the system without including any text, so that it is understandable and accessible to as many people as possible. The video is permanently pinned to the EMSC's Twitter account @LastQuake and it serves as an educational presentation. In parallel we created a repository of answers for our Frequently Asked Questions. The questions are organized around 6 mains categories: (1) about the Site (2) about LastQuake, (3) about earthquakes, (4) I felt an earthquake, (5) data and confidentiality, and (6) citizen seismology.

The answers to these questions meet users' expectations in a precise, sourced, and comprehensive way. The FAQ page is permanently accessible on the EMSC mobile and desktop website, and will soon be integrated into the mobile application. They also allow the EMSC team to refer to them and redirect the public if needed, especially after a significant earthquake when questions arise.

4.2. Fighting earthquake predictions

Social media moderation

In order not to give visibility to predictions made by earthquake predictors, EMSC's policy is to systematically block accounts related to predictions on social media. This allows EMSC not to be the target of negative or even insulting comments. Indeed, a few years ago the EMSC was the target of "raids" on social networks, where dozens of people wrote tweets in a synchronized way, mentioning the EMSC in order to support the predictions and alter the credibility of the institution (Bossu et al., 2022).

Conversely, in order to maximize the credibility of its overall content, the @LastQuake account is now certified by Twitter. This certification indicates to users the authenticity of a public interest account. Although this certification was not specifically requested in the context of the EMSC misinformation fight, it nevertheless shows users that the content is, a priori, reliable. The EMSC mostly publishes in English on its Twitter account. While this has allowed gaining a certain visibility, it only permits reaching an English-speaking public and therefore considerably reduces the scope of these actions to fight against misinformation.

Educational messages on the EMSC social media channels

The problem of predictions is particularly visible for the EMSC on social networks and in particular on Twitter, which allows easy, direct and timely conversation with the public. It is therefore primarily on this social network that the EMSC tested a tool to prevent the appearance and spread of misinformation concerning predictions.

First developed in 2012, the robot currently has more than 200 K followers worldwide; making it one of the most widely used seismological information channels at the international level. Although widely appreciated and used, the robot has over time shown rooms for improvement to better adapt to changes both in the platform and in the way citizens searches and share information in the event of an earthquake (Bossu et al., 2022).

In 2022 the EMSC redesigned its @LastQuake robot. This is further detailed in a sister paper (Bossu et al., 2022). A series of tweets was set up with the purpose of fighting against misinformation and fake news -particularly those related to earthquake prediction (Table 1). This evolution has actually automated what was manual before. Indeed after each damaging earthquake the questions about the predictability of the earthquakes (or even predictions as such) systematically flourished and we had to answer them manually on social media.

The new robot is now composed of a series of educational tweets as well as tweets debunking most common fake news and misconceptions, including predictions. New tweets, addressing emerging topics in earthquake misinformation, can also be

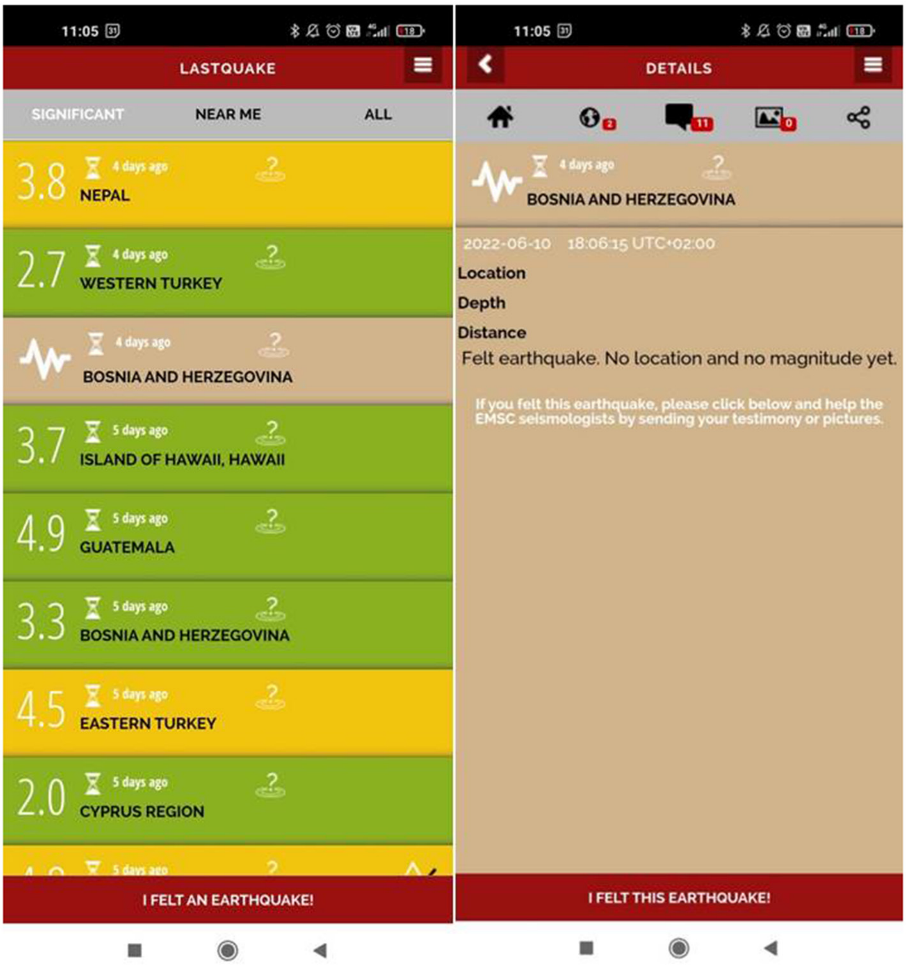

FIGURE 3
Display of the new event type in the LastQuake application.

added to the automatic system if required. The robot is versatile and adaptable in the long term.

To pre-bunk and debunk misinformation, we prepared a series of educational tweets which are published after widely felt non-damaging earthquakes to exploit the teachable moment they open. The ones against prediction are systematically published after damaging earthquakes. Generally, misinformation arises in the case of a large ($M > 4.5$) earthquake, especially if the seismic event retains the interest of the public and/or the media. It is in these circumstances that we publish our educational tweets to prevent the misinformation to arise and spread.

In the new robot we have therefore implemented a communication strategy that takes into account the perception, the prior knowledge, and the psychological state of the users. In particular, people better seize messages that are clear, short, compassionate, and positive. Hence, our wording and tone are carefully chosen to provide reliable and empathetic communication.

The EMSC will monitor the reactions to these educational tweets, whether automatic or manual (Bossu et al., 2022). Additionally, because twitter is only used by a small proportion of the population, the EMSC will study the opportunities to pre-bunk predictions on its other channels such as the app and its websites.

5. Discussion

After an earthquake, the vulnerability of those affected is not only physical and emotional but also informational. We posit that seismological institutes, among other actors, must be particularly vigilant on this aspect precisely because the propensity to believe and share false information is especially

TABLE 1 EMSC's educational tweets about earthquake prediction.

#	EMSC's educational tweet about earthquake prediction
1	❓Can #earthquakes be predicted? No. Seismologists can estimate the seismic hazard (the probability of ground shaking due to earthquakes) in time windows of decades that are used by engineers to design safe buildings. Educational video by @IRIS_EPO 👇 Available online at: https://youtu.be/MQNKpS0xrwM
2	❓Do you have an #earthquake prediction? The Collaboratory for the Study of Earthquake Predictability (https://scec.org/research/projects/CSEP/scec3.html) accepts predictions and evaluates them. Careful though: saying you did predict after the earthquake happens means nothing 🙂
3	❓Why can't seismologists predict #earthquakes? Find it out in this educational video from @IRIS_EPO 👇 Available online at: https://youtu.be/q8Ot3ToO_54
4	👉For an #earthquake prediction to be meaningful, it has to specify a time, location, and magnitude range that is unlikely to occur randomly. This is currently impossible. Learn more in this video from @IRIS_EPO 👇 Available online at: https://youtu.be/F4Ypv0PmDDE
5	"Earthquakes do their best to be as unpredictable as possible" - watch this video from @geosociety where seismologist Ross Stein explains why earthquakes cannot be predicted at present 👇 Available online at: https://youtu.be/ekTG-qjVHxc
6	To our friends and users: we hope you are safe 🙏. In the next hours you are likely going to hear about earthquake prediction. 👉 Earthquake prediction does not exist at present ☐. Please, only trust official sources and follow national authorities' directives.

#Indicate the number of the tweet.

high when one has just felt an earthquake. From the experiences recounted in this article, the tools developed over the years, and the research on earthquake misinformation, we can draw a number of lessons:

1. We observe three different types of patterns for earthquake misinformation, based on the timing of their appearance and the attention they generate. The first pattern concerns misinformation that is constantly present but captures relatively little attention. These are, for example, people who publish prediction bulletins on a regular basis. The second type appears more occasionally but almost systematically after strong earthquakes, these are the predictions of aftershocks and sometimes false information on the damage. These can be anticipated. The third pattern concerns false information which is also generated after earthquakes but which is more unprecedented and less predictable, as was the case in La Palma for example. Considering these three patterns of misinformation makes it possible to better prepare to act against this false information. Indeed, for the first type, constant but light attention is necessary, by simply not making this information more visible, or by systematically blocking the associated content. For the second type, pre-bunking activities can be effective since they aim to capture the attention of eyewitnesses and warn them against this misinformation likely to appear, according to our experience. Finally, the third type is more complex to manage since it is less predictable. It is therefore necessary to be attentive, not only rely on automatic tools and to be trained, to detect this misinformation quickly and respond to it by taking into account the local context. Institutions should provide trainings for professionals which cultivate their skills in scientific and/or crisis communication (Lamontagne, 2022).
2. Social and psychological aspects are key in the spread of misinformation. We must always keep in mind the reasons that lead people to believe and share false information. Anxiety, lack of knowledge, loss of bearings and the need to make sense of what is happening must be taken into account when establishing communication strategies. As pointed out by Dallo et al. (2022), people who believe in earthquake misinformation are not stupid, they need to make sense of what is happening to them and find answers to their questions, especially about what is going to happen next. Because they are the most vulnerable to misinformation, specific attention to eyewitnesses should be given after an earthquake. It is therefore important to fill in the information void and answer eyewitness's questions, even if the only information is "we don't know". Based on EMSC's experience the public generally accepts this information and is thankful for it.
3. The fight against misinformation is as much a matter of communication as of tools design. Seismic informational products should be designed so that information production methods are explicit, understandable and transparent in case users want to learn more. They can be explained in FAQs for instance or through explanatory documentation. This may not completely avoid misunderstanding and misconceptions of the system but it will help get ready explaining it when misinformation actually appears.
4. Preventing misinformation is a long-term task involving team work. The mutual support of seismology institutes, local partners, and fact-checkers is vital as proven by the La Palma example. We need to join forces by sharing resources, best practices and specific knowledge about the cultural context in which misinformation takes place and proliferates. Also, partnership with social media platforms could be useful to report more efficiently problematic content. This issue here is to dilute the visibility of misinformation by improving the findability and trustworthiness of verified and scientific information. It is important to ask ourselves the question of the audiences that we do not yet reach, the most vulnerable (McBride et al., 2022), those who do not speak English, or who do not have accounts on social networks. Yet we must remain humble in our ambitions. While we can work to limit the appearance and effects of earthquake misinformation, it

is likely that we will never be able to completely stem the phenomenon, i.e., convince each person individually of the veracity of certain information. This is all the more important since earthquake misinformation is not separated from the socio-cultural context. Beliefs can be rooted into other social phenomena (e.g., the political or religious context, or the willingness of the individual to trust in science) over which we have little control.

5. Taking into account the cultural context is one of the most challenging elements in the future of the fight against misinformation, as it reaffirms that we cannot rely solely on content automation to pre-bunk and debunk misinformation. If the EMSC Twitter robot can in part prevent certain misinformation, it will not be sufficient on its own to adapt to all the cultural variations of the same information. For example, from one earthquake to another, the so called creators of the earthquakes are not the same (local or foreign governments, private companies…). The Twitter bot publication is essentially in English and only reaches English speakers in that moment, which is currently a strong limit for the EMSC tool. Although we use the word "earthquake" in the local language and Twitter allows user to translate content this may not be sufficient. We must therefore further adapt our response and pursue with a combination of automatic and manual tweets. We will also study the opportunity to have language specific channels on other platforms.
6. Tools and response strategies to misinformation must be constantly adapted to the type of misinformation and enacted in a timely fashion. For instance, if sometimes, misinformation shows itself through regular patterns, responding to it can be done through some form of automation, however, automatic tools are never completely sufficient. Besides, they are not suitable for other types of misinformation that do not follow any pattern. Moreover, misinformation, science, and the means of communication are constantly evolving and we must keep up to always respond as well as possible. Technology will quickly interfere in the debate since messaging apps are becoming more and more important, not only in terms of uses but also in the role they play in the spread of misinformation (Resende et al., 2019). How it is possible to spot and respond to this misinformation circulating on private networks where it is difficult to speak to everyone and in a visible way? For now, we can already focus on ways to improve the communication that is done on traditional social networks, such a Twitter and Facebook. Part of this work includes constantly improving the content, as well as the tone of the messages, i.e., by making better use of humor (Simis-Wilkinson et al., 2018; McBride and Ball, 2022).
7. Both at the individual and at the institutional level, the fight against misinformation seems disarming. It can paralyze some, leaving the impression that the problem is too vast and that the fight is lost in advance. Legal aspects may also come into play and the L'Aquila case is known to have affected the seismological community by making it more hesitant to communicate directly with the public (Alexander, 2010; Jordan, 2013). The EMSC benefits here from the freedom to set up its own communication and moderation strategy (Bossu et al., 2022). For example, we make sure not to encroach on the communication of the national institutes in the event of an earthquake. On the contrary, we support them if necessary. The experience of the EMSC (e.g., the explanation of the production and dissemination of data and information, the attempts at pre-bunking and debunking, or the establishment of networks of experts to better spot and respond to misinformation, etc.) shows that solutions exist, but they deserve to be further improved and to be even more coordinated with partners such as the authorities, education professionals, and the media.

Presenting the case studies the EMSC has encountered, the examples of misinformation it has faced, and the ways it has attempted to respond to it is not paradigmatic here. The implementation of recommendations and measures to combat misinformation has been adapted to the context of the EMSC. Its independence and the multicultural and global dimension of its audience are parameters that influence the implementation of these communication tools. Presenting our fight against misinformation is a way of taking a critical look at what has already been done and what remains to be done. We are confident our experience will be useful to other seismological institutions that provide information to the public and to the research addressing misinformation and ways to fight it.

Wherever possible, the effectiveness and usefulness of these tools will be assessed through quantitative and qualitative data. This will be the subject of future research for EMSC. However, we face a well-known problem in the world of risk management and communication: while it is possible to know when tools have been seen or used, it is almost impossible to know with certainty whether the messages spread have actually prevented the appearance or dissemination of false information, since, precisely they have not appeared and we have no way to know if they would have had without our actions.

6. Conclusion

The practical case of the EMSC's fight against misinformation shows the extent of the challenges seismology institutes face for this growing issue. Earthquake predictions and misconceptions about what science can and cannot do should not be considered inevitabilities. Actions are possible to counter them, and they can prove efficient. The EMSC example shows that fighting misinformation means putting people at the center of science and crisis communication.

That is, understanding their expectations but also anticipating what they might misunderstand or not believe. Considering these questions in advance, before misinformation even appears, is more effective than having to do it afterwards. The actions of the EMSC to combat misinformation are also an illustration of the phenomenon that Naomi Oreskes described in her 2015 paper "any major questions in earth science research today are not matters of the behavior of physical systems alone, but of the interaction of physical and social systems" (Oreskes, 2015). If scientists want their information to be understood, they must then also care about the public. It is therefore a collective work, from scientists and science communicators which must allow, for example, to develop scientific practice and its general understanding by the public, and to restore confidence in science.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LF and MC took part in the earthquake misinformation working group and reviewed the literature. LF and RB analzsed the case studies and reflected on the solutions and worked on the redesign of the information system after the Mayotte case, along with other members of the EMSC staff. MC, J-MC, and RB worked on the redesign of the Twitter bot along with other members of the EMSC. LF wrote the first draft of the paper. RB, MC, and LF amended it and debated over the discussion section. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The whole story: Rumors and science communication in the aftermath of 2012 Emilia seismic sequence

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Controversies that stir the public debate on geological matters usually revolve around a few specific aspects, including the actual trigger of geological phenomena (i.e., natural vs. anthropogenic), their predictability, and the trustworthiness of the experts who provide information and advice on the phenomena. A typical example of such difficulties is the case of the 2012 Emilia, Italy, seismic sequence which struck an area of relatively moderate seismic hazard. In that period, geophysical prospecting was planned to assess the potential of a reservoir for gas storage, near the town of Rivara. The low frequency of important seismic events in the area, associated with the ongoing industrial planning prompted widespread rumors of an anthropogenic origin of the 2012 earthquakes. Controversy also arose about the actual size of the seismic events: earthquakes magnitude can be computed with different methods, and its value depends on the type, number, and geographical distribution of the available seismic stations. As a result, different institutions commonly release different estimates of the earthquake magnitude, casting doubts on the reliability of each estimate. Since 2012, public concern has also been caused by the repeated occurrence of unusual phenomena in the area, such as ground heating or bubbling well waters. Popular belief tends to establish a causal link between particular phenomena and seismic activity, reinforcing the false conviction that seismicity could be predicted. In this work we present and discuss some of the activities that INGV pursued through the years to contrast rumors and disseminate correct scientific information. In the aftermath of the 2012 seismic sequence, INGV worked in collaboration with the National Department of Civil Protection, the local administrations, the University Network of seismic engineering, the Regional Healthcare System and local volunteer organizations. The organization of public meetings, the collection and analysis of widespread rumors and the creation of *ad hoc* outreach materials all contributed to reinforce the mutual trust between our research institute and the local population.

KEYWORDS

earthquake, rumor, 2012 emilia earthquakes (Italy), science communication, risk perception

1 Introduction

On 20 May 2012 (02:03:53 UTC), a magnitude (Mw) 5.86 earthquake (Ml=5.9) hit the Po plain, in Italy, causing five casualties and damage in several towns, including Modena and Ferrara. Three hours earlier, a Mw 4.0 foreshock (Ml 4.1) struck the same area. These events initiated a seismic sequence that included six more shocks above magnitude 5.0, the greatest of which occurred on 29 May 2012 (07:00:03 UTC), had a magnitude Mw 5.7 (Ml 5.8) and was located 12 km to the west of the May 20 event (Figure 1). After this second mainshock, the death toll rose to 17 victims, while 13,000 people had to be evacuated. The economy of this wealthy, industrial area of Northern Italy was seriously impacted.

The occurrence of a strong earthquake increases the social awareness toward natural hazards, and commonly prompts a strong demand for information (Bossu et al., 2015). The need for a continuous flow of details becomes urgent, especially during prolonged seismic sequences. The availability of correct and exhaustive information affects people's capacity to cope with emergency situations, and may foster the resilience of single individuals and of the entire communities involved. On the contrary, the lack of timely and accurate information may favor the circulation of rumors and misinformation (Fallou et al., 2020). A good communication among different stakeholders during a crisis may improve the community response to the emergency and reduce the costs of the disaster. However, scientific communication also promotes a rational and transparent decisional process and facilitates the acceptance of the disaster consequences (Wendling et al., 2013).

However, science communication is not always straightforward in the aftermath of a natural disaster. In addition to the scientific complexity, which may hinder a proper understanding of the natural phenomenon, the scientific information provided may fail to address the specific fears and needs of the population at risk, adding to their frustration. The stressful circumstances emphasize the emotional reactions of the stakeholders involved, and the technical staff may be unprepared to cope with the irrational components of human interactions. Under these circumstances, fake news may grow and spread, and if not promptly addressed, may cause unwanted consequences (Lamontagne and Goulet, 2018; Fallou et al., 2020).

Nowadays, the need to fight earthquake rumors while ensuring a prompt and exhaustive flow of information is widely recongnized in the seismological community (Fallou et al., 2022). In this paper, we describe how our Institute (Istituto Nazionale di Geofisica e Vulcanologia, INGV) has worked to address this complex issue in particular after the 2012 seismic sequence, by promoting different kinds of actions. Proposed interventions were all aimed at engaging the local population in a fruitful knowledge exchange, and have been structured around three main principles: connect, listen, and share. The underlying concept is that knowledge transfer works when it is a

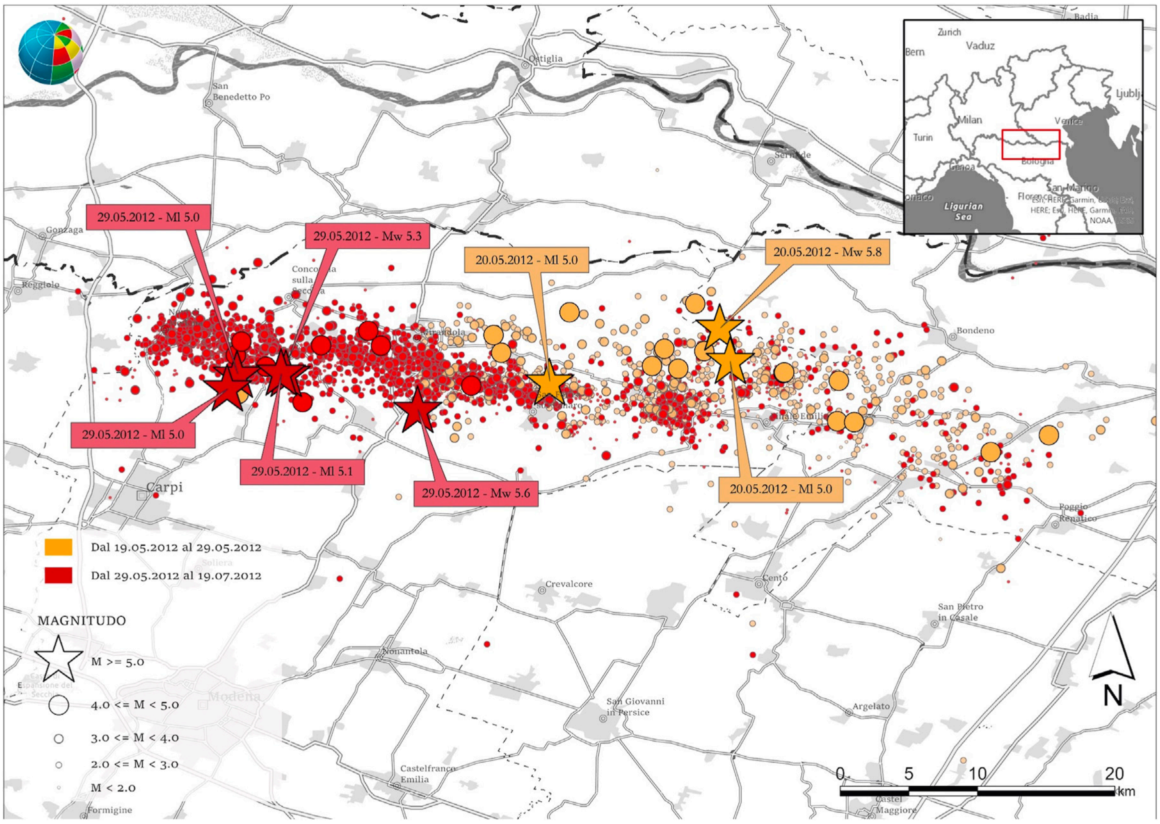

FIGURE 1
The main shocks of the 2012 Emilia Romagna seismic sequence. The size of the points reflects the magnitude, as shown in the legend. For the six greatest events (stars), the labels report the date (day.month.year) and the magnitude. The image is taken from a blog article published on the INGVterremoti blog on the 10th anniversary of the sequence (modified after https://ingvterremoti.com/2022/05/21/terremoti-in-pianura-padana-10-anni-dopo-i-numeri-della-sequenza-e-la-dashboard/).

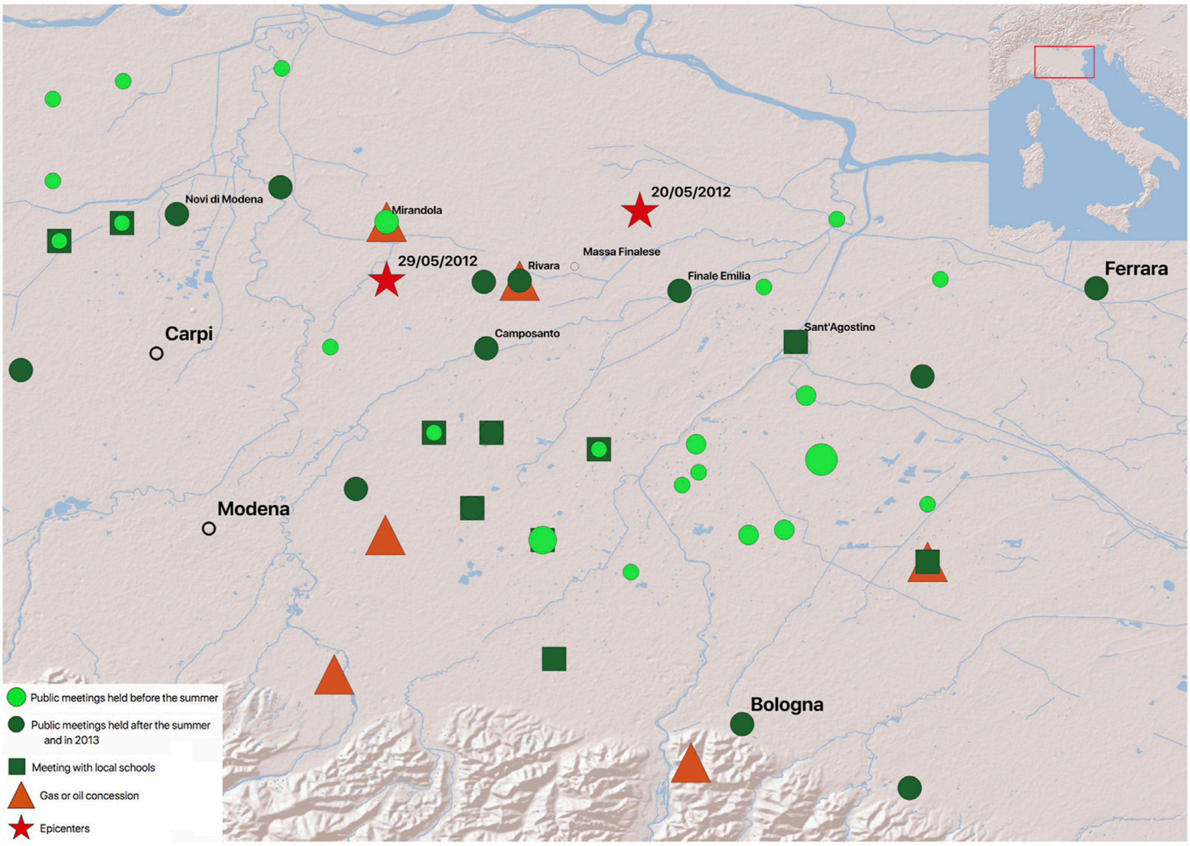

FIGURE 2
Locations of the public meetings organized in the region affected by the 2012 seismic sequence. The red stars indicate the two major events, on May 20 and 29, 2012. Orange triangles show the location of gas or oil concessions. Green symbols indicate the locations of the public meetings organized during and after the sequence. The size of the symbols reflects the number of meetings held at each location, with larger symbols corresponding to 5 encounters. Light green symbols indicate meetings held during the sequence (before the summer), while darker symbols show meetings organized after the summer. Square symbols refer to activities held in local schools, during the 2012/2013 school year.

mutual exchange, and where the scientific information that is released to the public is suited to address the public's questions and fears.

Accordingly, the first response to the seismic sequence was the organization of public meetings, which were held in different locations, upon request from local authorities, from May to September 2012 (Figure 2). These public encounters were realized thanks to the joint efforts of the Italian Civil Protection Department (DPC), INGV, and the regional administrative authority (Regione Emilia-Romagna), in collaboration with the Laboratory University Network of seismic engineering (RELUIS), the Regional Healthcare System and the organizations of civil protection volunteers. The meetings were announced locally with flyers and taking advantage of all channels available to the participating stakeholders (including announcements broadcasted on local radio or TV networks and institutional websites). Based on the fruitful experience carried out after the 2009 L'Aquila earthquake (Nostro et al., 2009; Moretti et al., 2011), the campaign was named "Earthquake: let's talk about it" and provided suitable spaces where citizens could meet the experts from the organizing institutions, receive information about the seismic sequence and its effects, and express their doubts and fears related to the earthquake. All these public meetings allowed ample space for open questions and informal discussion among the participants, providing a useful psychosocial support as the seismic sequence unfolded, accompanied by growing false information and urban legends.

Rumors about the ongoing sequence were then collected online, through various institutional websites, and analyzed to gain insights on the scientific information required to address common misconceptions or popular beliefs. Information on the rumor collection was provided during the public meetings, and advertised online. The collection of widespread rumors is a necessary step to counteract its effect, devising appropriate outreach material and providing authoritative and coordinate answers (Lamontagne and Goulet, 2018; Fallou et al., 2022).

On a longer term, the link established with the communities was maintained through different kinds of actions, including sharing of scientific results (through the institutional blog and social media, releasing interviews to traditional media), attending public meetings and cultural events, and participating in school activities. The scientific contents proposed during these outreach activities were tailored to address the specific needs that emerged in the public discourse about the earthquake.

In this paper, we describe the outcome of these combined actions and propose future steps to improve the communication of natural hazards.

2 Materials and methods

Our approach to the communication during the seismic sequence in 2012 was devised in collaboration with other national and local stakeholders, and was organized around three main pillars: connect, listen, and share. We sought a connection with the affected population by creating the conditions suited to allow a free exchange of information, thoughts and fears about the earthquakes. We listened to the questions that circulated among the people, and collected information on the widespread rumors and finally we produced outreach material suited to address those questions and rumors.

2.1 Connect: The psychosocial intervention

The traditional approach to emergency psychology has been primarily oriented toward clinical actions (aimed at both individuals or groups). In recent years, however, the guidelines released by international organizations of the field (Inter-Agency Standing Committee (IASC, 2007) and WHO, in particular) have emphasized more and more the psychosocial impact of the intervention, and its community and intercultural dimensions. Emergency psychology should not only take care of the clinic of single unrelated individuals, but also provide a systemic management of the psychosocial community scenario, where the emergency took place and whence it built its significance. Based on these indications, and taking advantage of the precious experience gathered in the aftermath of the 2009 L'Aquila earthquake (La Longa and Crescimbene, 2009), we organized a series of meetings with the local population. The meetings had different aims: to inform about the seismic sequence; to address people's anxieties and expectations; to promote resilience by increasing people's knowledge and self-consciousness (Lamontagne and Flynn, 2014). In particular, the psychosocial intervention was meant to.

- Share basic information about the geological setting of the area and available data about the ongoing seismic sequence.
- Provide basic knowledge about emotions, and individual and group reactions facing an emergency: psychological information was provided side by side with seismological information. The awareness of the state of arousal associated with the emergency allows to recognize the potential susceptibility to rumors, but also to acknowledge the individual and community capacity to cope with the emergency;
- Direct the population toward structures and practitioners capable of providing appropriate social and psychological support. The collaboration with the local public healthcare structures (AUSL) and institutions allowed to build a network of dedicated psychologists and psychotherapists for the population involved. Simple information on where to find these local services were provided during the meetings;
- Discuss and counter rumors and urban legend on the earthquake. A greater people awareness about these rumors contributed to lower the level of anxiety and to reduce the social tension within and between institutions;
- Encourage and promote open discussion where all stakeholders are present simultaneously. The availability of a space to discuss and exchange thoughts and fears has a strong "therapeutic" value and, when properly managed, it allows to ease tensions and conflicts, and represents an essential aid for those affected. Through this systemic approach, and thanks to appropriate listening skills, the emergency can be placed within its reference frame, and resources and responses can be oriented and calibrated according to the needs expressed by the communities affected;
- Favor the active participation of citizens and foster all the initiatives promoted by local communities.

This approach acknowledges the importance of a direct, continuous and empathetic contact with the population (Lamontagne and Flynn, 2014) and overturns a traditional perspective, according to which the authority needs to care for a sick or incapable population. In this case, the Civil Protection system stimulates curative effects toward objects that are damaged or destroyed, and toward responsible citizens: the people capable of taking care of themselves and up to take remedial actions. The community does not need to be rescued, but helped to get up again. An environment that promotes mutual exchange and that warrants timely and accurate information favors the population's engagement during the emergency and helps harmonize different stakeholders' perceptions (Wendling et al., 2013).

2.2 Listen: Rumors collection in 2012

Since the very beginning of our activities in the field, it was clear that we needed to address and counter the rumors about the seismic sequence that spread in a massive and uncontrolled way. Specific information on these rumors was considered of utmost importance in structuring the meetings of the campaign "Earthquake, let's talk about it".

Allport and Postman (1947) define rumors as faith propositions on specific (or current) topics, which pass from person to person, usually by word of mouth, with no clear evidence of their veracity. Media were shown (Ma, 2008; Dominick, 2010; Herriman, 2010; Doerr et al., 2012; Qin et al., 2015) to have a key role in their dissemination.

With the recent development of technology, especially mobile devices that have made social networks accessible 24/7, the spread of rumors has become faster than ever, regardless of the credibility of this information (Martin et al., 2021). This brings unprecedented challenges in ensuring the reliability of information. The spread of disinformation often occurs in the context of breaking news, where information released gradually often begins as unverified information. For these reasons, the automatic identification of rumors and fake news from online social media, especially microblogging sites, is a very important and current research topic (Zhao et al., 2015; Alzanin and Azmi, 2018; Fallou et al., 2022).

The scientific study of rumors began in America in 1940, when hearsay about the Second World War spread rising concerns about national security and social cohesion. The US government responded by appointing a committee meant to fight the rumors. Social scientists proposed the establishment of the so-called Rumor Clinic: operational facilities developed within the wider Rumor Project, involving several government agencies. Rumors were collected and cataloged throughout the country. Some newspapers, such as the Boston Herald, contributed to the effort, by publishing every week the most common rumor, together with a list of facts to counter it (Allport and Postman, 1947).

TABLE 1 Information requested when submitting a rumor report to characterize both the population sample and the collected rumor.

	Info about the reporting person		Info about the rumor	Indicator
P1	Name	Q1	Who told you?	Origin (O)
P2	Age	Q2	Did you tell anyone else?	Diffusion (D)
P3	Education	Q3	If so, how many people did you tell it to?	Diffusion (D)
P4	Sex	Q4	Do you believe it?	Trust (T1)
P5	Occupation	Q5	Did you check or verify it? If so, how did you check?	Trust (T2)
P6	Town of residence	Q6	How important is it to you?	Trust (T3)

TABLE 2 Descriptive information of the web users who reported rumors during the 2012 campaign.

Gender	
Males	112
Females	129
Age	
Range	da 15 a 72
Average age	42,77
Age class from 15 to 25	17
Age class from 26 to 35	39
Age class from 36 to 45	90
Age class from 46 to 55	64
Age class from 56 to 65	26
Age class from 66 to 75	5
Education	
Graduate	107
High school	114
Junior high school	18
Primary school	2
Geographic location	
Emilia-Romagna	178
Lombardia	27
Veneto	20
Altro	16

To gain information on the rumors spreading after the 2012 seismic events, a collection was carried out online, through the websites of the sponsoring institutions (the National Department of Civil Protection (DPC), the local administrative entity, Regione Emilia Romagna, our institute INGV, Edurisk, a long-term educational project on natural hazards). We devised an online form to acquire standard information about the rumors described by different participants. Web users were asked to report the rumor, together with some additional details on its origin, its perceived reliability and on its spreading patterns (Table 1). Some personal details on the users themselves completed the online survey (Table 2). From 16 June 2012 to 12 October 2012, we collected 241 rumors reports that could be subdivided into five main categories, as better described below.

2.3 Share: scientific contents to fight fears

The actions devised to contrast the rumors were designed to increase the critical sensitivity of the population involved. Critical sensitivity may indeed attenuate the rumor's strength (Chorus, 1953; Bordia and Difonzo, 2004). To reach this goal during the emergency, all the institutions involved in the public meetings with the population agreed on specific actions. Before each public meeting in a specific area, the strongest rumors at that location were discussed and analyzed to devise appropriate answers and information to be shared during the meeting. This approach meant to foster a healthy skepticism and the development of critical thinking by.

- Sharing seismological concepts and information on psycho-social aspects that influence rumors and their propagation (emotion, level of collective anxiety, uncertainty, social psychology mechanisms such as conformism);
- Promoting good practices such as careful checking on the source of information, instead of a blind trust on the news presented by traditional or new media;
- Suggesting that no institution should be considered authoritative *a priori* (not even those involved in the current information campaign).

After the emergency, the prosecution of outreach activity on themes that were perceived as relevant allowed to keep a strong and healthy relationship with the communities and their local institutions. Dissemination activities carried out in the affected area aimed at addressing the rumors described above. Ad hoc materials were prepared for display and discussed during public encounters of different kinds, including local fairs, public meetings organized by local authorities or cultural associations, science café, lessons in local schools (of all grades) and universities. We also published posts on institutional blogs INGVterremoti (Pignone et al., 2012) and gave interviews to local and national media (press, radio and television).

3 Results

3.1 Meeting with local communities

Based on the approach described above, during the 2012 seismic sequence we organized and held 44 public meetings, between June

FIGURE 3
Pictures taken during the public meetings at different locations, with the population **(A, D)** or with teachers **(B)** and personnel of the national health services **(C)**.

4 and 2 August 2012. Figure 2 shows the locations of these encounters that were attended by more than 6,300 people (Figures 3A, D). Eighteen more meetings were conducted in the following months, between September 2012 and April 2013, gathering another 700 people. This activity was flanked by more specific meetings targeting the schools since the opening of the school year, in September 2012: 800 teachers were engaged during 13 meetings (Figure 3B), together with healthcare professionals from the local structures (AUSL, hospitals, Figure 3C). Meeting duration was variable and depending on public response, ranging from 2 to over 3 h. Typically, two or three INGV researchers (both seismologists and psychologists) attended each meeting.

These meetings proved to be very useful to identify the issues that caused concern among the population. The most frequent questions were collected and updated after each meeting, and allowed to produce outreach materials specifically targeted to address people's worries. Table 3 reports some of these questions. The presence of different stakeholders allowed addressing very different but relevant topics during the same meeting, with the conversation easily spanning from the ongoing natural processes to the measure that can be taken to improve buildings' resistance to shaking. The availability of an open space with the presence of representatives of different institutions involved in the emergency allowed a public conversation that could address various causes of anxiety, related to both the ongoing seismic sequence and the efficacy of its management. Despite the tangible tension that often accompanied the opening of these encounters, the public discussion allowed expressing fears and doubts and most of the times granted the establishment of a positive bond of trust among various stakeholders involved.

3.2 Analysis and strength of the rumors

We classified the collected rumors into five categories, based on their contents: explanatory, conspiracy, catastrophic, paranoid (i.e. subject to persecution mania), and optimistic. Some of the rumors could fall in two or more categories (see Table 4), and in those cases we arbitrarily assigned the rumor to the first category listed. Figure 4A illustrates their relative proportions, with most of the rumors falling within the first three categories (explanatory, 35%, catastrophic, 29% and conspiracy, 26%), and a few exceptions grouped as "other effects". This prevalence of rumors with explanatory, catastrophic and conspiracy nature does not change even if rumors falling into more categories are assigned differently, to their second or third category. To classify and compare different rumors, we further analyzed the dataset assigning a score to the origin (O), diffusion (D) and trust (T) of each rumor. We identified three possible origins for the rumors: institutional sources and research institutes; national and local media; individuals and social media. To each source category we assigned a different degree of reliability, ranging from trustworthy (when the rumor originates from institutional sources, score O=1) to unreliable (single individuals, or social media, score O=3). Figure 4B shows how most of the rumors originate from untrustworthy sources. The diffusion of the rumor was assessed based on the number of people the rumor was repeated to, after being heard. We defined three levels of rumor spread (and associated scores): no diffusion (D=1), when the rumor was not reported to anyone else; sharing with a maximum of 6 people; and sharing with more than 6 people (score D=3). The threshold of 6 people stems from the theory of "six degrees of separation", according to which any person may be connected to any other person in the world through a chain of acquaintances with no more

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TABLE 3 List of common questions raised during the public meetings organized during and after the 2012 Emilia seismic sequence.

n	Question
1	Is there a historical cyclicity in earthquakes occurrence?
2	Are there any links between the various earthquakes occurring in Italy?
3	What are the most dangerous areas in Italy from a seismic point of view?
4	Why did we hear a roar with the strong earthquakes?
5	What is the magnitude of an earthquake?
6	What is the difference between magnitude and intensity?
7	Why do other institutions attribute a different magnitude to this earthquake?
8	Why are there different types of magnitudes to measure an earthquake?
9	Are public funds for the reconstruction calculated on the basis of the recorded magnitude value?
10	According to the seismic hazard map of Italy, this area was not supposed to be dangerous. Is this true?
11	How was this area classified from a seismic point of view?
12	No one told us that our territory was seismic. Why? Whose responsibility, is it?
13	How do you define the seismic classification of a territory?
14	How much does the kind of subsurface rocks influence the effects of an earthquake?
15	Have the Po plain sediments cushioned the tremors?
16	Could this earthquake have changed the morphology of the Emilia region?
17	Where did the sand come from? (Referred to liquefaction episodes that drove underground sediment at the surface)
18	Is the underground now empty?
19	Can drilling cause an earthquake?
20	Does the subsidence of the land (associated with water and hydrocarbons extraction), contribute to the occurrence of the earthquake?
21	Is the Emilia sequence extraordinary, or is Italy exposed to close events?
22	Why did the second earthquake [of 5/29] do more damage than the first?
23	Why was the second quake stronger even though it was of a lower magnitude?
24	According to the communiqué of the Major Risks Commission [held on June 7], will there be a new earthquake in the province of Ferrara?
25	What are the rules of conduct to follow before, during and after the earthquake?
26	Why do reinforced concrete houses also collapse? When can a building be considered anti-seismic?
27	How can I verify the safety of my home?
28	If my house was badly built, what can I do to improve it?
	What can I do, alone, to make my home safer?
29	If seismic retrofitting is expensive, are there other low-cost interventions that I can implement to make my home safer?
30	What interventions can be made on a house that has suffered damage?
31	Are the ongoing safeness checks on buildings reliable?
32	Could the buildings that were found to be accessible for inspection after the two strong tremors have suffered damage with the seismic sequence in place?
33	Following an inspection, my house was judged to be viable. After the numerous events that have taken place these days, can my home still be considered safe?
34	What is the procedure for checking the building in which a production activity is located, such as sheds?
35	Does the same procedure for safeness check for production activities, such as warehouses, also apply to schools and hospitals?

(Continued in next column)

than five or 6 intermediaries (Milgram, 1977). While 33% of the rumors were repeated at least a few times, half of them were shared with more than 6 people (Figure 4C). The last three points of the survey (Table 1) were used to measure the confidence in the rumor. This was done combining three different indicators meant to: measure the degree of belief in the rumor, according to the rumor reporter (T1); check if the content of the rumor was verified by the reporter by consulting other trustworthy sources (T2); and the importance of the rumor content, according to the reporter (T3). The degree of belief T1 was assessed by asking the reporter "Do you believe it?“. The five possible answers (not at all, very little, little, much, very much) were converted into a numeric value ranging from 1 (little, or no trust) to 3 (high degree of belief). The indicator T2 was established from the responses to the question "Did you check or verify the rumor content?“, T2 values could range from 1, when the content was verified by consulting an authoritative source, to 3 if no check was made. The indicator T3 was computed by asking the questionnaire filler "How important is this content for you?“, and ranged from 1 (not important at all) to 3 (very important).

The reporter's degree of belief in the rumor was then computed according as:

$$T = \frac{T1 * T2 + T3}{3}$$

Obtained T values range from 0.67 to 4 and were then classified into three levels of trust (low, medium and high), according to their T values within this range (Figure 4D). In most of the cases, the responders have a medium or high level of confidence in the rumor, while only 30% of the rumors are considered unreliable by the reporting person.

In order to identify the most frequent and dangerous topics, we used the indicators described above to compute the rumor strength (La Longa el al., 2014). According to Allport and Postman (1947), the strength of a rumor, ***R***, is the product of the subject relevance, ***S***, and its degree of ambiguity, ***A***. In our case, the subject of all rumors is always the earthquake and, given its major impact on people's lives at the time of the survey, we assigned ***S = 1*** to all rumors. More details about the limits and strengths of this approach are provided below, in the Discussion section. Rumor's ambiguity was computed as a sum of the scores attributed to the reliability of its source (O), its diffusion (D) and the confidence in the rumor itself (T):

$$R = O + D + T$$

Table 4 shows an excerpt of the collected rumors, together with their classification according to rumor type, origin, diffusion, trust and strength. The distribution of strength computed for all collected rumors is shown in Figure 5, while Figure 6 shows the distribution of rumors strength

TABLE 4 Excerpt from the list of collected rumors, classified according to their type (explanatory, catastrophic, conspiracy, positive, paranoid, other); their origin (O); diffusion (D), Trust (T) and strength (R). See text for discussion.

	Classification	Rumor description	O	D	T	R
1	Explanatory catastrophic	*The underground gas reservoir could easily explode with a new seismic event*	3	1	3	7
2	Conspiracy	*The strongest events had a magnitude larger than officially declared*	3	3	3	9
3	Explanatory	*The earthquake is due to fracking or to "seismic" exploration; the government lowers the magnitude to avoid refunds*	3	3	2	8
4	Catastrophic	*We expect another fault will generate similar events*	2	1	2	5
5	Catastrophic	*Mice, rats and moles are dying because of an underground temperature increment (up to 50 °C). This indicates that a volcano is forming in the Po Plain (just as in the 1997 LA movie)*	3	1	3	7
6	Explanatory	*Landslides (a few m deep) occurred last year near Sant'Agostino while explosions were heard, likely related to underground fracking*	3	2	3	8
7	Explanatory	*They say that the seismic swarm is due to the underground gas storage*	3	2	3	8
8	Other	*I've heard of a solar storm that will end in 2013, which could affect earthquakes*	2	2	3	7
9	Catastrophic	*Very likely, we'll have another strong earthquake due to a third fault that has not completely slipped yet*	3	2	3	8
10	Explanatory	*A lot of fishes died near Bondeno, after the May 20 event, because of the gas that were released and reached the water at the surface*	3	2	2	7
11	Explanatory	*An oil company exploded underground charges to create natural reservoirs for gas storage. They removed their installation overnight*	3	1	3	7
12	Other	*The earthquake is related to heat*	3	1	1	5
13	Catastrophic	*If it is very strong, it will last 3 years*	3	3	3	9
14	Other	*After the shocks, one could smell sulfur*	3	1	1	5
15	Explanatory	*Gas injected into groundwater causes earthquakes. There is not enough control on private companies*	2	1	2	5
16	Explanatory Conspiracy	*Earthquakes are due to the work carried out by "the Americans" at the Rivara gas storage site. They remove their equipment right before the event*	3	1	3	7
17	Explanatory	*The earthquake was caused or enhanced by gas extraction, which left void space underground*	3	1	1	5
18	Conspiracy	*The Emilia earthquake was not M 5.9 but 7.5, according to NASA and other international institutions*	3	1	2	6
19	Catastrophic	*It's getting closer and will be here soon*	3	1	1	5
20	Other	*A pigeon breeder reports that birds flew away the day before the earthquake and returned past mid-June*	3	3	3	9
21	Explanatory	*In Cremona earthquakes cannot happen because of the alluvial terrain. No strong earthquake ever struck here*	3	3	2	8
22	Explanatory Positive	*I've heard that the activity at the mud volcano in Nirano was stronger days before the earthquake. This could be a potential precursor*	3	2	3	8
23	Paranoid	*Too much badness in the world, God punished us*	3	1	1	5
24	Conspiracy	*The earthquake is caused by the HAARP antennas that the US government uses to study the atmosphere*	3	3	1	7
25	Catastrophic Paranoid	*An old lady dreams of her brother who says that between October 7 and 8 there will be another earthquake that will occur between Bologna and Ferrara, on the other fault. She was ready to leave before the first event thanks to her brother's warnings*	3	1	1	5

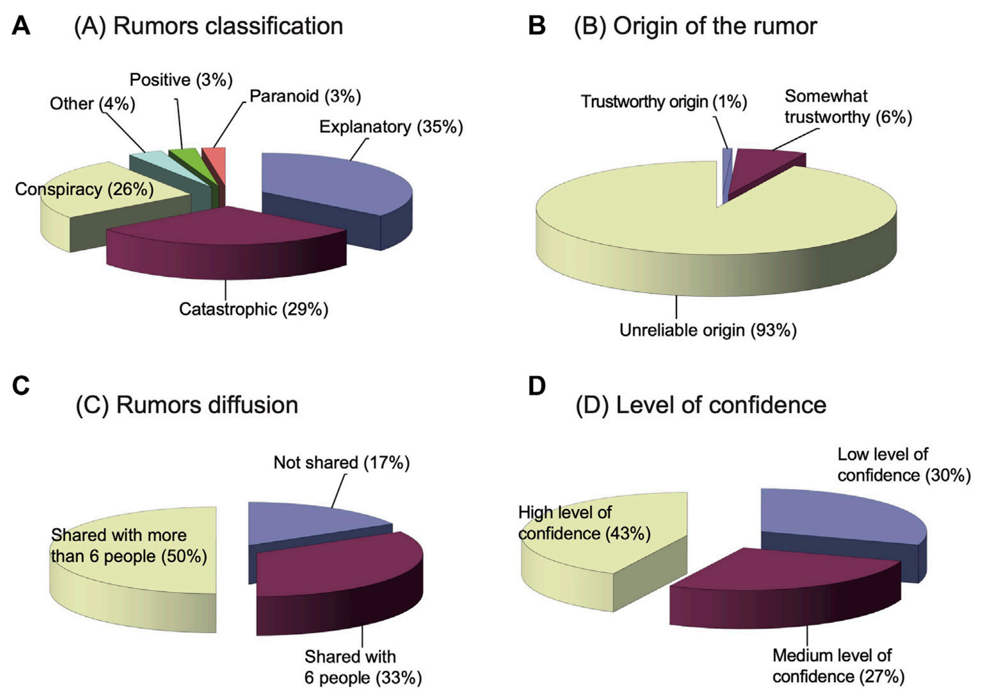

FIGURE 4
(A) Rumors classification. Collected rumors were classified in different categories based on their content. The most common are: explanatory (when the rumor focuses on the cause of the earthquake); catastrophic (when it suggests disruptive outcomes); conspiracy (when the emphasis is on alleged truth distortion by media or public institutions). **(B)**. Reliability of the rumor's source. We considered the institutions (such as the national Civil Protection Department) as trustworthy sources, while individuals and social media are considered unreliable. According to this classification, most rumors originated from unreliable sources. **(C)**. Rumor diffusion indicates if and how much the reported rumor was shared with other people. Most rumors had ample diffusion. **(D)**. The level of confidence, or trust, expresses how much the survey respondents believed in the reported rumor. Most rumors are accompanied by medium or high level of confidence.

for different rumor subjects. The main topics are better described below, and include: the occurrence of anomalous phenomena (often considered possible precursors); the anthropogenic nature of the seismic sequence (supposedly triggered by fluid injection or extraction); the actual forecasts of imminent seismic events; and the existence of a conspiracy to conceal the real magnitude of seismic events. The figure shows that most of the strongest rumors (R = 9) fall in the subject of an "anthropogenic triggering" of earthquake, but strong rumors are present in all subjects. Table 5 lists all the strongest rumors collected (R = 9) and the recurrent topics are described in the discussion. Specific outreach content was devised to debunk these rumors.

3.3 Sharing scientific knowledge

Scientific information was made available in the form of maps, geologic sections, images and pictures of present and past seismic events, sketches or diagrams, written text. These materials were displayed or distributed on site as posters, booklets, leaflets, bookmarks, or projected on screen. The topics included details on the seismic sequence: maps showing the distribution of epicenters and their magnitude were particularly appreciated, together with maps illustrating the temporal evolution of the seismicity. We found it important to provide information on the geology and tectonic setting of the region: geological sections and maps were used to describe the thrust and folds buried underneath the Po plain sediments, and to justify the occurrence and position of the seismic sequence. Historical seismicity completed this geological picture of the region: maps showing the location and magnitude of the historical events allowed a comparison with the most recent activity, while the temporal distribution of the main sequence helped to constrain the timescale of tectonic plate interactions. In some specific cases, even written explanations proved useful. By keeping the text simple and concise, we could provide clear definitions for some relevant concepts that easily enter the public discourse about seismicity without being fully explained: people showed appreciation for bookmarks describing the difference between magnitude and intensity, or reporting the different grades of the historical Mercalli scale. After the controversy about the alleged anthropic origin of the earthquake, we also provided simple definitions for terms like "fracking" and "gas storage", or explained the difference between "triggered seismicity" and "induced seismicity" (National Research Council 2013). These definitions were complemented by brief information on where (and since when) gas and oil are actually exploited or stored in the affected region. This kind of information gained a lot of attention during public events, despite their format (written explanations) apparently not appealing in a busy context. The short length of each body of text and the relevance of the topic at that time compensated for the little charm of the presentation.

Outreach efforts also focused on the phenomenon of shallow ground heating, commonly associated with diffuse degassing and bubbling well water (Capaccioni et al., 2015 and references therein). The occurrence of these phenomena captured the attention of a frightened population and has entered the local news several times

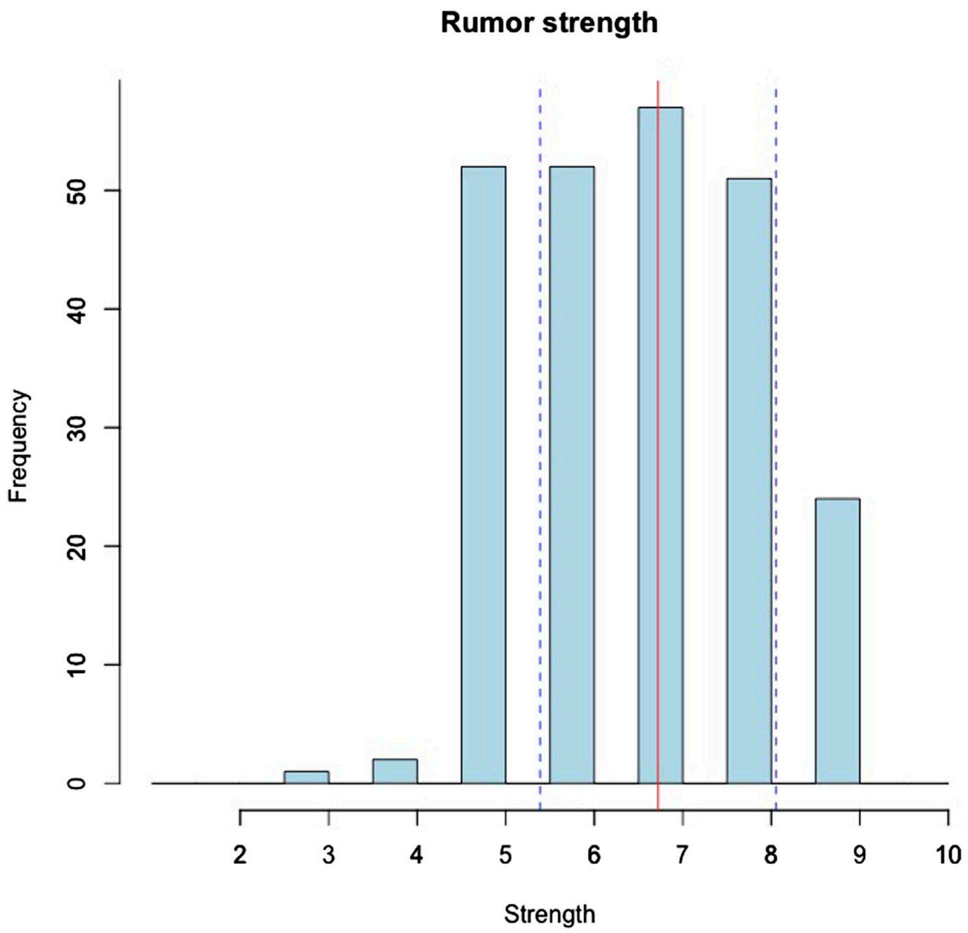

FIGURE 5
Rumor strength distribution. Vertical lines indicate the mean value (red) and standard deviation (blue, dashed). The strongest rumors (R = 9) are more than one standard deviation above the mean. They are listed in Table 5.

since the 2012 sequence. Repeated episodes, sometimes accompanied by the death of small animals, fed the rumors about their potential role of these anomalies as precursors of impending seismic activity. The phenomenon, and the public attention about it, motivated a scientific study that was carried out by the University of Bologna, in collaboration with INGV (Capaccioni et al., 2015; Nespoli et al., 2015). This study showed that observed changes in ground temperature and gas composition are well explained by an exothermic oxidation of biogenic methane, which is abundant in the soil of the Po plain. This explanation does not imply a direct connection with the seismicity in the area, as the phenomenon occurs any time ambient conditions are favorable to methane oxidation. These scientific results were shared during public meetings, and commented during interviews released to local media and were described in a post on the institutional blog INGVterremoti (https://ingvterremoti.wordpress.com/2015/11/18/cosa-sappiamo-delle-terre-calde-di-medolla/).

4 Discussion

During the emergency phase, direct contact with the population and local institutions (administrative and health institutions, cultural associations . . .) proved to be a strategic asset to ensure prompt and effective communication among the different stakeholders involved. These direct contacts had an important role in building mutual trust and dialog with the citizens.

The analysis of hearsay provides a special point of view on widespread fears and feelings about the earthquake. The relation proposed by Allport and Postman (1947) to compute the strength of rumors is certainly a good starting point for a preliminary assessment, even though this approach never went through a proper validation and critical analysis. One of the main criticisms risen about this approach regards the link between the topic of the rumor and its strength: according to some authors the importance and ambiguity of the theme cannot be considered a correct predictor of the rumor strength, as other features (such as the anxiety of the individuals involved) need to be considered. The criticism came primarily from the fact that the basic law of rumor postulated by Allport and Postman (1947) was not empirically grounded in any rumor research, but was adapted from the earlier work of McGregor (1938) on factors influencing predictive judgments (Rosnow, 1980). One difficulty with the basic law of rumor was that the factor of “importance” was elusive and not easy for researchers to operationalize. Also of concern was that the basic law of rumor ignored the emotional context of rumor. Based on subsequent research findings, Rosnow (1991, 2001) proposed a modified theory in which rumor-mongering is

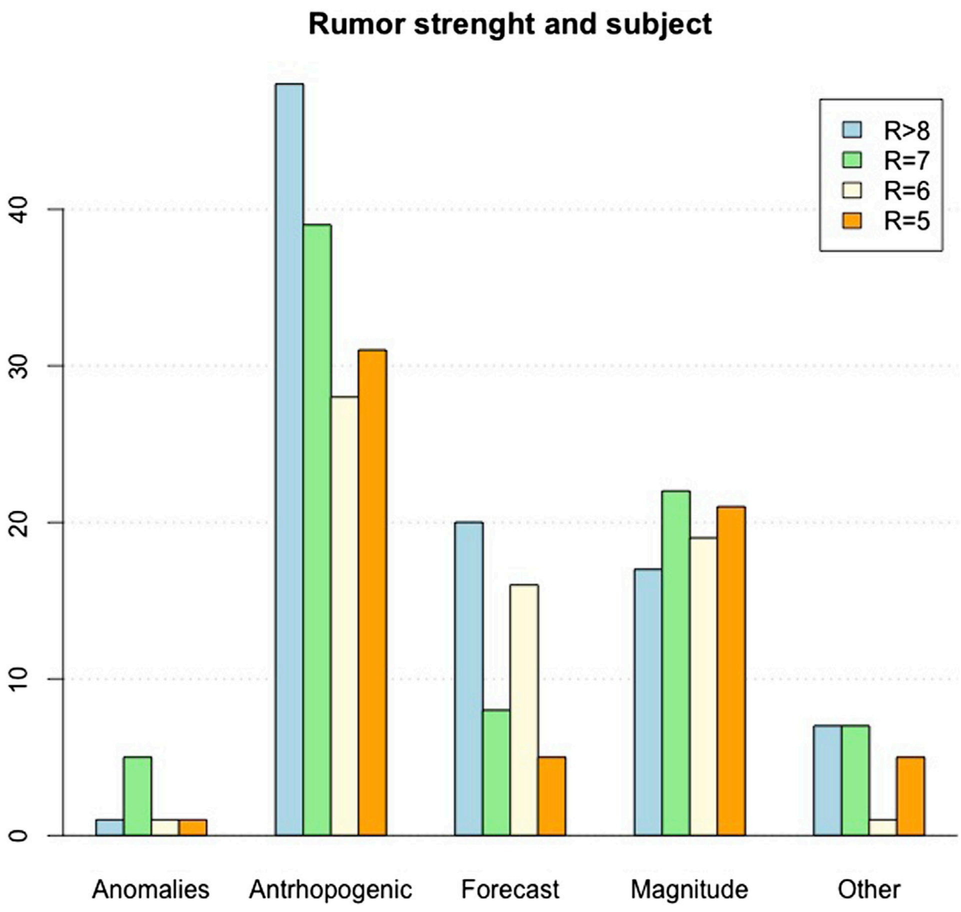

FIGURE 6
Distribution of rumors by strength and subject. Most of the rumors revolve around the anthropic nature (146 rumor reports, with an average strength of 7.0) and the supposedly hidden magnitude of the earthquakes (79 rumor reports, with average strength 6.7). Other rumors forecast future events (49 reports, average strength 7.3) or report the occurrence of anomalous phenomena, possibly related with the seismic sequence (8 reports, average strength 6.9). Twenty other rumors regard other topics (average strength 7.2).

viewed as an attempt to deal with anxieties and uncertainties by generating and passing stories and suppositions that can explain things, address anxieties, and provide a rationale for behavior. At a moral level, we can usually distinguish between two types of rumors (Rosnow et al., 1986), those invoking hoped-for consequences (wish rumors) and those invoking feared or disappointing consequences (dread rumors), but finer distinctions within each category have been described as well (e.g., Difonzo & Bordia, 2000). Another addendum is that people have a tendency to spread rumors that they perceive as credible (even the most ridiculous stories), although when anxieties are intense, rumormongers are less likely to monitor the logic or plausibility of what they pass on to others (Rosnow, 2001). More recently, the extensive use of social media allows to gather significant amounts of data on rumors' spreading. Large data sets are used to explore the rumors' propagation across the community using natural language processing and the mathematical characteristics of complex networks (Cheng et al., 2021).

In our case, however, we limit our analysis following the Allport and Postman approach. The theme of earthquake in the aftermath of the seismic sequence certainly had a strong societal importance in the impacted area, and the individuals involved collectively suffered a high level of anxiety. We therefore applied the Allport and Postman formula focusing on the degree of ambiguity of the theme, and we used three indicators (source, diffusion and trust) to compute the rumor's strength. This allowed us to identify and address the strongest rumors.

Most of the rumors that spread up immediately after the May 20 event focused on three main topics: the anthropogenic trigger of the seismic sequence, the prediction of forthcoming earthquakes, and the real (higher) magnitude of the events. The strongest rumors were carefully analyzed and debunked during public meetings and accompanied with sound scientific information.

4.1 The manmade earthquake

The theme of induced seismicity, in particular, stirred the public discussion for months, in a region where both the exploitation of geo-resources (mostly gas and minor oil) and gas storages within aquifers have been going on for decades. Not long before the seismic sequence started, a British corporation submitted a project to open a new gas storage facility near the town of Rivara, very close to the epicenter of the May 29 main shock. While the proposal was eventually rejected by local and regional authorities, the corporation could perform the

TABLE 5 List of the strongest rumors collected (R = 9).

Classification	Rumors
Conspiracy	*The strongest events had a magnitude larger than what officially declared*
Catastrophic, paranoid	*This sequence is just a precursor: the biggest event still has to come and will create a new mountain where now is the Po plain. Remember the date 21 December 2012: a millennial cycle closed then and people, things, animals from that cycle will be swiped away*
Explanatory	*Gas and oil extraction in the area, the emission of water at high pressure and drilling and storage of billions of cubic meters of gas in a huge underground storage. This intervention is called fracking and can be the cause of seismicity. This is well known and is why in the United Kingdom they are closing the reservoirs. These activities broke a natural equilibrium that was established in the past*
Explanatory	*The most common rumor about the earthquake is that fracking is responsible for it*
Explanatory	*They say the earthquakes were caused by underground explosions in natural caves underneath Rivara and Finale Emilia, triggered to study the effects with the aim of exploiting the caves for gas storage. According to the rumor, these explosions would have awakened our sleeping fault*
Conspiracy	*The May 20 event had a Magnitude 6.1 instead than 5.9 as mentioned by mass media and INGV. A web search shows that other institutions suggest magnitudes higher than 6. Why are Italian estimates always lower?*
Explanatory, conspiracy	*The cause of earthquakes are the obscure drillings related to gas storage in Rivara. Magnitude is supposed to be much higher than 5.9 (6.3 or 7.3). This information is not shared to prevent the State from repaying the damage*
Positive	*The sequence may last a year or more, with events of similar magnitude. In the 1,500 the lords of Ferrara lived in shelters for 4 years because of the earthquake*
Conspiracy	*The power of these shocks was stronger than what was declared. Otherwise, the State should have paid more than what is available. Who works in civil protection knows this*
Conspiracy	*all major shocks were officially under 6 but in reality, they were stronger, in fact at least one was lowered later. This is a strange case, as it happens, they do not pay us just for earthquakes below six; they say they were lowered on purpose*
Conspiracy Explanatory	*This earthquake is different from the others; we are in a non-seismic area and therefore its occurrence is strange; then all those shocks and they just happen to be where they're drilling. There are drilling exactly where the earthquake happened and they could have told us since they triggered it*
Catastrophic	*If it is very strong, it lasts 3 years*
Explanatory	*Drillings for gas storage stimulate earth crust movements*
Explanatory	*The shock in Ravenna was caused by drilling for gas and oil*
Conspiracy	*The rumor is that the magnitude of the 29 May event was much greater than reported (up to 6.8–7.4)*
Explanatory Conspiracy	*Fracking responsible for Emilia earthquakes, with approval of the Monti government. This technique is banned in several countries like France. The population was kept in the dark about the danger, even after the event on 17/07/11. Now the menace of a third fault about to break. But we live in the Po plain where the seismic hazard is zero. This is what they always told us. They will not pay us as they did in case of other earthquakes. It's time to stop it*
Other	*A pigeon breeder says that the day before the earthquake a group of birds went away and returned only in the middle of June*
Explanatory Conspiracy	*Shocks are probably caused by drilling in Rivara. Excavations are protected by the Army, also the American one. Who signed the project cannot be found. In Solara, near Modena, fire peaks spreader alternating with high water jets from the ground*
Positive	*I heard that the top manager of your organization is a P.E. sent there by the Minister of Education*
Conspiracy	*I've heard more than one person that the magnitude of the May 20 event was higher than that reported by INGV.*
Conspiracy	*With increasing insistence, we hear and read that the earthquake of 5/20 had a magnitude greater than 6 and that it was purposely "downsized" as the Italian government, in the first case, would have had to provide for the full compensation of all damage suffered*
Paranoid	*You're losers, what the fuck you wanna monitor? Everybody knows the secrets you hide,,,, Be ashamed to live*
Catastrophic	*Between 13 and 16 of July another earthquake will occur with magnitude between 4.5 and 6.1 in Emilia Romagna*
Explanatory	*Many different hypotheses about the causes of this earthquake ..... From the preliminary studies conducted on the ground for the construction of the rivara deposit ..... to fracking used to extract materials from the subsoil .... and in general from the extraction of gas or oil ..... up to "targeted" scientific experiments currently underway on our territory (they did not tell me what purpose) .... ah! also the famous underground Apennine ridge that moves to emerge and of which we are the summit ..... coincidentally ...*

required preliminary studies and geophysical prospecting. Sparse information on this industrial plan quickly merged with hearsay on the damage caused by fracking (which was never permitted in Italy), resulting in a confused picture where dangerous operations, involving gas and underground explosions, were carried out to benefit unspecified interests. Despite the lack of industrial activity at this specific site, the public concern was such that the regional authorities appointed a commission (ICHESE) to address the issue. The committee report concludes: "the Commission believes that it is highly unlikely that the activities of hydrocarbon exploitation at Mirandola and the geothermal activity at Casaglia have produced sufficient stress change to generate an 'induced' seismic event. While it cannot constitute proof, the current state of knowledge and all the processed and interpreted information does not allow ruling out the possibility that the actions involved in hydrocarbon exploitation in the Mirandola field may have contributed to 'trigger' the Emilia seismic activity". The Committee continues by stating: "The study does not indicate any evidence which can associate the Emilia 2012 seismic activity to the operation activities in Spilamberto, Recovato, Minerbio and Casaglia fields, whereas it cannot be ruled out that the activities carried out in the Mirandola License area have had a triggering effect". Finally, a brief note regards communication, suggesting that it is "critically important to implement an Outreach and Communication Program targeting local residents/administrative authorities so that they can gain confidence that operations are being managed optimally". (ICHESE, 2014).

4.2 The earthquake about to happen

The rumor about a forthcoming major earthquake, predicted by various individuals or institutions, was also very common and spread out quickly after the main shocks on May 20 and 29. Our survey allowed us to identify three different versions of this catastrophic rumor. The first version is simple: a major shock is forecasted at a certain time. The rumor started on 31 May 2012 and circulated by word of mouth (telephone calls, texting and social media) in various urban areas (Bologna, Modena, Reggio Emilia, Mantova). In some cases, it was intentionally spread to allow actual profiteering, with people pretending to be civil protection operators and inviting citizens to evacuate their houses. In one case, the rumor led to the evacuation of the National Bank (Banca d'Italia) offices in Bologna. The resonance of this episode, which involved an authoritative institution, contributed to increase the psychosis, leaving abundant tracks in local press and social media. The strength of the rumor was such that the National Department of Civil Protection, the local public authorities and INGV had to release official statements to counter it. These actions lowered the public's concerns and, together with the lack of seismicity at the predicted time, could finally downgrade the rumor to its actual nature. On 1 June 2012, the district attorney's office announced the possible opening of a legal procedure for false alarm.

A second version of this rumor was more sophisticated and malicious, and was triggered by the so-called Northern Independent Center for Seismology (CSIS). CSIS created a blog and published a video forecasting a strong event between July 13 and 16, 2012, roughly in the same area hit by the May sequence and with magnitude between 4.5 and 6.1. The video gained about 40,000 visualizations on YouTube. Furthermore, in an attempt to gain credibility, the rumor was also published on a faked copy of a very popular blog, and thanking the author (Beppe Grillo) for posting the rumor.

The third version was more articulated and refers to an alleged earthquake prediction attributed to a parish priest in Massa Finalese. According to the rumor, the Virgin Mary appeared to the priest in a dream, announcing a devastating earthquake due to occur on Saturday, September 22, before 9 a.m. The rumor spread out quickly, especially around Ferrara, Modena, Bologna and Mantova. Different accounts attribute the vision to other priests in the area, or to a parishioner, and indicate different sites (Ferrara) or timing (September 29) for the predicted earthquake. The rumor was accompanied by hearsay according to which the parish priest was about to be arrested or beaten by angry citizens, all baseless news. Fact checking on the site allowed to tie the rumor to a homily by the priest in Massa Finalese, during a mass at the end of June 2012. In the homily, the priest considered that the worst period for the people hit by the seismic sequence in May, was going to be in September, with the re-opening of the schools and the resumption of the customary habits, and with lesser attention from the rest of the country.

The theme of earthquake prediction is closely associated with the issue of precursory phenomena. Hearsay (sometimes reinforced by local media) often highlighted the occurrence of "clear" signs of a forthcoming earthquake that accountable institutions (scientists, civil protection) either fail to recognize or do not address properly. Popular precursors include strange animal behavior or particular weather conditions. A particular phenomenon that periodically raises public attention in this area is the increment of ground temperature, sometimes associated with heated well water, bubbling with gas (Bonzi et al., 2017). In some cases, the combination of heat and gas can cause the death of crops or small animals (fishes, in particular). These episodes are rather common in the area: they are found in historical chronicles and even entered the local toponyms (such as "Terre Calde", Hot lands). The long seismic sequence, however, promoted a renewed attention to the environment and its changes. Studies prompted by this renovated attention finally provided a scientific explanation for the phenomenon which is totally unrelated to the seismic sequence (Capaccioni et al., 2015; Nespoli et al., 2015). Nevertheless, these events are noted and still interpreted as potential precursors of future events.

4.3 The concealed magnitude of the events

The alleged falsification of the magnitude values by the institution in charge of seismic surveillance (INGV officials, in particular) is another persistent false news. This rumor had different versions, and stems from the observation that the magnitude values released by INGV may change with time or may not coincide with estimates performed by other, real or alleged, international agencies (from France, Poland, USA …). Magnitude values reported abroad tended to be higher than those officially released by INGV (5.9), with values ranging from 6 (according to USGS) and 6.1 (provided by the European Agency CSEM-EMSC) up to 7.3. A version of the rumor mentions an amateur seismologist living in Novi, near Modena (or a pharmacist from Carpi, or Mirandola) who could "record" magnitude values well above 7, with his own two instruments located on the second floor in his house. According to all these rumors, INGV conspired to keep the magnitude below 6, as this would be a threshold value above which the State would fully cover for the damage. According to another version of the rumor, the Civil Protection promoted a major reformation just 1 month before the earthquake (perhaps knowing it was about to happen) only to prevent any compensation of the damage caused by natural disasters (this position being eventually retracted after the event, for mere political expediency). This hoax is not new and is directly tied to the L'Aquila earthquake, in 2009. At that time, coverage of full damage was only granted for those towns where the macroseismic intensity was found above the VI grade of the MCS scale. The confusion between magnitude and macroseismic intensity raised malicious suspicions against the normal process of magnitude manual revision that is always carried out immediately after major events.

5 Conclusion

In the aftermath of the 2012 seismic sequence in Northern Italy, INGV carried out an extended outreach effort to address the need for information of the impacted population.

The impacted community and their administrative authorities received these diverse outreach activities with great favor. Even though we cannot provide a quantitative measure of the efficacy of these activities, the overall response of the public suggests that timely outreach was both appreciated and needed.

The organization of several public meetings were possible thanks to the fruitful collaboration between the Civil Protection, INGV, the representatives of the local communities, the regional network of healthcare assistance, and the involvement of local volunteering associations. The combined efforts of these stakeholders contributed to the establishment and formalization of a good practice that promotes effective communication during emergencies. Preliminary contacts with local representatives proved particularly useful to identify the specific themes or topics that were of interest for each community. This allowed us to prepare and share scientific or psycho-social contents that were both relevant and timely for those participants, at the time of that particular meeting. An informal structure of the public encounter, that leaves ample time for questions and open discussion, and where the presentation of scientific information is limited to a brief, initial overview, proved to be successful in building a positive relationship among all participants. The identification of fears and beliefs allowed to contain and counter uncontrolled rumors and prevent them from driving the public discussion. Future studies, encompassing a quantitative analysis of rumors diffusion and the comparison with other case studies, such as the recent SARS-COV2 pandemic, will provide further tools to counter misinformation.

The approach based on multiple meetings with the population has been followed in 2014 (Camassi et al., 2014), in the occasion of minor seismic sequences, as in the case of Gubbio, when about 400 events (mostly with magnitude below 3) were recorded between December 2013 and December 2014. The strongest event (Mw 3.9) was recorded on the 22nd of December 2013 (Marzorati et al., 2016).

More recently, the Amatrice seismic sequence taking place in 2016, has proven more difficult to address in terms of emergency communication, given its dramatic consequences over a very wide area in Central Italy. The sequence initiated on the 24 August 2016 with the Mw 6.0 Amatrice earthquake and was followed on 26 October 2016 by the Mw 5.9 Visso earthquake; the largest event, the Mw 6.5 Norcia earthquake, occurred on the 30th October. Each mainshock was followed by sustained aftershock activity. In that occasion, 24 meetings were organized with several schools in the area, involving almost 1,500 teachers and parents. Despite greater logistic difficulties, the 2016 experience confirms the positive outcome of the open interaction between scientists, civil protection and local communities.

Planning and participating in these public encounters favored mutual trust and reciprocal knowledge, improving the coordination among the different components of the civil protection system. The direct interaction with the communities affected provided important hints for the development of outreach strategies that go well beyond the emergency phase, and contributed to defining the scientific contents for awareness campaigns and educational activities.

These experiences affected the way in which we develop educational materials, promoting a transition from science-oriented contents, reflecting our interests and our results, to society-oriented contents, designed to address people's questions, accounting for their fears and understanding of geological processes.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

MC and FL conceived and organized the rumors' collection and analysis. RC participated in the organization of the outreach campaign "Terremoto, parliamone insieme" and MT conceived and wrote the first draft of the manuscript. All authors participated in the public outreach campaign, attending some (MT) or many (MC, RC, EE, FL) meetings, collecting FAQs and elaborating outreach materials for the campaign. All authors were involved in the analysis of the rumors and contributed to writing the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Officially social: Developing a social media crisis communication strategy for USGS Volcanoes during the 2018 Kīlauea eruption

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The USGS Volcano Science Center has a long history of science and crisis communication about volcanoes and their eruptions. Centered mainly on websites, email notifications, traditional media, and in-person interaction in the past, our toolkit has expanded in the last decade to include social media channels. This medium has allowed us to communicate with both long-standing and new audiences in new ways. In the process, social media communication has further developed trust in USGS researchers. In particular, the nearly 4-month-long 2018 eruption of Kīlauea volcano in the State of Hawaii necessitated the rapid development of a communication strategy that more deeply incorporated web and social media (Facebook and Twitter) channels to share critical eruption information. This was the first major volcanic eruption response where the USGS used official social media accounts as a significant form of public communication and outreach. These timely and conversive interactions furthered engagement with residents and reinforced the USGS as an authoritative and approachable voice on the eruption with U.S. and international audiences. In many cases, USGS Volcanoes' social media channels were also sampled directly by media outlets looking to provide current information, particularly by local reporters and citizen journalists. This helped disseminate scientific information directly to those who needed it and removed pressure from observatory scientists to respond to media requests. In short, the conversational tone and engaged and inquisitive online audience allowed the USGS Volcanoes' social media channels to act as a virtual community meeting, which nurtured a nearly continuous educational environment for both directly affected and distant members of the public. We present the history and details of this strategy here in hopes that it will benefit volcano observatories and other official agencies and crisis communicators.

KEYWORDS

social media, Kīlauea, United States Geological Survey, crisis communication, volcanic eruption, Hawaii, hazard communication

1. Introduction

Within the Federal government, the U.S. Geological Survey (USGS) Volcano Hazards Program is responsible for reporting changes in volcanic behavior in the United States to authorities and the public to minimize losses from a volcanic event (Stovall et al., 2016). The five USGS volcano observatories accomplish this goal by monitoring volcanoes and providing critical alerts, notifications, and situational awareness to mitigate the impacts of volcano hazards. USGS volcano observatories employ a multi-pronged approach that includes a suite of communication products and channels. Social media was an important medium through which USGS shared official information during the 2018 eruption of Kılauea volcano in the State of Hawaii (Figure 1).

The communication of natural hazards information can positively or negatively impact people's lives, livelihoods, and mental health, depending on the quality of the information and what is conveyed. To be effective, it is paramount that official messages (such as those from volcano observatories) be seen and trusted as authoritative sources of scientific information (Petty and Wegener, 1998). Trust is built by forming relationships, being a present, active part of a community, and exhibiting expertise and transparency in communicating hazards (Covello, 2010). Reliable scientific communication also reflects *benevolence*, *openness*, *competence*, and *integrity* (Besley et al., 2021).

But how can an institution like a volcano observatory build and maintain trust? Volcano observatories are made up of people, often from the same community as the one they serve. Observatory staff learn about community concerns and gain greater empathy by participating in community events, answering questions, and holding conversations with community members. Benevolence is conveyed with empathic communication of safety and hazard information. The same community engagement fosters openness because it shows the willingness of observatory staff to listen. Scientists are generally seen as experts in a specific subject matter (Fiske and Dupree, 2014), and providing consistent information within that area of expertise promotes perceived competency. For example, the level of expertise of the USGS Hawaiian Volcano Observatory (HVO), which is closely integrated with the communities it serves, was ranked highly by a sampling of Island of Hawaii residents based on a study of their communication of eruption information in 2018 (Goldman et al., 2023). By fostering trust before a volcanic crisis occurs, volcano observatories can be more effective and considered a reliable and credible source of information in times of increased hazard (Lowenstern et al., 2022).

Trust can be built in a virtual setting as well. When government agencies actively share information, especially *via* social media and accessible websites, citizens are more informed about current events and policies, which increases their perception of transparency and trust in government (Song and Lee, 2015). The nature of social media is just that—social—and online spaces can be fostered to feel like communities. First-person storytelling promotes authenticity (Saffran et al., 2020), and participation in continued dialog with social media users enhances this virtual community's willingness to engage with government agencies on social media (Chen et al., 2020). In all cases, trust is more easily achieved when communicating in a conversational style that matches the social media channel upon which content is served (McBride, 2018; McBride et al., 2020).

Sennert et al. (2018) stated that volcano observatories should use social media in addition to more traditional methods to deliver authoritative information and remain in constant contact with the diverse communities that care about and need volcano hazards information. Volcano observatories and those managing related social media accounts must display the same traits of benevolence, empathy, and engagement as shown in in-person communities but in a virtual setting. These traits can be displayed by engaging with followers, answering questions, and conversing with commenters. The USGS Volcanoes social media accounts on Facebook and Twitter upheld the advice of Sennert et al. (2018) and operated as a virtual community meeting during the 2018 eruption of Kılauea.

In this manuscript, we describe the communication methods used by the USGS Volcanoes' social media team, and we explore the effectiveness of those methods. We also summarize the advantages and pitfalls of our approach as insights for other agencies involved in disaster response. However, our "lessons learned" are by no means applicable only to government agencies or volcanic eruptions; we hope that our strategy for building a trusted communication platform can apply to the broader community of emergency and disaster responders and science agencies.

2. History of USGS volcano-related communication

The USGS has a long history of communicating information about volcanoes in both calm times and during crises. When it was established in 1912, HVO published a series of bulletins and special reports describing volcanic activity in Hawaii (Bevens et al., 1988). By 1980, when Mount St. Helens erupted, telephone, fax, radio, television, and newspaper were the primary means of delivering information about volcanic unrest to stakeholders and the public. Since then, communication channels have evolved to include, in addition to these portals, automated email alerts, webpage postings (Neal et al., 2005; Driedger et al., 2008; Frenzen and Matarrese, 2008), and social media.

The USGS Volcano Science Center[1] (VSC) is the umbrella under which all five United States volcano observatories operate to monitor volcanic activity and communicate about volcanic hazards within specific geographic areas. The Alaska Volcano Observatory (AVO) is a joint program of the U.S. Geological Survey (USGS), the Geophysical Institute of the University of Alaska Fairbanks (UAFGI), and the State of Alaska Division of Geological and Geophysical Surveys (ADGGS). AVO monitors volcanoes in Alaska and the Commonwealth of the Northern Mariana Islands. The Cascades Volcano Observatory (CVO) monitors volcanoes in Washington, Oregon, and Idaho. The California Volcano Observatory (CalVO) is responsible for California and Nevada. Yellowstone Volcano Observatory (YVO), a consortium of multiple State, Federal, and academic partners, covers Yellowstone and distributed volcanic systems in the four-corners states of Utah, Colorado, Arizona, and New Mexico. The

1 https://www.usgs.gov/centers/volcano-science-center

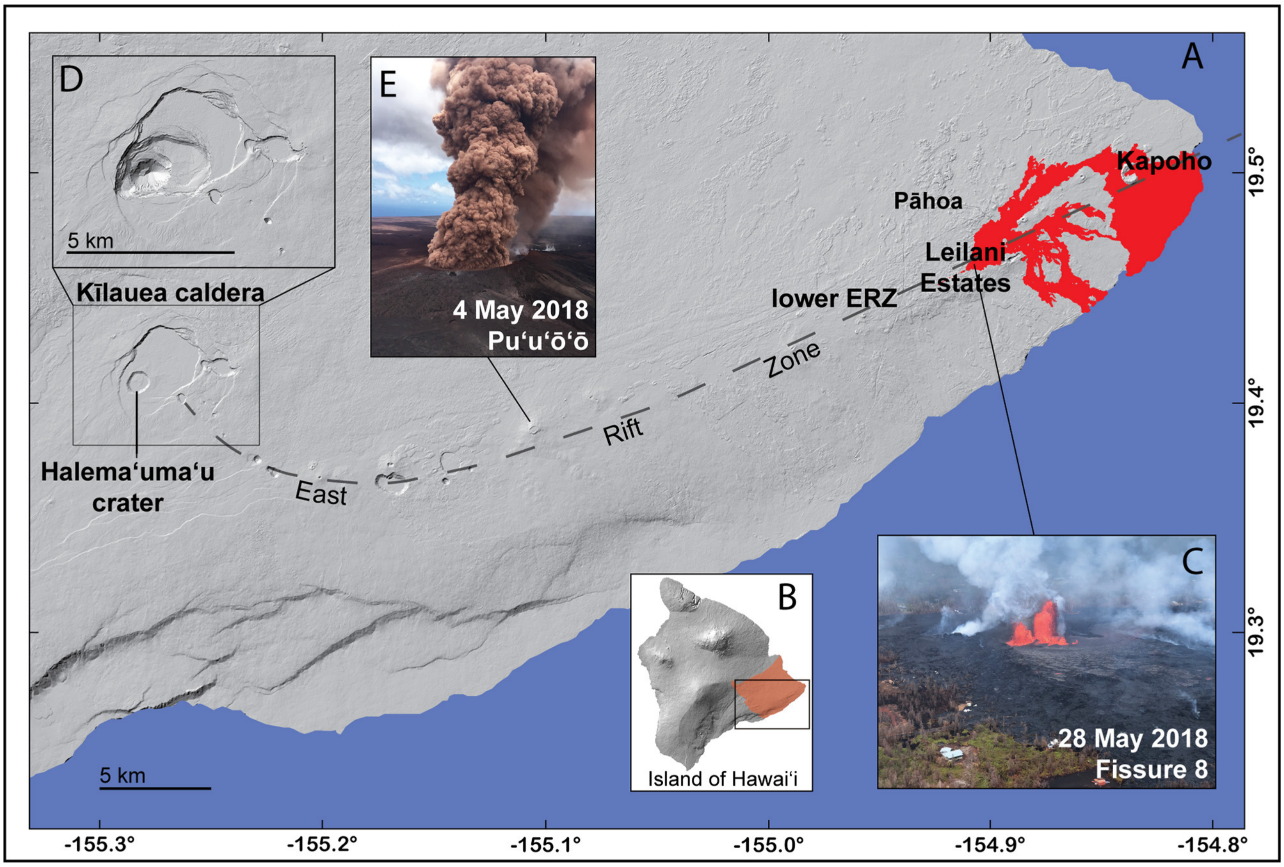

FIGURE 1
Digital elevation model of Kīlauea volcano prior to the 2018 eruption **(A)**. Kīlauea, located on the Island of Hawaii **(B)**, is the state's most active volcano and was the site of two eruptions in 2018. Lava flows (red area on the right side of **A**) erupted through neighborhoods **(C)** and added new land to the island's shoreline. Fissure 8 **(C)** was the primary source of destructive lava flows that originated in Leilani Estates and eventually reached Kapoho. A total of 612 residences were lost[a] in the Puna district (orange shaded area in **B**) during the eruptions. Halema'uma'u crater floor within Kīlauea caldera collapsed by about 500 m during the 2018 eruption. The post-caldera-collapse digital elevation model (inset **D**) is based on airborne lidar surveys flown in 2019 (Mosbrucker et al., 2020). On May 4, 2018, 12:44 p.m. HST, a column of robust, reddish-brown ash issued from Pu'u'o'o **(E)** after a magnitude 6.9 earthquake beneath the south flank (Neal et al., 2019). Pu'u'o'o had been the primary eruption center on Kīlauea for 35 years prior to the changes in 2018, USGS photographs. [a]https://recovery.hawaiicounty.gov/resources/2018-eruption.

HVO monitors all the volcanoes in the State of Hawaii and American Samoa.

Technology and methods used to monitor volcanoes are relatively uniform across all observatories. Similarly, communication tools and general strategies can be shared; however, each observatory also liaises with constituents within their designated regions, requiring some degree of individualized communication to reflect differences in culture, volcano types, and hazards. Scientists-in-Charge and communication professionals at the observatories develop relationships with regional government officials and the communities they serve. Observatory staff prepare regional eruption response coordination plans and conduct outreach to communities. This outreach now includes a suite of digital communication tools, such as websites, social media, and push alert notifications. Together, these tools broaden the reach of observatory communication.

In 2018, dramatic changes to the eruptions of Kīlauea volcano on the Island of Hawaii (Figure 1) tested the USGS's capacity to provide timely volcanic crisis information through modern communication channels. The USGS VSC's social media accounts (referred to as USGS Volcanoes in this publication) became a pivotal part of how local, national, and international audiences could see eruption imagery, learn about eruptive events, and have questions answered.

2.1. Social media and USGS volcano observatories

In 2007, the USGS set up social media accounts that spanned the breadth of USGS science. A Facebook page and podcast series (USGS CoreCast) greatly expanded the ability to push information to a broad audience. As social media gained popularity worldwide, a USGS-wide Twitter account was launched in 2009. Throughout the early 2010s, the number of people using social media grew dramatically (Auxier and Anderson, 2021). Facebook gained about one billion users in the first 5 years of that decade (Ortiz-Ospina, 2019). Followership of USGS science on social media also increased, highlighting the reach of such platforms.

A qualitative review of early USGS social media content shows that the topic of volcanoes was consistently among the most popular on the USGS channels. In 2011, a representative from the VSC began posting content and answering volcano-related questions on the USGS Facebook account, which was the most prolific of all the USGS-wide social media platforms. Between 2011 and 2014, volcano-related posts consistently rose to the top of content analytics for the USGS. Scientists invested in communication at volcano observatories and interested citizens often requested a separate USGS channel dedicated to volcanoes. The tipping point occurred during the Pāhoa lava flow crisis in Hawaiʻi (see Section 2.4) when lava flows threatened communities. As a result, the USGS Volcanoes' Facebook page (@USGSVolcanoes) was launched in January 2015, with two USGS staff acting as content managers.

At the behest of followers and staff who preferred Twitter over Facebook, USGS Volcanoes established a Twitter account in August 2016 (@USGSVolcanoes). The short character count opened the door for less formal, more succinct, and creative dialogue with volcano-interested followers *via* Tweets and strings of replies. The audience and reach of USGS volcano-related content grew with the addition of the Twitter account. Two additional USGS staff members began contributing content to social media in August 2017.

Due to the picturesque nature of volcanoes and volcanic eruptions, it was evident that Instagram (a photography-based platform) was also an opportunity to extend the reach of volcano-related social media. Discussions began in early 2018 about expanding to the platform, but an account had not been opened by May 2018, when the Kīlauea eruption began. Although an Instagram account might have been an impactful educational tool, staff time was limited, and the platform launch was delayed until June 2019.

USGS Volcanoes' social media accounts currently feature content related to all U.S. volcanoes, but predominantly feature science about CVO, CalVO, YVO, and HVO. AVO maintains its own social media channels, and USGS Volcanoes' social media accounts share its content.

2.2. Social media strategy in calm

The primary goals for the USGS Volcanoes' social media presence are to inform and educate affected communities about volcano hazards, provide situational awareness in times of crisis, and engage a broad audience in the science of volcanology. The general strategy to achieve these aims is simple:

- Post photo and video content 5 days per week (Monday–Friday). Ensure social media content is available on USGS or affiliate (and linked) websites.
- Generate automated postings of formal USGS volcano alert notifications (Gardner and Guffanti, 2006) and status changes with an Application Programming Interface (API).
- Consider each post a conversation starter; check posts multiple times daily for comments and answer all questions.

    a. Respond to comments briefly, with a genuine, helpful tone.
    b. Provide follow-up resources that point to additional information.

- Counter mis- and dis-information with non-combative, science-based statements.
- Maintain a quasi-regular schedule of topical posts based on when the U.S. volcano observatories publish informational products (e.g., weekly updates or articles).

As of mid-2022, four USGS Volcano Science Center (VSC) staff develop content to support the overall strategy. In blue-sky times (when no volcanic unrest or crisis response is underway), the schedule for weekly posts depends on notable historic volcanic events (e.g., anniversaries and discoveries), volcano observatory activities (e.g., fieldwork, public events, new publications, and staff introductions), or monthly themes. For instance, the 1980 eruption of Mount St. Helens was a watershed event for the science of volcanology and the USGS (Lipman and Mullineaux, 1981). On the anniversary of events associated with that eruption, the USGS Volcanoes' social media accounts share legacy photographs and videos as "this day in history" types of posts to educate about the evolution of volcano science and our understanding of hazards. Pictures and videos of scientists conducting field and laboratory work provide opportunities to discuss volcano monitoring methods and the scientific process of developing hazard assessments. Interest in Yellowstone National Park and its volcanic system is always high, and the USGS Volcanoes' social media accounts provide a platform to combat the persistent misinformation about doomsday scenarios associated with the Yellowstone volcanic system.

2.3. Integration of USGS volcano activity notifications with social media

In 2009, when Redoubt Volcano in Alaska began showing signs of volcanic unrest (Bull and Buurman, 2013), the public in Alaska asked AVO to post informational updates *via* Twitter. Alaska Division of Geological and Geophysical Surveys (ADGGS) initiated a Twitter account for AVO (@alaska_avo). Official long-form volcano alert notifications and activity updates were published *via* the USGS Hazard Notification System (HANS). AVO staff tailored statements to fit Twitter's character limit, which were automatically posted to @alaska_avo. Observatory ADDGS staff also created manual Twitter posts to provide images and more detailed information. AVO's Twitter account grew to 7,000 followers within weeks, becoming the most prolific Alaska-based Twitter account of the time. The response was overwhelmingly positive and quickly became a valuable two-way communication tool between the observatory and members of the public, who often had scientifically valuable volcano observations, photos, and videos to share with AVO. In response to requests from the public, AVO began a Facebook account (@alaska.avo) in 2013 and an Instagram account (@alaska_volcano_observatory) in 2015.

The USGS Volcanoes' social media accounts emulate the work done by AVO. Official volcano observatory HANS notifications are pushed to social media *via* a social-media-specific Really Simple Syndication (RSS; Curran and McCarthy, 2009). The RSS can be modified to include only certain types of HANS notifications. This is useful because some observatories send out multiple notifications per day or week, which can clog the USGS Volcanoes' social media feed with content that people may not want. Typically, the social-media-specific RSS is limited to notification types that signal a change in volcano alert level, provide critical situational awareness about an ongoing eruption, or share information about atypical but non-hazardous activity at a specific a volcano (Gardner and Guffanti, 2006).

2.4. Decades of HVO outreach and communication

While HVO scientists had communicated with diverse stakeholders since the 1912 establishment of the observatory (Babb et al., 2011), 1991 was the first instance of regularly scheduled media outreach. In the throes of Kılauea's Pu'u'ō'ō eruption (Figure 1), HVO launched a weekly article and activity update titled "Volcano Watch" (Volcano Watch—Volcano Watch approaches its 9th year | U.S. Geological Survey). Local newspapers published the series to keep Island of Hawaii residents informed about Kılauea's eruption. Over time, the weekly series evolved to include general information about many different volcano topics, including native Hawaiian oral traditions, historical accounts, monitoring methods, scientific partnerships, collaborative efforts, and research results. The Volcano Watch series—published in the local paper, then later by email and website—was the cornerstone of HVO's persistent communication effort and continues today. Its reliability helped build a knowledgeable and trusting group of loyal and enthusiastic fans.

For the decade leading up to 2018, HVO became even more active in outreach and community engagement. A dedicated communication professional was hired at the observatory from 2008 to 2020 to help manage public information, particularly during Kılauea's first summit eruption since 1982 (in Halemaʻumaʻu Crater, Figure 1). HVO staff frequently spoke about volcano hazards, including vog (volcanic smog) at community meetings. They responded to local media questions and were guests on radio talk shows. The HVO webpage included a photo and video chronology showing scientists at work with descriptions of activities and how the work served to mitigate hazards. HVO created an "askHVO" email and responded to individual questions. The observatory hosted student visits from local K-12 schools and university classes.

In 2010, HVO worked with Hawaiʻi County to proclaim January as "Volcano Awareness Month". This annual month-long series of public programs—talks, hikes, public meetings, poster sessions, and other means of community interaction with HVO staff and affiliates—has acted as a way for the local community to build personal relationships with HVO staff.

HVO's standing in the community was strengthened during the 2014–2015 Pāhoa lava flow crisis (Poland et al., 2016; Tsang et al., 2019). In June 2014, a fissure broke out on the east flank of Puʻuʻōʻō—the vent for Kılauea's 31-year-long East Rift Zone eruption (Figure 1). The new vent sent lava flows eastward toward the community of Pāhoa and other lower East Rift Zone residential areas. HVO provided information to support situational awareness for county emergency management (Hawaiʻi County Civil Defense), Hawaii Volcanoes National Park, and threatened communities (Brantley et al., 2019; Tsang et al., 2019). HVO scientists participated in multi-agency Pāhoa-based community meetings that were held regularly, as well as occasional meetings held in other nearby communities and subdivisions. Hundreds of residents whose property and livelihoods were threatened by the lava attended. Residents interacted directly with HVO scientists responsible for monitoring the activity and forecasting possible progress (Brantley et al., 2019; Tsang et al., 2019). These personal interactions and community-embedded outreach efforts helped grow trust in the organization (Tsang et al., 2019). This trust-building was critical in bolstering the authoritative voice of HVO during the 2018 crisis.

Social media played a minor role in communicating information during the 2014-15 Pāhoa crisis. Photos and captions from the HVO website were mirrored on the primary USGS Facebook account, as there was not yet an established USGS Volcanoes topical presence. Pāhoa content was intermixed with content covering unrelated science topics from other divisions of the USGS. This was one of the primary reasons the USGS Volcanoes account was spawned in January 2015—to provide a dedicated social media communication stream to meet the needs of an audience experiencing a volcanic crisis.

3. 2018—A changing Kīlauea volcano

March 2018 marked the 10th anniversary of the start of the summit eruption in Kılauea caldera's Halemaʻumaʻu crater (Figure 2). HVO organized several events in coordination with Hawaiʻi Volcanoes National Park. The USGS Volcanoes' social media account hosted two Facebook live events overlooking the crater's lava lake, where an HVO volcanologist discussed monitoring activities and answered questions. All anniversary-related HVO-produced materials (videos, photos, and Volcano Watch articles) were shared *via* social media.

By April 2018, it was clear that the magmatic system beneath Kılauea's summit and East Rift Zone (Figure 1) was becoming increasingly pressurized. HVO published a Volcanic Activity Notice on April 17, 2018, conveying that increased pressurization at Puʻuʻōʻō may result in the formation of a new eruption site on or near the Puʻuʻōʻō cone.[2] On April 24, HVO released a second Volcanic Activity Notice that warned of a greater risk for rockfalls and small explosions from the summit lava lake in Halemaʻumaʻu[3] (Patrick et al., 2020). USGS Volcanoes' social media accounts

2 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2018-04-17T14:51:15-07:00

3 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2018-04-24T19:17:20-07:00

FIGURE 2
Screenshot of a Facebook live event March 19, 2018, where an HVO geologist describes monitoring the rising lava lake. The event commemorated the 10-year anniversary of the Halema'uma'u eruption at the summit of Kīlauea volcano. Total statistics for the two events: 405 comments, 1,370 likes, 60,400 views[a, b]. [a]https://www.facebook.com/watch/live/?ref=watch_permalink&v=1967239793304572; [b]https://www.facebook.com/USGSVolcanoes/videos/1967225443306007.

featured imagery from the HVO website, showing summit lava lake high-stands and overflows[4] as well as a time-lapse video of the formation of a perched lava pond within the crater of Puʻuʻōʻō.[5]

On April 30, 2018, eruptive activity at Kīlauea changed dramatically. The crater floor of Puʻuʻōʻō collapsed as the lava within and beneath the cone drained, and earthquakes began progressing eastward on the island as magma migrated through the East Rift Zone (Neal et al., 2019). HVO released another Volcanic Activity Notice on May 1.[6] This notice stated that the collapse, along with earthquakes and deformation propagating down Kīlauea's East Rift Zone, indicated that an outbreak of lava farther down rift was possible, perhaps even within a residential area.

By May 2, 2018, residents of Leilani Estates (Figure 1) began to report cracks in roads and yards. By May 3, the neighborhood became the locus of a nearly 4-month-long eruption (Figure 3) that displaced residents, destroyed hundreds of homes, and dramatically changed the lives of lower-Puna (Figure 1) residents. Simultaneously, the lava lake in Halemaʻumaʻu crater drained, and the Kīlauea summit caldera experienced a piecemeal collapse over several months. Individual collapse events generated fine ash that drifted downwind (Figure 3), and hundreds of daily earthquakes rattled the summit area (Neal et al., 2019).

On the 1st day of the lower East Rift Zone eruption, HVO adopted an internal internet-based collaboration platform built on the open-source communication platform, Mattermost (Williams et al., 2020; Lowenstern et al., 2022). This tool was accessible as both a website and mobile application, and its primary use was for scientists to communicate eruption situational awareness to emergency response personnel. However, the tool's usefulness was much broader—volcano monitoring data were shared, photos and videos were uploaded directly from the field, scientific discussions occurred in discipline-specific channels, and the communication team could interact remotely with the eruption response team. The latter was vital to the success of the social media response.

4. Media team operation during the 2018 Kīlauea crisis

The dramatic changes at Kīlauea volcano in May 2018 emphasized the substantial need to communicate timely information to residents and visitors on the Island of Hawaii. As the crisis progressed, residents increasingly requested situational awareness updates *via* email to askhvo@usgs.gov and as comments and direct messages to the USGS Volcanoes' social media accounts.

4 https://www.youtube.com/watch?v=fQRq4jdAU_s

5 https://www.facebook.com/watch/?v=2003197056375512

6 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2018-05-01T07:33:24-07:00

However, if released through traditional channels (VNS, website, TV, radio, and print media), the information could become out-of-date within hours (Williams et al., 2020). The nature of social media, including its ability to be swift, agile, and interactive, made it a powerful tool to increase the speed and reach of communication throughout the months of the crisis response (May–August). During the eruption, the USGS media team, which included visiting USGS staff working together closely with local HVO staff, created online text and video updates, developed a system for posting automatic status updates to social media, helped conduct press briefings and phone conferences, gave interviews, updated the HVO webpage with photos from the eruption, aided in setting up a live stream of summit activity on YouTube, and assisted in community briefings and Q&A sessions. While not every member of the media response was part of the social media team, the whole social media team contributed to the overall media response, which was led by HVO staff.

4.1. Researcher positionality

Most authors participated in the social media team during the 2018 eruption of Kılauea, with varying degrees of knowledge about Kılauea and experience communicating hazards. Stovall (Author 1) is a volcanologist and communication professional who lived in Hawaii before 2018 researching Kılauea volcano. During nearly 6 years of residence, Stovall developed close working relationships with HVO scientists, taught students about Hawaiian volcanism, and participated in hazard outreach to local communities. The 2018 eruption was the first time Stovall witnessed the dramatic impacts of volcano hazards. Stovall communicated about volcanoes *via* USGS social media for 7 years before the 2018 eruption.

Ball (Author 2) is a volcanologist who had spent time in Hawaii as a student in an immersive volcanology field methods class before the 2018 eruption. Ball had self-taught expertise in geoscience communication and social media through personal blogging and a Twitter presence but had not interacted extensively with residents of the Island of Hawaii either online or in person.

Westby (Author 3) is a volcanologist stationed at the USGS Cascades Volcano Observatory in Vancouver, Washington. Before 2018, Westby served two 4-week stints at HVO, conducting education and outreach about Kılauea's history and hazards, HVO's monitoring program, and learning how the public and public officials can receive information about changes at the volcano.

Poland (Author 4) is a volcanologist with expertise in studying volcano deformation and gravity change. Poland was stationed at HVO during 2005–2015, involved in the scientific and communication responses to numerous volcano and earthquake events. Poland developed a strong understanding of the local perception of volcanic hazards and the effectiveness of different outreach activities.

Wilkins (Author 5) is a volcanologist at the USGS office in Reston, Virginia, who provided surge-capacity assistance to the USGS Volcanoes social media team. Before 2018, Wilkins had several years of experience using social media for science communication at USGS. While Wilkins had visited Hawaii briefly before and had experience analyzing remote sensing data of Kılauea lava flows as a college student, this was Wilkins's first experience responding to a volcanic crisis.

Mulliken (Author 6) is a Research Corporation of the University of Hawaiʻi geologist working at HVO. During 2018, Mulliken was working with the DGGS branch of the Alaska Volcano Observatory and was deployed to Hawaii to aid in the Kılauea eruption field response. Since 2020, Mulliken has been involved in HVO communication and works closely with the USGS social media team but is not a part of it. Mulliken grew up in Hawaii, near the summit of Kılauea and appreciates first-hand the impact of volcanic events on Island of Hawaiʻi residents and visitors and the importance of diverse communication strategies.

4.2. Ramping up to crisis communication

Before 2018, the USGS Volcanoes' social media team did not have a crisis communication plan. A loose formula for communicating eruption information on social media took several days to assemble and implement, which meant the social media response to the first few days of the crisis was largely improvised. Crisis response practices were primarily based upon the "intense media interest" scenario in a (then) draft of the USGS Cascades Volcano Observatory media management guide (Driedger and Westby, 2020).

Social media work was initially conducted by team members based in the contiguous U.S., not Hawaii. Principal social media priorities were to push out official activity updates (from both USGS and emergency response partners) and to post USGS photos and videos as they appeared on the HVO website. An event-specific hashtag (#KılaueaErupts) was defined early and used consistently for primary posts on Facebook and Twitter, and imagery was duplicated on the two platforms. A standing priority was to answer all questions and relay citizen reports to HVO scientists. At the start of the event, addressing these critical questions was considered most important:

- What happened?
- Why did it happen?
- What will happen next?
- What action can I take?

Between the April 30 collapse of the Puʻuʻōʻō crater floor and the May 4 magnitude 6.9 earthquake (Figure 1) (Neal et al., 2019), followership of the USGS Volcanoes' Facebook and Twitter accounts grew (Figure 3). In the week following the earthquake, USGS Volcanoes' Facebook posts were being seen by more Island of Hawaii residents than ever. The percentage of total USGS Volcanoes' Facebook posts being viewed by the local population grew from nearly 1% on May 3 to about 40% by May 11 (Figure 4), 1 week after the onset of lava flows in Leilani Estates (Figure 1). This statistic indicates that most new followers were from Hawaii.

The social media team prioritized answering questions and providing updates with videos and imagery as quickly as permitted by HVO. Simultaneously, traditional media outlets were interested in the eruption and submitted fast-turnaround media inquiries

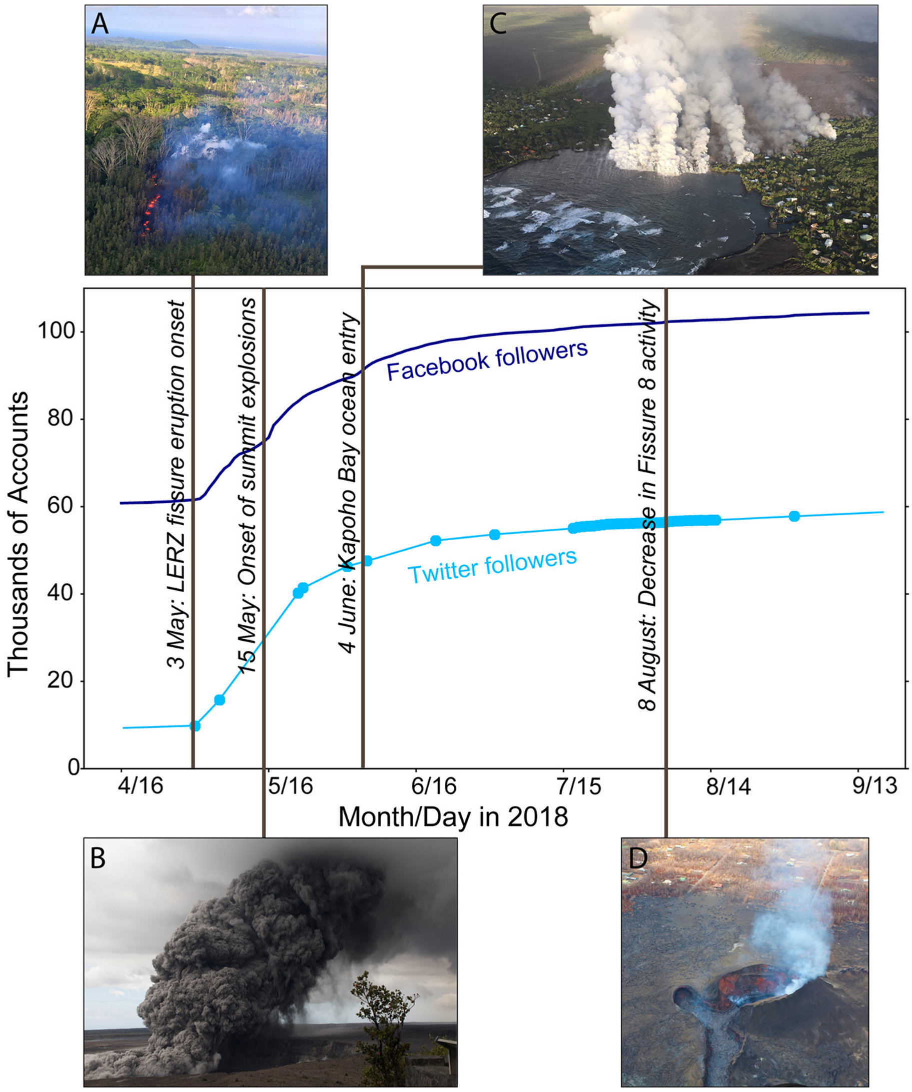

FIGURE 3
Audience growth for both Facebook and Twitter occurred rapidly following the onset of the Kīlauea lower East Rift Zone eruption on May 3, 2018. Similarly, followership gains occurred after significant events in the eruption timeline, notably the onset of explosions at Kīlauea's summit and as lava encroached into Kapoho and filled the bay. Data for Facebook are daily follower counts. Follower counts from Twitter were recorded for the first day of each month until the middle of July when daily tallies were made. USGS Photographs: **(A)** On May 3, 2018, at ~5:00 p.m. HST, fissures opened in the forested neighborhood of Leilani Estates and began erupting low lava fountains and volcanic gas (blue-tinged plume in image). **(B)** May 15, 2018, 11:05 a.m. HST, a dense ash plume rose from Kīlauea volcano summit. **(C)** An aerial photograph of June 4, 2018, 6:13 a.m. HST, shows the lava flow originating from Fissure 8 (not visible in photograph, Figure 1) entering Kapoho Bay. **(D)** The fissure 8 vent had minimal visible lava activity through September (this photo from August 8, 2018).

to the USGS Office of Communications and Publishing—the primary USGS division for handling media inquiries. Some USGS Volcanoes' social media team members were designated subject matter experts for media interviews that could not be handled by HVO staff, limiting their full-time ability to help with social media.

4.3. Adding staff and field visits

The four USGS Volcanoes' social media team became overwhelmed in the 1st week of the eruption. On top of communicating eruption information, three social media team members were involved in organizing previously planned non-HVO-related meetings and events in the first 2 weeks of May. Due to this limitation on available staff, an additional USGS scientist with volcanic expertise was added to the social media team on May 11 in a surge capacity through June. Duties were quickly divided into 8–10-h shifts, 7 days per week. Team members were spread across several time zones, allowing coverage throughout the day (and partially overnight) in Hawaii.

In the 1st month, most of the social media work was conducted by team members on either the west or east coasts of the United States. In mid-May, team members began 2-week rotations onsite in Hawaii. Travel often overlapped, resulting in gaps in social media coverage (Figure 5). Primary responsibilities while in Hawaii

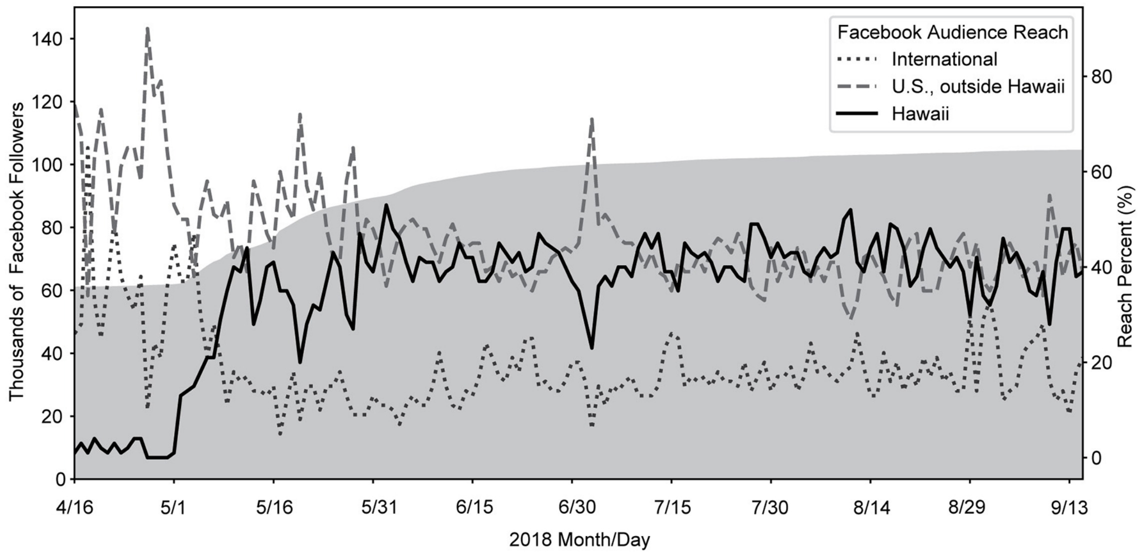

FIGURE 4
USGS Volcanoes' Facebook data from April 16 to September 15, 2018. Cumulative followers (shaded gray area, left axis) grew quickly during the 1st month of the eruption as a greater percentage of people from the State of Hawaii (solid black line, right axis) viewed content.

were to assist HVO staff with community outreach, participate in press briefings, staff the HVO position at the joint Emergency Operations Center (EOC), and record daily YouTube video updates describing the eruption status (videos have an average of 46,000 views on the USGS YouTube channel). These tours in Hawaii allowed team members to understand the significance of the eruption response effort more intimately.

5. Procedures and lessons learned

The USGS Volcanoes' social media team established a prioritized flow of information delivery. Following the checklist (Figure 6), content was posted on a schedule that provided predictability for those following the USGS Volcanoes' Facebook and Twitter accounts. Posting priority was defined by content type and the timeframe for each type to be released to the public.

The highest priority was given to official eruption notifications. On a typical day, the HVO daily update was issued in the morning. The text from this update was copied onto Facebook and posted with photos taken from the field the previous night or from that morning's helicopter flight over the lower East Rift Zone eruption. The same photographs were used on Twitter with a short synopsis of the update and a link to the full text on the HVO website. Emergency messages from Hawaii County Civil Defense or Hawaii Volcanoes National Park were immediately shared or retweeted. Daily video updates were posted as soon as they were live on YouTube.

Second-tier content priority included multimedia from official sources. This included HVO maps of lava flow advancement, recent photographs, and videos from the field. If press conferences that featured HVO staff were recorded (either *via* audio or video), we shared those from the host organizations (e.g., Nā Leo TV or Big Island Video News[7]).

Once new content was posted, USGS Volcanoes' staff scoured prior posts and tweets for questions to answer. This was undoubtedly the most time-consuming task for the USGS Volcanoes' social media team, and it was the action that most fostered trust with followers (Goldman et al., in press). Once questions were addressed, we checked with other eruption information sources for content to share or retweet.

We generally adhered to communication guidelines suggested by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Subcommittee for Crisis Protocols (Newhall et al., 1999). However, due to the age of this article, the guidelines do not include specific information about social media. It is worth noting that in late 2018, the IAVCEI Communication Working Group within the Hazards and Risk Commission (members include USGS Volcanoes' staff) developed communication considerations for official accounts on social media (Supplementary material 1). These guidelines include many best practices developed during the 2018 USGS response.

5.1. Audience growth = Adaptive communication strategies

As with any significant event, having a plan in place is good but being flexible and adapting as situations evolve is imperative.

The 2018 Kīlauea volcanic crisis was widely publicized in the media and impacted people's livelihoods, tourism, public health, and safety. These impacts, plus the fascinating imagery, are reasons people sought more information about the eruption. This

7 https://www.youtube.com/watch?v=YEt_sFoJ8kg

FIGURE 5
Specific posts were made during times when the social media team was going to be less able to post content and answer questions than usual **(A)**. The photo in the post shows Wendy Stovall measuring the exact location of the flow front on a residential road in the Leilani Estates neighborhood. Comments and replies to these posts were overwhelmingly positive and included messages of thanks for staff providing information *via* social media as well as the people on the ground monitoring the eruption. The word cloud **(B)** represents the most frequently used words from the 159 comments to the post shown in **(A)**, which is characteristic of positive-sentiment feedback received throughout the 2018 response.

FIGURE 6
Prioritized checklist of content types and information shared on USGS Volcanoes' social media channels during the 2018 Kīlauea eruption response.

was especially true of the local population. As USGS Volcanoes' Facebook and Twitter followership grew (Figure 3), posts and tweets' reach (number of people who viewed content) also grew as others shared content.

The policy for posting content to social media was that it had to first be published on the HVO website. However, due to the compounding crises of losing the HVO facility to summit earthquake activity and managing the response to the ongoing eruption, it often took many hours for photos and videos from the field to be posted to the website. In the first 2 weeks of the eruption, this delayed content posting to social media. The audience more frequently asked for situational awareness information and was critical of the perceived slowness of photos and videos being shared on social media. To stay informed, followers increasingly viewed and relied upon information from unofficial accounts (Goldman et al., 2023) that sometimes displayed risky activities by eruption onlookers in hazardous areas closed to the public.

To increase the pace of information to the public, the order of information delivery shifted to meet the demand. By mid-May, content was first posted to social media and replicated on the HVO website. Internal communication *via* email and messaging software, Mattermost (Williams et al., 2020; Lowenstern et al., 2022), permitted the social media team to stay apprised of minute-to-minute developments, ask responding scientists clarifying questions, and access video and photos posted directly from the field as observations were made. HVO management set strict guidelines (Supplementary material 2) for the types of content that could be posted to social media and retained the ability to approve or veto items before posting. However, HVO staff were spared from the logistics of posting imagery and other content to either the website or social media.

A month into the 2018 crisis, the eruption became relatively steady state. After lava flows resulted in the loss of hundreds of

FIGURE 7
Example of a post to Twitter that featured a USGS photograph from the field with accompanying scientific information and educational content.

homes, the main pathway of lava flowing eastward toward the ocean was established (Neal et al., 2019). Continued reporting from the national and international mainstream media kept global interest in events at Kılauea high. Social media followership rose dramatically in the 1st month—Facebook audience grew by 50% and Twitter audience by 375% (Figure 3). With a stable eruption, continued engagement, and increasing followership, the social media team reassessed and shifted communication objectives to include a greater frequency of educational content rather than focusing on observations and official notifications. Content was tailored to follower requests identified in real-time. The number of frequently asked questions posted to Facebook and the HVO website grew through time. The team developed multimedia posts to communicate answers to these questions and showcase data collection and scientific insights (Figure 7).

5.2. Stay in communication lane and share official information

A significant benefit of social media is the ability to amplify messages from partner organizations (Panagiotopoulos et al., 2016). The USGS Volcanoes' social media team shared and retweeted emergency management updates, official government evacuations, and closure orders posted on Hawaii County Civil Defense (local), Hawaii Emergency Management Agency (State), and Hawaii Volcanoes National Park (Federal) websites and social media streams. This meant that people who may not have been aware of those information sources had the chance to see them *via* USGS volcanoes. Furthermore, by sharing emergency management partner messages, non-Hawaii-based followers and the press were directed to official information rather than unofficial accounts (Sutton et al., 2015). In addition, the USGS could draw attention to the radio broadcasts and SMS-based update system being operated by Hawaii County Civil Defense, which provided information to people even in areas with spotty cellular reception or poor internet access. Finally, the USGS used social media to advertise and promote co-sponsored events (such as community meetings and ash safety briefings) conducted with State, County, and academic partners.

6. Successes

We now consider the social media response to the 2018 Kılauea volcanic crises in the context of follower engagement and our team's ability to uphold best practices and principles of crisis communication (Coombs, 2010; Maal and Wilson-North, 2019). Overall, we conclude that the social media team provided critical, actionable hazard and safety information (Fearnley et al., 2018). The information shared was consistent, factual, and non-speculative. We aimed to speak with empathy and courtesy (McBride and Ball, 2022). Our actions were crafted to foster credibility and build trust (Haynes et al., 2008). We adapted, answered requests, and engaged in dialogue (Eriksson, 2018). The content we shared served our social-media community—it was relevant to those impacted by the eruption and kept more distant followers engaged, curious, and learning about the science of volcanoes.

6.1. Delivering consistent factual information

The USGS Volcanoes social media team worked closely with HVO eruption response staff throughout the eruption, promoting HVO messages and observations. The core social media team included two scientists who had previously served at HVO or conducted research at Kılauea. This intimate knowledge of the volcano's history of eruption and unrest made it easier to quickly give contextual details to posts' content and provide factual answers. All team members had a volcanology background and expertise in science communication. We communicated regularly with each other *via* an internal "chat" system. When a question posed by a follower was suited for a specific team member's expertise or familiarity, we called upon them to answer or reached out to HVO staff if necessary.

Throughout the volcanic crisis at Kılauea, the social media team made it standard to answer all questions and maintain back-and-forth communication with followers. As the eruption progressed, similar questions were being asked repeatedly. A shared document of common questions and answers was developed to ensure consistent information across all platforms. These became a set of frequently asked questions (FAQs) added to Facebook as "Notes" (a feature no longer available), which were vetted by HVO staff and added to the HVO website. As questions were posed, the social media team could point people to FAQs for more detailed information while providing personalized and empathetic answers that contained consistent responses.

6.2. Growing a community of informed followers

By being responsive, friendly, consistent, and thorough, the USGS Volcanoes' social media team built an informed and dedicated group of followers who became willing, themselves, to share knowledge, answer questions, and help police misinformation. Regular followers became knowledgeable of answers to frequently asked questions and sometimes commented on others' questions before the USGS Volcanoes' team (Figure 8). These "regulars" responded, answered follow-up questions, and became a welcome part of the conversational dynamic of the USGS Volcanoes' accounts. They often rallied to defend our positions and statements if adversarial comments appeared. USGS Volcanoes' team members saw value in the followers who spread correct information and provided encouragement in the form of "likes" or approving follow-up comments.

6.3. Fulfilling traditional media requests

The 24-h news cycle increasingly relies on social media for scoops and current information (Farhi et al., 2021). While many local news sources had worked closely with HVO and were accustomed to interfacing with the established media and outreach coordinator, some national and international news outlets sought contact with HVO through the USGS Volcanoes' social media channels. The social media team sent these requests to the USGS Office of Communications and Publishing (OCAP), which maintained a central media-tracking spreadsheet and ensured requests were addressed. In cases when questions from the media could be answered quickly by the social media team, replies were sent directly without involving OCAP or already overtaxed HVO staff. In other cases, traditional media directly cited content from USGS Volcanoes' posts in news reports (McBride and Ball, 2022).

6.4. Meeting followers' requests and receiving citizen scientist reports

The USGS Volcanoes' social media channels were an easy way for followers to access daily information about the progress of the summit and rift-zone activity. We posted HVO maps, photographs, and videos, but imagery captured by USGS field personnel was vastly more significant than what we could share daily. Followers often requested map-based animations of eruption progression, additional videos, and even a live-stream camera. The social media team sometimes could fulfill these requests by piecing together short animations or videos, but we also conveyed requests to HVO. As time allowed, HVO and other USGS technical experts created animated map sequences[8] that showed the evolution of lower East Rift Zone lava flows (Figure 1) and subsidence of the Kılauea caldera.[9] Through conversations with the National Park Service and agreements made with the central USGS social-media management, a live webcam was eventually installed at the summit of Kılauea and streamed to the USGS YouTube channel.

Occasionally, affected residents attempted to report hazardous developments to HVO scientists and other authorities, which highlighted a communication gap. The general HVO email address and phone number were overwhelmed, and responses to inquiries were delayed. Because of the agility of social media and the speed with which the USGS social media team was able to respond, a process developed organically whereby citizen reports of ground cracks, gas emissions, and lava outbreaks were received on social media channels and relayed quickly to HVO field crews through Mattermost (Williams et al., 2020). For example, one resident regularly reported the temperature, width, and fume acidity of ground cracks on their property to HVO's gas team *via* Facebook. This led to HVO monitoring a site that they would otherwise not have known about or been able to access and had the ancillary benefit of building trust between the resident and HVO staff.

6.5. Experiencing appreciation

Research suggests that there was a general attitude of gratefulness for the work done by the HVO staff responding to the eruption (Goldman et al., 2023) and the USGS Volcanoes' social media team (Goldman et al., in press). Comments complementing posts' informative and educational content and appreciation for answering so many questions were common (Figures 5B, 8). Appreciation was also noted when we creatively communicated science and inserted well-timed attempts at humor. McBride and Ball (2022) posited that this communication method helped us connect and build empathy with at least some of our audience.

7. Challenges

Running a crisis communication response of any type is challenging. In news-heavy community crisis events, there are inevitably those who seek attention, spread rumors, or are dissatisfied with the information they are getting. Sometimes a concerted effort of multiple parts of an organization is needed to quell or correct falsehoods. This is especially the case when misinformation is spread, impacted communities are disrespected, or self-proclaimed experts spread dangerous disinformation that becomes viral (Hagley, 2021).

8 https://www.youtube.com/watch?v=lr_Gqu7HGPM

9 https://www.youtube.com/watch?v=-5pHpsY9cp0

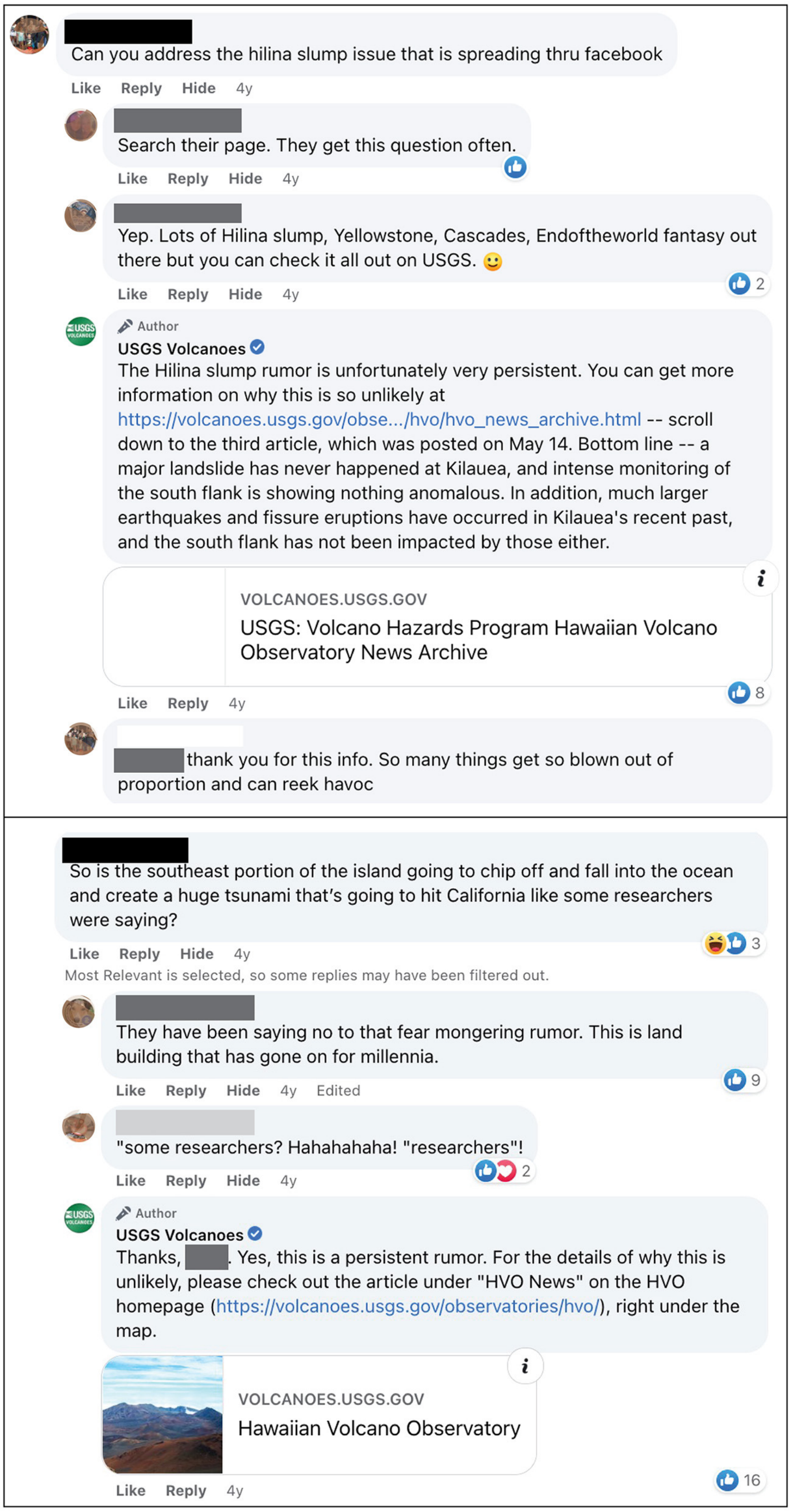

FIGURE 8
Two comment strings related to a common concern that the southern portion of the Island of Hawaii was going to slide off into the ocean in a catastrophic fashion. Followers addressed questions to USGS Volcanoes, and often the community answered with recommendations of where to find additional information.

7.1. Addressing misinformation and disinformation

In all types of crises, people seek to make sense of events that might be difficult to comprehend. Storytelling is a part of the sensemaking process. The process of storytelling can sometimes lead to rumors and the spread of misinformation (Starbird et al., 2016; Starbird and Maddock, 2019) or disinformation. Misinformation is incorrect information that is not intended to mislead, but disinformation is false information that is spread deliberately to deceive (Starbird and Maddock, 2019). Disinformation tactics can elicit distrust in authoritative and official sources, such as the USGS. Andrews et al. (2016) suggested that official accounts can correct misinformation by refuting falsehoods with a composed and civil response that avoids condescending remarks.

It is challenging to battle disinformation directly, as the source may have reasons for spreading falsehoods (e.g., monetary gain from advertisement clicks). During volcanic crises, disinformation can be eclipsed when responsible agencies and accredited subject matter experts disseminate factual information quickly and often before it is channeled through sensationalizing outlets. Rumors were certainly an issue during the 2018 eruption, and HVO published a Volcano Watch article to combat misinformation.[10]

When false information and rumors were identified, USGS Volcanoes' staff posted corrections without reference to the offending source. An example of the USGS's role in dispelling damaging rumors occurred when hundreds of earthquakes per day were happening at the summit of Kılauea volcano. Computer programs automatically located the events, and only those above magnitude three were reviewed by a seismologist. Due to the frequency of events, several earthquakes were inaccurately auto-located and shown to be occurring around Mauna Loa volcano. A person managing a non-USGS YouTube account posted a video highlighting these earthquakes and showed that some were being removed (actually, relocated) from the area around Mauna Loa. In the same YouTube video, this person claimed that Mauna Loa was building toward eruption and that the USGS was withholding information about an impending eruption and deleting data. The USGS Volcanoes' social media team immediately developed factual and concise messaging that refuted these claims. The specific message was, "Earthquakes are automatically located by software, which a human must check. Sometimes the software locations must be corrected, leading to earthquakes appearing to move or vanish from our records. We are not observing any unusual activity at #MaunaLoa." Though factual arguments did not sway some followers, the number of questions about Mauna Loa decreased over time, and the topic was rarely raised in the latter months of the response.

10 https://www.usgs.gov/observatories/hvo/news/volcano-watch-turn-usgs-and-other-trusted-sources-kilauea-eruption-info

7.2. Considering local sensitivities

During an eruption, particularly in Hawaii, responders must deal not only with the immediate threats to safety and property but with the history and sensitivities of residents affected by volcanic impacts. This can include past land and environmental conflicts, religious beliefs, cultural practices, etc.

The USGS Volcanoes' social media team dealt with several locally sensitive or controversial subjects. One example was the presence, and community history of the Puna Geothermal Venture (PGV), a geothermal power plant built in the lower East Rift Zone. The plant provided about one-quarter of the electrical power for the Island of Hawai'i (Hawaii Energy Facts Figures, 2018) but, over its 25-year history, had been a source of some public concern.[11] During the eruption, parts of PGV were inundated by lava, and it was determined that its geothermal wells needed to be filled, capped, and sealed. Additionally, chemicals stored onsite for geothermal well operations (n-pentane, a common additive to reduce the boiling point of water injected into wells; Evans et al., 2015) were removed, but not immediately. The Environmental Protection Agency cited PGV for hydrogen sulfide releases in 2013 (Higuchi, 2016), and residents were generally suspicious of the plant, including whether PGV activities had triggered fissure eruptions. A highly viewed social media video post of burning methane-producing blue flames through road cracks[12] (Goldman et al., in press), which was initially deemed harmless by the social media team, ignited an argument about whether the gas was indeed methane or a new release of hydrogen sulfide (which is more toxic) from PGV. Repeated reassurances from USGS Volcanoes were not enough to quell the uproar, and subsequent posts about similar phenomena, or information about PGV, were restricted to bare facts and kept to a minimum.

Although numerous requests were made to the USGS for a live-stream of the lava-flow eruptions, it was not feasible (from both a bandwidth and technological standpoint), and limitations on personnel and access were also a factor. Another primary concern was the sensitivities of residents experiencing tremendous loss. Balancing sharing the visual beauty, excitement, and fascination of the event with concerns for those impacted was a recurring challenge.

A related sensitivity that became difficult to navigate was posting images of burning homes. General USGS policy is not to show these events, as it can be traumatic for residents to see their homes destroyed through a public platform. However, in some cases, evacuated residents had no access to their homes for weeks; images posted on USGS Volcanoes was one of the only ways to get information about conditions in restricted areas and to find photographic confirmation of the extent of lava inundation. In the case of the Kapoho Bay and Vacationlands subdivision, regular USGS helicopter overflights prompted inquiries from residents wanting to know if their homes had been destroyed. While this was a way to provide closure, the social media team encouraged

11 https://www.washingtonpost.com/news/powerpost/paloma/the-energy-202/2018/06/18/the-energy-202-kilauea-s-eruption-reignites-debate-over-hawaii-s-geothermal-plant/5b2652f21b326b3967989b27/

12 https://www.facebook.com/watch/?v=2039809729380911

residents to send direct messages to the USGS Volcanoes' accounts and HVO directly regarding specific video footage so that those conversations could be conducted privately. This solution appeared to be satisfactory, but due to the additional burden on the social media team, it was approached as an *ad hoc* courtesy and not part of the formal communication plan.

7.3. Meeting content and mission critical demands

During disasters, the desire for round-the-clock updates is amplified, and many people seek information wherever they can find it. This became obvious during the 2018 Kılauea crisis when reports of the eruption "trended" on media channels like Facebook and Twitter.

Amid this turmoil, the USGS Volcanoes' Facebook and Twitter accounts posted updates about Kılauea numerous times per day—up to a dozen per day during the height of the eruption crisis. However, there were still complaints about too few posts, and followers wanted more photo and video content. The demand for "more (social media) content now" was at odds with the government mandate for USGS communication to provide rapid situational awareness of volcanic events to emergency partners (first and foremost). Mission-critical work always rose above the call for more social media content. Several times during the eruption, particularly related to video and drone content, the USGS Volcanoes' team was obliged to remind commenters seeking more posts that the USGS is not a news outlet but has to conduct mission-critical work first.

A specific example of this challenge was the constant conversation about HVO's lack of multiple streaming videos, prompting the social media team to spend much time explaining HVO's priorities and technological constraints and access limitations in the field. To address resource limitations, posts were added that specified when there would be "radio silence" from team members due to more pressing duties, staffing changeovers, and other interruptions. These posts were generally greeted with support and praise from social media followers (Figure 5), and they served to humanize the social media team members for online audiences. These posts also reminded the public that the USGS's first and most important mission during the eruption was safety for crisis responders and affected communities.

Notably, no Joint Information Center (discussed in Driedger et al., 2008) was assembled for the 2018 Kılauea eruption. Such a center would have combined all response agencies' communication professionals and provided the opportunity to share the load of informational requests.

7.4. Identifying and clearing bottlenecks

A related internal concern was a bottleneck for information flowing from HVO to websites and social media. During the 2018 response, the scientific team was committed to round-the-clock monitoring and data collection; interpretation to provide forecasts; and dealing with requests for information from emergency management, civil defense, and other public officials. While they provided products that could be publicly released (maps, updates), it fell to the media/social media team to obtain, vet, and distribute other material, such as photos and videos. While these were being collected as part of the monitoring activity, it was incumbent on the social media team to sort through and choose the most appropriate content to post to the website and social media channels and work with HVO staff to caption and catalog the imagery. In the early stages of the eruption, this task was made difficult by the remote location of the social media team. Photos and videos were stored on a computer hard drive in Hawaii, and internet bandwidth issues made it challenging to access shared file storage. Additionally, it was time-consuming for field staff to transfer media files and provide a file of accurate and informative captions after long and difficult field shifts.

One significant change, which alleviated many of these problems, was the Mattermost collaborative working platform (Williams et al., 2020; Lowenstern et al., 2022) discussed in Section 5.1. The social media team was given access to Mattermost after the 1st week of the eruption, which provided access to up-to-the-minute information and near-real-time photos and video. Using the robust messaging platform, social media team members could solicit timely information from the scientific team with minimal disruption to monitoring activities—requests were directed to an entire scientific team or multiple individual users and then answered by whoever was available.

7.5. Communicating uncertain outcomes

In an eruption crisis, inaccurate forecasts of future state or impacts can backfire and erode credibility, with consequences for people's safety. This is also true for other crisis response situations. Sometimes, social media audience members asked for precise predictions for what would happen next. However, USGS forecasts are carefully considered and framed as scenarios of possible outcomes. They can only be made relative to analogous past eruptions, the state of volcanic activity, and conditions under which an eruption progresses.

To provide the most transparent and honest information possible, the USGS Volcanoes' team echoed official notifications and aimed to precisely state knowns and unknowns, what can and cannot be forecast, and where uncertainties lie. For example, the question of "How long will the eruption last?" was typically answered not with "we don't know for sure," but *why* it is difficult to know, with information about how eruptions can evolve, what the volcano has done in the past, and the limits of USGS sensors and forecasting abilities.[13] If uncertainties were conveyed, they were voiced in relatable terms rather than ambiguous jargon. Admitting the limits of knowledge upset some followers and sometimes led them to spurious social media. Still, speculation erodes trust (Maal and Wilson-North, 2019) and is counterproductive to providing timely, accurate information.

13 https://www.facebook.com/USGSVolcanoes/photos/a.984262971602264/2148821148479768

7.6. Polite responses and policy breaches

Official USGS social media accounts strive for neutrality. Although difficult to convey tone in the written word, sometimes comments or questions from USGS posters might appear patronizing or out of touch with community needs, which can undermine critical messages during a crisis. This was occasionally an issue in comments made by both the official USGS Volcanoes' staff and followers. When followers' concerns were seen, we quickly aimed to remedy the issue with a genuine and empathetic reply, an explanation or restating of the original post, and requested courtesy be given in commentors' responses to others.

In many conversations, it is also important—but difficult—to consider a follower's level of expertise and comfort with a topic. A jargon-filled response can erode trust and give an ivory-tower flavor to communication, but overly simplistic language can be insulting (McBride, 2017). Asking questions or taking a moment to look over previous interactions with a follower was helpful in appropriately tailoring a response.

The expectation of politeness and courtesy extends to the social media community also. USGS Volcanoes' social media Facebook account has a clear comment policy (Supplementary material 3). Automatic filtering prevents public view of offensive language on Facebook (but not Twitter), and immediate action is taken to remove spam, offending, or hateful speech. Commenters who disregard rules are provided a reminder of the policy by the social media team and given a second chance. USGS staff can mute or ban repeat offenders from the ability to interact with USGS social media accounts. Protocol for dealing with troublesome commentors is as follows:

- Provide a quick policy reminder and a short factual response to any question.
- Hide comments if appropriate.
- Do not engage in a back-and-forth argument.
- Consider archiving and then deleting comments.
- Discuss banning repeat offenders with USGS social media lead.

As a Federal government agency, we must always consider that our actions are part of the public record. Therefore, deleting comments requires social media managers to record offending comments and the associated policy breach in a document before deleting them. Additionally, offensive commenters can only be banned if offensive behavior is repeated and egregious.

7.7. Making and reconciling unintended mistakes

The USGS Volcanoes' social media made rare factual errors during the 2018 eruption. There were also some insensitive, rushed responses or inaccurate descriptions. Admitting mistakes demonstrates integrity and benevolence (Hendriks et al., 2016), both fundamental traits that help maintain trust. Therefore, USGS Volcanoes aimed to acknowledge mistakes and issue corrections quickly. It is impossible to edit Twitter after posts or replies have been submitted. Still, corrections can be threaded to the original tweet, or the original tweet could be quoted in a new one with a corrected addendum. On Facebook, mistakes could be edited, but the team often either noted the edit in a follow-up comment or used strikethrough text to indicate that the change had been made. These techniques showed a commitment to transparency and were in keeping with overall DOI and government social media policy not to delete content.

8. USGS Volcanoes' social media strategy for future eruptions

The coordinated scientific plus traditional and social media responses to the 2018 Kılauea eruptions were a proving ground for the practices that have become official guidelines for USGS Volcanoes' social media crisis communication. A seasoned team of official USGS social media "ambassadors" who have both remote and on-the-ground experience in crisis response means that future social-media responses to volcanic events can be organized quickly and with clearly defined roles. A rotational posting schedule exists for routine observatory communication and can be modified to accommodate increased activity from any observatory. Best practices created *ad hoc* during the 2018 response are continually updated and revised for future volcanic crises.

8.1. Testing the social media strategy during Kīlauea and Mauna Loa eruptions

By early 2019, magma was refilling the Kılauea's depleted summit magma storage region (Poland et al., 2019). And in the 2 years following the 2018 eruption, a water lake formed within the collapsed Halemaʻumaʻu Crater (Flinders et al., 2022). In late November and early December 2020, geodetic measurements indicated magma was moving from the storage region toward the ground surface at Kılauea's summit.[14]

On the night of December 20, 2020, magma reached the surface. Fissures opened along the wall of Halemaʻumaʻu Crater, and lava poured down the steep slopes. The water lake quickly boiled away, forming billowing clouds of vapor, and lava began pooling on the crater floor. The eruption lasted into May 2021, was confined to the crater, and the main hazard was increased volcanic gas emissions for areas downwind.

With the experience of 2018, the USGS Volcanoes' social media team quickly ramped up the effort to report on and respond to inquiries about the new eruption. The primary HVO communication professional retired earlier in 2020, and other HVO staff without 2018 communication experience backfilled that role. HVO notified the VSC social media team immediately when the activity began. The following morning, the four-person team established a schedule to ensure at least one person was on duty to post content and respond to questions. We defined "social media

14 https://www.usgs.gov/news/volcano-watch-small-notable-magma-intrusion-kilaueas-summit

crisis response" time as monitoring social media 18 h per day in 6-h shifts with 4 people on rotation, essentially covering the hours between 9 a.m. on the East Coast to 10 p.m. in Hawai'i. Due to the uncertain progression of the eruption, schedules were set only a few days in advance.

As in 2018, there was an internal online collaborative communication space (MS Teams) to share information. Two staff members at HVO managed website content, including gathering images, creating publishable videos of the eruption activity, and posting content, including maps and infographics, to the HVO website in the morning and afternoon. Different from 2018, the two staff dedicated to HVO website management prevented a bottleneck in information flow. The social media team shared USGS photos, videos, maps, and infographics as they were made available. Throughout the eruption, the social media team remained vigilant in answering questions from followers as quickly as possible.

The first 2 weeks of the eruption drew the most media attention, with local HVO staff responding to most of the inquiries. As in 2018, some social media staff answered inquiries from traditional media, but the demand was much less than in 2018, and diminished as the eruption remained confined to Halema'uma'u Crater. The eruption stabilized into a pattern of lava flowing into and filling the crater with a rising lava lake, vents being overtopped, and "islands" of solidified lava floating around the surface (Segall et al., 2022). These events proved curious to social media followers, but without significant and visually destructive hazards to communicate, overall interest was lower than in 2018, and the role of the social media team was scaled down. Staffing hours reverted to a regular schedule of one person on duty for an 8-h shift with occasional check-ins beyond that to answer questions. By May 2021, active lava ceased to be seen on the surface.

On September 29, 2021, lava fountains again erupted from Kīlauea's Halema'uma'u Crater, pouring lava on top of the lava lake that had formed in late 2020 and earlier in 2021.[15] The social media team rapidly responded, enacting the "social media crisis response" protocol. However, the decision to scale down came more quickly this time (within days), as it was apparent that the eruption once again did not pose significant hazards to people or property.

During 2020–2022, HVO's attention was also focused on Mauna Loa.[16] The most recent previous eruption of the volcano was in 1984 (Lockwood et al., 1987), but seismic and ground deformation data, which had been mostly elevated above background levels since late 2014, indicated that the magmatic system was pressurizing and could erupt with little warning (Thelen et al., 2017). HVO staff heightened efforts to coordinate with State and County emergency management officials and plan long-term for an eruption response. A marked uptick in activity began in September 2022, which prompted HVO to issue official notifications[17], [18] and switch to daily updates for Mauna Loa in early October. Volcano Watch articles throughout the fall were either dedicated to Mauna Loa[16] or mentioned the need for preparedness in the event of an eruption.[19] HVO staff coordinated with Hawaii County Civil Defense to schedule public community meetings in October, November, and December in areas of the Island of Hawai'i potentially at risk from Mauna Loa lava flows. Three in-person meetings were held before the eruption occurred. The meetings were streamed locally and on Facebook Live. The meetings provided information about activity and encouraged residents to build relationships with new or existing community groups (for example, CERT groups—Community Emergency Response Teams), seek preparedness and hazard information from USGS and partner resources (for example, Hawaii County Civil Defense Agency family emergency plans and the Hawaii Interagency Vog Information Dashboard), and follow Hawai'i County and State guidance related to any evacuation measures.

Around 11:30 p.m. HST on Sunday, November 27, 2022, an eruption began in Mauna Loa's summit caldera, and HVO raised the alert level and aviation color code.[20] By early the following morning, the eruption was localized on the volcano's Northeast Rift Zone,[21] where vents at around 3,600 meters elevation fed multiple lava flows until activity focused to a single site, designated "Fissure 3" (being the third discrete fissure to have formed on the rift zone). Lava flows quickly channelized and moved downslope into unpopulated areas, cutting road access and power to the National Oceanic and Atmospheric Administration Mauna Loa Baseline Observatory on the volcano's north flank. By November 30, forward movement of the main Fissure 3 lava flow slowed significantly as it reached gentler topographic slopes and spread out. Ultimately, lava stalled about 3 km from the Daniel K. Inouye Highway, an important east-west transportation corridor. Eruptive activity waned significantly on December 8; by December 10, lava output at the vent had ceased, and sulfur dioxide emissions were near background levels.[22] HVO lowered the alert level and aviation color code, indicating the volcano was no longer erupting on December 13.[23]

The night it began, HVO quickly informed the USGS Volcanoes social media team of the Mauna Loa eruption. The USGS Volcanoes' social media team remained in frequent contact with HVO staff in the following hours and generated the first informational post (not counting the automated eruption alert post) at 11:48 p.m. HST on November 27, noting the change in the alert level and aviation color code, describing the eruption onset, and highlighting webcam imagery from the summit. HVO released

15 https://www.usgs.gov/news/volcano-watch-new-eruption-halemaumau

16 https://www.usgs.gov/observatories/hvo/news/volcano-watch-recent-events-mauna-loa-remind-us-be-prepared-quick-changes

17 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2022-09-23T13:24:04-07:00

18 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2022-10-05T19:26:56-07:00

19 https://www.usgs.gov/observatories/hvo/news/volcano-watch-earthquakes-and-volcanoes-recipe-preparedness

20 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2022-11-28T01:28:44-08:00

21 https://www.usgs.gov/observatories/hvo/news/volcano-watch-mauna-loa-reawakens-0

22 https://www.usgs.gov/observatories/hvo/news/volcano-watch-response-mauna-loas-2022-eruption

23 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2022-12-13T08:57:10-08:00

FIGURE 9
Image of one of the most popular tweets from the Mauna Loa eruption. This video[a], published first on the HVO website, was viewed over 105,000 times and shows the rapid movement of lava through a channel fed by Fissure 3. [a]https://twitter.com/USGSVolcanoes/status/1600252502217211904.

several formal notifications[24], [25] about the activity in the first hours of the eruption, which were echoed in a series of social media posts. An important theme in early posts was to address concerns that the eruption had entered the Southwest Rift Zone (it had not). The USGS Volcanoes social media team answered questions, identified sources of more information on preparedness and monitoring data, and reinforced information from HVO regarding the nature and status of the eruption.

Traditional media attention was intense during the first full day of the eruption. A virtual Joint Information Center (JIC) allowed staff from HVO, USGS OCAP, Hawaii Volcanoes National Park, Hawaii County Civil Defense Agency, and the State of Hawaii Emergency Management Agency to be in constant virtual contact *via* a virtual meeting and chat platform. There, they discussed agency messaging and the sequencing of communication to the media and the public. The USGS Office of Communications organized daily, morning, virtual video and telephone press briefings with representatives from JIC agencies to provide situational awareness information to all interested media outlets simultaneously, a similar approach used in the 2018 eruption. USGS Volcanoes social media team members participated in the JIC and, as in 2018, assisted HVO in responding to traditional media inquiries. The JIC coordinated the timing of social media posts when new and important information was to be released, tagged each other's accounts, and amplified each other's content to ensure consistent messaging among responding agencies.

Over the 2 weeks of the Mauna Loa eruption response, the social media team posted about 100 photos, videos, or other pieces of content to each of the three primary social media platforms (Twitter, Facebook, and Instagram, e.g., Figure 9). HVO deployed a live stream video camera aimed at Fissure 3, which was added to the

24 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2022-11-28T04:32:59-08:00

25 https://volcanoes.usgs.gov/hans2/view/notice/DOI-USGS-HVO-2022-11-28T09:00:26-08:00

USGS YouTube channel by the 5th day of the eruption. During the eruption, YouTube gained about 13,000 followers with 1.8 million views (1 million of those were for the live stream). Some social media posts had more than 100 follow-on comments, including questions from followers and answers from USGS Volcanoes staff or others. According to social media analytics, there were more than 8,200 comments to USGS Volcanoes' posts between November 27 and December 13, 2022. As in 2018, we had significant gains in followership (about 39,000 total), the reach of the posts was extensive (about 10 million unique individuals), and engagement was high (1.5 million unique individuals). Instagram, which wasn't used in 2018, saw the largest gains of the three platforms, with a 23% increase in followers, while Facebook and Twitter gained 6.5 and 14%, respectively. And as in 2018, the reach for our Mauna Loa eruption coverage was primarily to people who live in Hawaii. Four of the top seven locations of people viewing USGS Volcanoes Facebook content were in the State, with the top ranking coming from Hilo, the largest city on the Island of Hawaii.

In summary, thanks to the social media experience in 2018 and techniques tested and refined in 2020 and 2021, the social media team was quickly integrated into the HVO and VSC eruption response communication team. Additional staff with experience in writing and posting content to social media were brought into the team, and 8-h shifts covering 18 h per day were assigned by the 2nd day of the crisis. A USGS strategy to provide information and answer questions *via* social media has now been implemented in multiple eruption crises. Each successive response incorporates lessons learned from previous experiences. The ability to communicate quickly and directly *via* social media with Island of Hawaii residents, and to answer their questions, has, in the view of authors, added important value to and extended the reach of USGS communication efforts during eruption responses.

9. Summary

Research has shown that information disseminated by official sources is better received and acted upon when those sources are trusted—that is, perceived to be transparent, competent, benevolent, and acting with integrity (Petty and Wegener, 1998; Seeger, 2006; Covello, 2010; Besley et al., 2021). Sustained outreach and two-way communication are important ways to build trust, and social media provides a powerful tool to do so. Not only does social media operate in near-real-time, but it also allows public members a chance to interact with science organizations in a way not possible with traditional media or static websites. This interaction humanizes people on both sides of the screen and contributes to the understanding and awareness of information-seekers of all kinds.

Although prior eruption response communication by USGS volcano observatories has involved substantial interaction with both traditional media and affected communities (Neal et al., 2005; Driedger et al., 2008; Frenzen and Matarrese, 2008; Brantley et al., 2019), the 2018 eruption of Kılauea was the first opportunity to test the USGS Volcanoes' social media accounts as crisis communication tools. Given the difficulties of cascading hazards experienced by HVO, including the loss of the main facility, it was a benefit to have the social media team primarily offsite for the duration of the eruption and, therefore, unaffected by HVO's displacement. However, it would benefit the USGS Volcanoes' social media team to have a dedicated HVO staff member. Internal communication within HVO and the responding team of scientists, and the ability to deliver timely and accurate information to audiences *via* social media, was greatly enhanced by online collaboration software. Information provided through the USGS Volcanoes' social media accounts helped to build a growing, supportive online community that was both local and global in its reach.

While the USGS Volcanoes' social media strategy and experience in 2018 were shaped by USGS policy, communication capabilities, resources (staffing, time, and expertise), and the cultural landscape of Hawaii, lessons learned may be applicable at other observatories and similar science agencies in crisis response. Fostering community relationships, emphasizing transparency, admitting limitations, and interacting consistently and often with different audiences can benefit any observatory, particularly in building trust with the local population. We hope that the lessons learned in 2018 and applied during subsequent smaller-scale eruption responses in Hawaii can help create effective social media communication plans for a wide range of crisis responses.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Most authors (WS, JB, EW, MP, and AW) were part of the USGS Volcanoes' social media team during the 2018 Kılauea eruption and posted original content and answered follow-up questions on Facebook and Twitter. WS is the USGS Volcanoes' social media team lead and conducted the literature review and wrote the bulk of this manuscript. JB was the primary Twitter affiliate during 2018 and contributed to Sections 6, 7, 9, and several figures. EW was the primary Facebook affiliate during 2018 and provided early input to the manuscript's organization, reviewed drafts, and added material throughout. MP's primary role was answering Facebook questions during the 2018 crisis, he contributed to the manuscript's HVO background section, and provided reference material for recent research at Kılauea. AW was the surge-capacity addition to the USGS Volcanoes' group in 2018 and contributed to the structure and flow of the manuscript through a thorough review. KM became involved in HVO communication in 2020 and provided information that was shared during the 2020 and 2021 Kılauea and 2022 Mauna Loa eruptions. All authors contributed to the article and approved the submitted version.

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Conflict of interest

KM was employed by Research Corporation of the University of Hawaii.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2023.976041/full#supplementary-material

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A social bot in support of crisis communication: 10-years of @LastQuake experience on Twitter

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Social media such as Facebook or Twitter are at present considered part of the communication systems of many seismological institutes, including the European–Mediterranean Seismological Center (EMSC). Since 2012, the EMSC has been operating a hybrid Twitter system named @LastQuake comprising a bot for rapid information on global felt earthquakes and their effects, which is complemented by manual moderation that provides quasi-systematic and rapid answers to users' questions, especially after damaging earthquakes and earthquake sequences. The 2022 release of @LastQuake transcends a mere alert service and possessess additional capabilities, including fighting against misinformation and enhancing earthquake risk awareness and preparedness by exploiting the teachable moments opened by widely felt but non-damaging earthquakes. @LastQuake significantly increases the visibility and audience of the European–Mediterranean Seismological Center services, even in regions where its smartphone application (app) and websites are well known. It also contributes to increasing the volume of crowdsourced eyewitness observations that are collected, notably through the publication of rapid non-seismic-wave-based detections, as well as by reaching out to Twitter users who post about felt experiences through individual invitation messages. Although its impact, especially in raising awareness and preparedness is difficult to evaluate, @LastQuake efficiently supports crisis communication after large earthquakes and receives positive feedback from users for satisfying identified information needs of eyewitnesses automatically and in a timely manner. This study shares the experience gained over the last 10 years of operating the bot, presents the impact of users' feedback on empirically driving its evolution, and discusses the ways by which we can move toward a more data-driven assessment of its impact.

KEYWORDS

Twitter bot, social media in emergency situations, risk reduction, crisis communication, people-centered communication, citizen science, earthquake, risk awareness

Introduction

The use of social media in crisis management has been studied extensively over the past decade, with three main topics, namely, the effects of emergencies on social media (how populations use them following a disaster), the ways to exploit information shared on social media for improved situational awareness (e.g., event detection and crisis mapping), and, finally, social media usage in crisis and disaster communication (for a recent review, see Saroj and Pal, 2020). The role of social media in disaster communication is at present well established, as illustrated by the number of organizations publishing their own usage recommendations, from the Organization for Economic Co-operation and Development (OECD) and the International Air Transport Association (IATA) to the Red Cross (Eriksson, 2018). Despite the existence of such recommendations and although they could help to handle some of the many tasks in crisis communication, social media bots, i.e., the software programs that automatically publish messages and/or interact with users, have received little attention to date in the literature. In this study, we focused solely on bots that support crisis communication and excluded from this discussion social media bots that aim to influence online discussions by promoting the visibility of some content (e.g., by sharing or liking them) (see Khaund et al., 2018). Hofeditz et al. (2019), the main research on this topic, concluded in their study that no overview was available for the tasks that social media bots could perform to support crisis communication and that there were very few such bots despite their significant potential and that the ones identified were basic and often limited to simple alert systems.

In the field of seismology as well, social media has revolutionized the dissemination of rapid public earthquake information over the last decade in various ways. Many institutes have advantageously complemented their traditional websites with Facebook and/or Twitter accounts to better serve and extend their audiences. This strategy is beneficial due to the large base of active users on such platforms, often including journalists and other potential information intermediaries, while being free to use. Importantly for seismology, they can easily cope with the large traffic surges observed after widely felt earthquakes which often render the institute websites inaccessible at the very moment when they are the most needed by the public (Schwarz, 2004; Bossu et al., 2008, 2012, 2019; Quigley and Forte, 2017). In addition, being present on popular social media can expedite the circulation of information and in turn raise the efficiency of risk communication after a strong earthquake. This occurs in part due to the familiarity principle, whereby people tend to turn first to tools that they are already familiar with during emergencies (Steelman et al., 2015), and also because of user-defined notifications that push information to users.

The microblogging site Twitter has become the *de facto* source of recent news as a result of its concise, real-time, and unrestricted (i.e., accessible to anyone) lines of communication. This makes it well suited for public information during emergencies, particularly for rapid onset, unpredictable events such as earthquakes. Several usages of Twitter may be distinguished regarding seismology specifically. One use concerns the public discussion and dissemination of research results, especially after a significant earthquake, a process that publicly illustrates how scientific collaborations work and how new knowledge is built and, therefore contributes to the dialogue between science and society (Britton et al., 2019; Lacassin et al., 2020). Other initiatives focus on education, for example, @IRIS_EPO regularly publishes existing education materials on Earth sciences and seismology concepts (e.g., magnitude vs. intensity) while some individual scientists, such as @JudithGeology, devote time to preparing detailed and easy-to-understand threads on questions such as "Why earthquakes cannot be predicted?" or "The reason why rocks often naturally break at 90-degree angles" (Hubbard, 2022). National monitoring agencies, on the other hand, often operate bots for the rapid publication of information on recent earthquakes in their region (e.g., source parameters); some of these bots have a large number of followers, such as, @INGVterremoti (from the National Institute of Geophysics and Volcanology in Italy), with 280,000 followers, or @BMKG (from the National Institute for Meteorology and Geophysics of Indonesia), with 6.4 million followers. These bots generally only broadcast information by publishing automatic tweets, have no (or very limited) interactions with their followers, do not follow any (or only a few) other accounts, and are, as identified by Hofeditz et al. (2019), mere alert systems. When an institute engages in direct dialogue (questions/answers) on Twitter (exchanges which are the raison d'être of social media), it generally takes place on a separate and dedicated account. This is the scheme used by the United States Geological Survey (USGS) where @USGSted publishes recent earthquake locations, while @USGS_Quake is a manually operated account focused on science communication and public interactions.

The European–Mediterranean Seismological Center (EMSC) also operates two accounts, a classic bot—or alert system—@EMSC that reports all EMSC seismically located earthquakes worldwide (50,000–70,000/year) and @LastQuake, a hybrid system combining a bot and manual publications but focused on earthquakes known to have been felt and their effects. There are 3,800–4,200 felt earthquakes per year; defined in this article are events that have been detected *via* crowdsourcing (see later) or for which at least three consistent felt reports have been collected through the app or websites. In addition, @LastQuake covers institutional matters, answers Twitter users' questions, and has manual moderation of exchanges. There is a quasi-systematic rapid response to users' questions, and the incoming queries are generally numerous after damaging earthquakes or during a sequence of earthquakes when significant efforts are often devoted to answering rapidly.

The purpose of this study is not to describe all of the features and technical details of @LastQuake but to present its main characteristics as well as to share the experience gained and lessons learned over the last 10 years of this global experiment in event-driven and people-centered dynamic risk communication by a Twitter bot. More precisely, we intend to illustrate how, at little cost, a Twitter bot can complement existing communication tools, enlarge the audience, engage with global earthquakes' eyewitnesses, and contribute to improved crowdsourcing. We will also describe how the second release of the bot intends to contribute to the fight against earthquake misinformation (such as prediction claims), as well as improve seismic risk awareness and preparedness. Finally, we will discuss the tools put in place to move toward more data-driven performance evaluation systems.

In order to do so, we first outline the empirical methods and principles that led to the development and evolution of the bot. We then present the objectives and features of the first version of the bot, and how lessons learned from damaging earthquakes and user feedback drove its evolution, guided the establishment of a moderation policy, and led to the design of its 2022 version. Finally, we discuss the perceived benefits, limitations, and challenges of such a tool and argue that a Twitter bot can advantageously complement existing information systems and enhance people-centered dynamic risk communication.

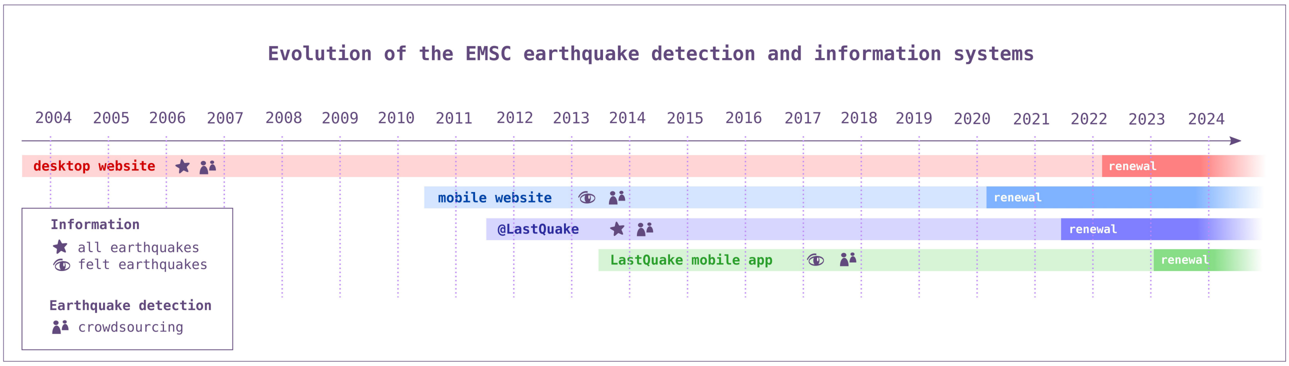

FIGURE 1
Evolution of the different components of the LastQuake information and crowdsourcing system, along with their principal individual features. The website for desktops provides data for all earthquakes (felt and not felt) while the other components target eyewitnesses and are focused on felt and damaging earthquakes. For the sake of completeness, there is also a Telegram account that publishes the same messages as the @LastQuake Twitter bot but more details are not deemed necessary because of its limited audience and the absence of interactions with users.

Method and principles guiding @LastQuake bot evolutions

The goal of the @LastQuake bot is to make information on felt earthquakes readily available and circulate their effects to the public in a timely and easy-to-understand manner while remaining as consistent as possible with the LastQuake smartphone app. Feedback from users has been the main driver of the bot's evolution. Feedback has been collected through direct exchanges on Twitter but also *via* feedback from app users [collected through online questionnaires (Bossu et al., 2015) and on publicly available reviews on app stores] or emails. For example, the systematic questions about earthquake prediction after damaging earthquakes led us to integrate advice to combat misinformation into the 2022 bot's features. Furthermore, the confusion generated by many felt events swiftly occurring in the same area in a short period of time during aftershock sequences led to the numbering in the tweets of events constituting the sequence. The publication of felt report maps on both the app and the bot even when no earthquake has been seismically located resulted from exchanges about the app during the Mayotte earthquake sequence in 2018 (Fallou et al., 2020). A moderation policy was also gradually developed following the same experimental and empirical approach. Ultimately, we consider that we have fulfilled the public's information needs when the number of questions decreases even while increasing followership and level of interactions (likes, views, retweets, etc.). In other words, this method aimed to develop a bot to support crisis communication by automatically answering as many of the recurrent information needs as possible that appear after felt and damaging earthquakes and thus limit direct (human) answers to only the trickiest and/or unusual questions.

A Twitter bot for engaging with global earthquake eyewitnesses

The @LastQuake bot, launched in 2012, was part of the development of the people-centered LastQuake communication system initiated a year earlier by a new website for mobile devices and completed in 2014 by its eponymous smartphone app (Figure 1). LastQuake is an information and crowdsourcing system focusing on felt earthquakes and their effects, an approach that implicitly assumes that this is the most important information for the general public (Bossu et al., 2011, 2018). The Twitter quake bot, the website for mobile devices, and the app publish the same information (detections, earthquake parameters, felt report maps, and comments) but in different formats (e.g., a rolling banner on the website and a white text box on the app). Felt experiences are crowdsourced through the websites and the app (Figure 1). Beyond increasing the EMSC's reach to new users, the bot's purpose is to pull earthquake eyewitnesses from Twitter to our websites to crowdsource their felt experiences. Twitter users are known to be present within tens of seconds of tremor in regions where Twitter is popular (Earle et al., 2011).

To do so, fast preliminary information is published so as to engage with eyewitnesses (Figure 2) (Bossu et al., 2011, 2019) which comes from "crowdsourced detections" whereby a felt earthquake is detected through the digital footprints generated by eyewitnesses seeking information (e.g., traffic increase on the EMSC websites or concomitant launches of LastQuake, the EMSC's smartphone app) (Bossu et al., 2008, 2012, 2019). Since these detections are fast (12 to 120 s after an earthquake occurrence), they initiate early and efficient crowdsourcing (Bossu et al., 2018). The tweet (the name of a message published on Twitter) reporting a crowdsourced detection is geo-located at the detection location and includes a hashtag (a tag that eases the cross-referencing of content by topic) of the keyword "earthquake" in both English and the local language to improve its findability by eyewitnesses of this specific event.

A widely felt earthquake in Jakarta in Indonesia, a country known for its extensive Twitter use (Carley et al., 2015), illustrates the significance of this early and preliminary information (Figure 2). The resulting impact is illustrated by the user interaction metrics measured for each tweet, especially the number of retweets (7,000), which is the reposting of the initial message to the user's followers and so is an indication of the viral propagation of the information, and also the number of "likes" (20,000) given to

FIGURE 2
An example of an automatic tweet reporting a crowdsourced detection, in this case based on the online reactions of eyewitnesses following a M6.6 earthquake in Sunda Strait in January 2022 that was widely felt in Jakarta. It includes a hashtag with the keyword earthquake in the local language ("gempa" in Indonesian), as well as the name of the region, the country, and a link to the EMSC website to encourage sharing of felt experiences. It was published 97 s after the earthquake while the first seismic location was available 440 s later. Two-thirds of the 438 felt reports collected were crowdsourced through the websites.

the tweet which indicates users' appreciation (Figure 2). As the author of the tweet, the EMSC has access to additional impact measurements such as the number of views and the number of times users visited its profile, which were 2 million and 12,000 for this tweet, respectively (significant numbers compared to an estimated 15,000 Indonesian followers of @LastQuake Twitter handle).

The link to EMSC's website (Figure 2) pushes eyewitnesses toward the website and nudges them to share their felt experiences. In this case, the link did increase eyewitnesses' visits immediately after the earthquake with 77% of the 4,873 Indonesian website visitors within 30 min of the earthquake arriving *via* this link. There is no known method to evaluate the actual numbers of felt reports collected from these referred visitors; however, the vast majority (66%) were collected through websites (rather than the app) and half of them were collected before the first seismic location was available (537 s after the earthquake occurrence). Beyond this specific case, the publication of this early detection has likely contributed, among other factors, to the large increase in the number of felt reports collected yearly by the EMSC from 2012 to 2021 (14,000–576,000) as well as the rapidity of their collection. Indeed, the proportion of reports collected before seismic information was available or an app notification was issued increased from 8 to 37% during the same period.

The Twitter bot publication did not stop with this first tweet (Figure 2). For each crowd sourced detection, a thread of tweets was published within a 90 min window. Typically, they included the seismic location, macroseismic maps (representing collected felt reports), and when necessary, some updates (e.g., due to revision of earthquake parameters, or large collections of felt reports). More tweets were published in the same time window in cases of tsunamigenic or destructive earthquakes. For example, 42 automatic tweets were published within 90 min of the 2015 destructive Nepal earthquake, which are available as an electronic supplement in Bossu et al. (2015).

Lessons learned from past earthquakes

Widely felt and destructive earthquakes can expose flaws or limitations in the @LastQuake automatic information system and provide hints for possible improvements. We list in this section, the main lessons learned since 2012. After the Nepal 2015 destructive earthquake, LastQuake app users requested the integration of behavioral recommendations to guide them after shaking. These were introduced both in the app and in the Twitter bot through a set of cartoons (*dos and don'ts*) that are systematically published after destructive earthquakes (Bossu et al., 2015; Fallou et al., 2019) and were complemented by similar tsunami safety tips after the 2018 Palu (Indonesia) earthquake and tsunami (Carvajal et al., 2019).

In 2018, in Mayotte, an island located between Mozambique and Madagascar, a widely felt M5.9 earthquake was followed in the next 6 months by more than 100 widely felt aftershocks with 12,000 accumulated felt reports, the vast majority being non-seismically located due to the then poor local and regional seismic coverage (Fallou et al., 2020). The possibility that some widely felt earthquakes would not be seismically located had not been anticipated. A crowdsourced detection not confirmed by seismic data within 15 min was assumed to be a false detection. As a consequence, even when numerous felt reports had been associated with it, in the absence of seismic location, the crowdsourced detection (Figure 1) was simply deleted from the app and website after 15 min, which fed rumors and conspiracy theories (Fallou et al., 2020). Following this experience, preliminary macroseismic maps are published on Twitter (and made available on the app) as soon as the crowdsourced detection was confirmed by consistent felt reports regardless of the availability of seismic data. This not only avoids possible misunderstandings by the users but also speeds up publicly available impact-related information. To avoid possible misunderstandings, a video presenting the functioning methods of crowdsourced detections and of the LastQuake system is online as an @LastQuake pinned tweet (a Twitter post that remains at the top of the profile).

In 2018, Lombok, a tourist region of Indonesia, was shaken by a sequence of three earthquakes (one M6.4 event and two M6.9 events) between 28 July and 19 August (Supendi et al., 2020). This

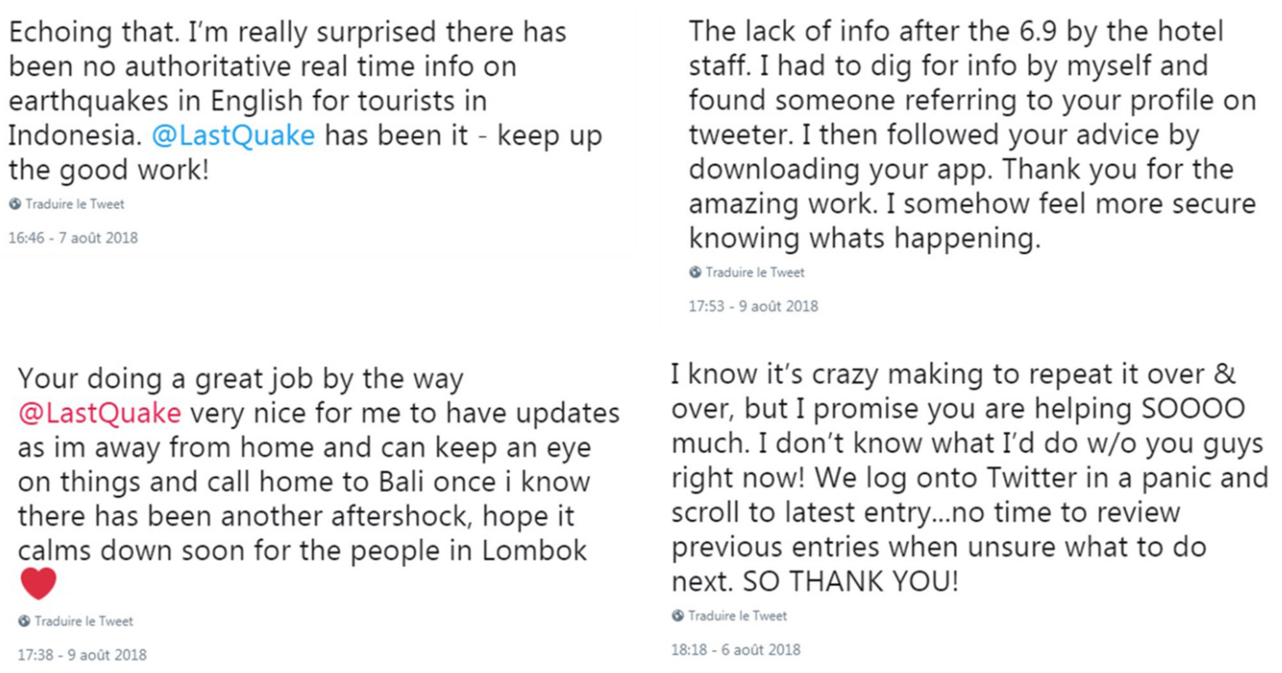

FIGURE 3
A set of example tweets received during the Lombok (Indonesia) earthquake sequence illustrating the difficulty for tourists to find information in English, the usefulness of the @LastQuake information also for people from Indonesia's diaspora and how timely people-centered information can reduce anxiety.

inevitably generated many questions on the possible evolution of the seismicity and whether it was safe to stay for holidays. Users were grateful that we took the time to answer with empathy, even if our answers on the possibility of future larger shocks fell short of their initial expectations (Figure 3). The questions came from foreigners, not from Indonesians who were probably receiving satisfactory information from national authorities in their native language. Hence, this case illustrated the need for seismological institutes to offer information services not only to their nationals but also to foreigners (e.g., tourists) present in the area and also to their diaspora (Figure 3).

There were extensive exchanges with Twitter users over significant periods of time in relation to two of the recent destructive earthquakes in Europe: the M6.4 2019 Albanian (Bossu et al., 2020) and M6.4 2020 Petrinja (Croatia) earthquakes (Markuši et al., 2021). When they occurred, the EMSC's local audiences and visibility were already significant as they were both preceded by significant earthquake activity in the previous months: an M5.6 foreshock 2 months before the Albanian event and the M5.5 Zagreb earthquake 9 months before the Petrinja event and 50 km away (Markušić et al., 2020; Contreras et al., 2021). At its peak, the penetration rate of the LastQuake app reached 7% of the Croatian population. There were lessons similar to the ones learned from the Lombok earthquake. Users sought the reduction of anxiety conferred by answers and rapid information (see Figure 10 in Bossu et al., 2020 for tweets), a well-identified phenomenon in psychology (Saathoff and Everly, 2002), and confirmed by independent studies of the Zagreb earthquake (Mustać et al., 2021). In addition, both cases had individuals claiming to predict future events that required rebuttals with dedicated tweets (Fallou et al., 2022a) (Figure 3). The most important lessons were linked to the high visibility and large adoption of EMSC's information tools by the local population. Since crowdsourced detections reflect eyewitnesses' online reactions, a large local user base means an enhanced detection sensitivity as the number of "human sensors" increases, i.e., as more earthquakes are detected, many of low magnitude, and for larger magnitude earthquakes, the online reactions become much larger. For example, out of the 38 earthquakes detected to date, for which at least 4,800 felt reports have been collected, 35 were in Croatia and one was an M1.4 Petrinja aftershock. Outside Croatia, the smallest magnitude earthquake in this list was an M4.8 in Bosnia and Herzegovina.

Improved detectability impaired the clarity of the information of the Twitter quake bot by causing multiple threads about small magnitude aftershocks, with very similar tweets from one thread to the next (as aftershocks are close in time and space). These threads could even be intertwined when the aftershocks were close enough in time. This lack of hierarchy, with a timeline dominated by tweets about small-magnitude events, made the information about larger events (the more important ones) difficult to find.

Large online reactions overloaded EMSC servers, slowing services and interrupting them on a number of occasions, especially during the first weeks of the aftershock sequences. In both Croatian and Albanian cases, the ability to maintain the information flow on Twitter and explain to some of our users with full transparency and openness the reasons for these difficulties proved essential. Explanations were, with a few exceptions, well accepted despite the inconvenience for users. When it was explained that the EMSC is a not-for-profit NGO, Twitter users exhibited a strong willingness to help with actual financial donations, an invitation to a hackathon organized in Albania in February 2020, or propositions from experts to improve our services (the ergonomics of the next version of LastQuake app is being defined with the pro bono help of a Croatian professional). Casual and open exchanges about these service interruptions, including local media interviews (web, radio, and TV), gradually personalized the EMSC team on Twitter and especially our main IT staff member ("Fred"), who began to receive tweets of encouragement at each service interruption, which themselves were reported by local media on several occasions (e.g., https://www.rtl.hr/vijesti/hrvatska/saznali-smo-tko-je-misteriozni-fred-i-tko-stoji-iza-popularne-aplikacije-koju-su-hrvati-srusli-5639294c-b9f3-11ec-8db4-0242ac120035, last accessed 8 July 2022. In Croatian language).

@LastQuake allows users to ask questions and some general questions appear repeatedly, such as the cause of magnitude discrepancies between agencies. Others, based on their personal experiences, challenged the very possibility for a given aftershock to have been felt, or questioned the magnitude estimate, a misunderstanding due to the frequent confusion between intensity and magnitude. This highlighted the need for educational messages on seismology and the way the LastQuake system operates.

In addition, the LastQuake system has also detected some non-seismic events. This was the case in 2017 when the online reaction of the public proved to be related to an earthquake prediction that did not materialize in Punjab India (Martin et al., 2021). In other cases, the cause can be identified by Twitter users themselves, such as in the cases of sonic booms and of a meteor's atmospheric entrance on 20 February 2020 over the region of Zagreb (Croatia).

Finally, in practice, @LastQuake is the place to communicate with the public about the different components of the LastQuake system (Figure 1). A seismic activity grid pattern was observed on an interactive seismicity map of La Palma (Canary Island) during the 2021 eruption of the Cumbre Vieja volcano, occurring due to the rounding up of earthquake location coordinates; in a related article, Fallou et al. (2022b) present how the grid pattern was exploited in support of conspiracy theories and how EMSC attempted to debunk them on Twitter. There are also far more positive usages; Twitter has been used to identify volunteers for translating the LastQuake app, which is now available in 42 languages due to their contributions.

Moderation policy for @LastQuake

The @LastQuake moderation policy was developed from experiences faced over time. It is applied to any tweet containing our Twitter handle. This can be an interaction with one of our own tweets, a direct question, or an attempt to benefit from our large followership (e.g., for advertising purposes). The policy aims to maximize the reliability and credibility of our timeline and avoid the exposure of inappropriate messages or content *via* @LastQuake. Inflammatory, insulting, and offensive language is banned, as well as spam, advertisements, proselytism, and any type of discrimination or political statements. More specifically to @LastQuake, we refuse the association of our timeline with any non-scientifically based claims, notably earthquake predictions. This moderation has been implemented by asking for the deletion of the tweet by its author and/or by blocking the account.

This strict moderation policy has been made necessary by experience and is explained to @LastQuake users when it is enforced. Earthquakes occurring close to a disputed territory often generate nasty inflammatory comments which need to be rapidly deleted to avoid attracting more inappropriate exchanges and trolls. On one occasion, several dozens of tweets reporting the same prediction claim were received in a few tens of minutes, and when these accounts were blocked (following their refusal to delete them), a second wave of tweets still associated with the @LastQuake timeline and still about the same prediction claim complained about our supposed lack of willingness for scientific debate and suppression of free speech. Since then, this possibly concerted effort has not been observed again. There are currently several hundreds of blocked accounts.

Main features of the 2022 @LastQuake bot

The new version of the @LastQuake bot was released in February 2022. Besides technical changes (e.g., maximum tweet length changing from 140 to 280 characters) and visual improvements, the February 2022 release's aims were: (1) adapting the rate, duration, and content of publications to the estimated societal importance of each earthquake, (2) ensuring the diversity of threads through the utilization of alternative tweets expressing the same information, (3) exploiting teachable moments produced by felt earthquakes for enhanced public preparedness and awareness, (4) fighting misinformation, (5) extending the audience of the bot beyond eyewitnesses, and (6) nudging users tweeting about earthquakes to share their felt experience with us. In addition, we developed a performance analysis tool to quantitatively monitor public interactions with the different tweets, which will be useful for steering future improvements and evolutions of the bot.

The implementation of these objectives required the definition of six categories of earthquakes and their association with five classes of information and time windows for their publication (Figure 4). The category of "Destructive earthquakes", i.e., causing significant damage and/or fatalities as identified by our internal impact assessment tool (Julien-Laferrière, 2019; Guérin-Marthe et al., 2021), is the category with the longest publication time window. The last tweet is published 12 h after the earthquake occurrence and is intended to fight misinformation, especially earthquake predictions. It may contribute to "pre-bunking" if misinformation has not yet been propagated or in debunking it otherwise (Fallou et al., 2022a,b, which is a sister paper in this same issue that contains more details on EMSC's practices to fight misinformation). The threads contain information about the event, its effects, safety tips, and a wrap-up summarizing the available information (which is aimed at people not directly affected and journalists) (Figure 4). Earthquakes of M7.5 or greater, because they are rare, are a category on their own even if not felt.

The final four categories are for non-destructive earthquakes (i.e., not identified as such) defined using two criteria, the magnitude (above and below M4.5) and whether or not they have

FIGURE 4
Schematic view of the possible types of information automatically published by the @LastQuake bot as a function of the classes of earthquakes and time. Large earthquakes are arbitrarily defined as having magnitudes above 4.5. The existence of an audience is defined by the number of collected felt reports (the threshold being set at 50). A specific category of earthquake has been made for unfelt $M > 7.5$ events which due to their magnitude may still attract public interest. While key information on earthquakes (e.g., parameters) and their effects are systematically published, additional publication parameters are used to avoid repetition of the same tweet within a short period of time. Educational tweets or misinformation debunking ones contain some external resources; some concepts have multiple variations of tweets. Consecutive educational or misinformation fighting tweets are always different. Altogether, the bot can generate 56 different tweets.

attracted public attention (as measured by the number of collected felt reports) (Figure 4).

The M2.9 earthquake of 25 October 2021 below the city of Athens for which 1,500 felt reports were collected is an example of a "small magnitude earthquake with audience" (Figure 4). Such events create a teachable moment where eyewitnesses and people concerned by this earthquake are actively looking for information and are more receptive to learning about earthquake risk. Such events are therefore an opportunity to share some educational or awareness materials and potentially reach people efficiently (Stallings, 1986; Bravo and Hubenthal, 2016). Once formal education in science has ended, this may be one of the few opportunities available to widely teach seismologically related information (Baram-Tsabari and Segev, 2015). We also invite Twitter users to join our LastQuakers forum to have more targeted and in-depth interactions. In contrast, a small magnitude earthquake or aftershock only felt by a few people does not set up such a teachable moment, and in such cases, tweets are limited to earthquake parameters and a macroseismic map within a time window limited to 20 min (Figure 4).

The magnitude threshold has been set to M4.5 because, above it, the existence of undetected damage immediately after the event is possible in the absence of *in situ* observations (Bossu et al., 2016). The M5.9 Afghanistan earthquake of 21 June 2022, which killed more than 1,200 people, falls in such a category. In such a case, the Twitter thread avoids the casual tone that can be used for smaller magnitude events but would be highly inappropriate here (Figure 5). For comparison, the thread automatically generated for a small-magnitude earthquake in South Carolina is presented in Figure 6. All earthquake threads end with a final message referencing the EMSC websites and app, where further updates can be found.

We have also replicated a system first set-up for the PetaJarkata project (@petabencana) in Indonesia (Ogie and Forehead, 2017) to optimize the crowdsourcing of eyewitness observations immediately after a disaster. Using the Twitter API (application programming interface), tweets containing the keyword "earthquake" in the local language and published after the occurrence of a felt event are automatically detected. An automatic reply is then published, inviting its author to share her/his observations using the LastQuake app or website to help document the earthquake's effects. To avoid spamming, especially during aftershock sequences, the same user cannot receive more than one invitation every 6 months.

Finally, after destructive earthquakes or a sequence of earthquakes, contact with the national seismological institutes is established to avoid possible unwanted hindrances to their own communication. Such contacts were established in Albania, Croatia, and very recently in Cyprus; in these three cases, the national and EMSC's activities on social media proved to be synergetic.

A performance evaluation tool

Along with the new LastQuake bot, a tool has been developed to monitor the key parameters associated with each published tweet that are available through the Twitter API (e.g., number of views, retweets, and likes) as well as utilize external services to determine, when possible, the geographical origin of followers. This tool's goal is to move EMSC toward a more data-driven evaluation of the LastQuake bot's performance and weaknesses, a need for social media monitoring also identified in other cases like the 2016 Kaikoura earthquakes in New Zealand (Woods et al., 2017). Statistics are derived for each category of tweets and threads (Figure 4). We ultimately aimed to identify effective and ineffective tweets in terms of user interactions. This is of particular importance for assessing the interest raised by educational or misinformation messages but also for understanding how reactions may change during an aftershock sequence. The same applies to the number of followers and learning how it evolves with time in relation to local seismic activity and determining the typical follower retention duration. This tool is essential for moving toward a more data-driven service enhancement and to better understand the roles of the different LastQuake components in a given region and during earthquake sequences.

Discussion and conclusion

@LastQuake is a Twitter bot developed to automatize rapid public information about global felt earthquakes and their effects. While the potential of such bots to support crisis communication is well recognized, we have not identified in the literature other bots going beyond basic alert systems (Hofeditz et al., 2019), making @LastQuake a potentially unique experiment to date. This bot complements the LastQuake websites and smartphone app even in regions where the latter is well known, increasing the visibility and reach of the information service. For example, on the day of the 2020 Petrinja (Croatia) earthquake, an area with a high LastQuake app penetration rate, there was a similar number of views on Twitter and the app (9 and 10 million, respectively) (Table 1) compared to the 5 million on our websites. Nevertheless, one should not overestimate the actual reach among the public affected by such an earthquake, which remains low compared to traditional media (e.g., TV and radio).

The use of bots is also rendered necessary in seismology by the speed needed to engage efficiently with eyewitnesses. The speed of automatic systems, from crowdsourced detections, earthquake locations, or the collection of felt reports is such that it does not leave time for human intervention. Despite the limited information they convey, the large visibility of crowdsourced detections tweets (Figure 2) and the efficiency of the felt report crowdsourcing they trigger, both illustrate the public need for immediate information during emergencies, even if that information is incomplete.

The new version of the @LastQuake bot outlined in this article has extended its objectives beyond rapid public information and efficient crowdsourcing to include actively fighting misinformation and testing the possibility of utilizing the teachable moments created by widely felt but non-damaging earthquakes to raise awareness, enhance preparedness, and foster new behaviors. It uses an enhanced hierarchy of information (essential during aftershock sequences), the integration of educational content, and dedicated tweets to refute the existence of earthquake prediction. It also improves the links between the different components of the LastQuake system.

In addition, the bot encourages the collection of felt reports from people reporting an earthquake on Twitter through a system of individual invitation tweets. The invitations have so far been well perceived, with nearly 90% of invitees clicking on the link to the EMSC crowdsourcing tool. We cannot demonstrate at this stage whether @LastQuake has had any impact to fight misinformation or raise awareness and preparedness. However, a precondition for success is to reach an audience as large as possible, i.e., both the direct audience on Twitter itself and the indirect one

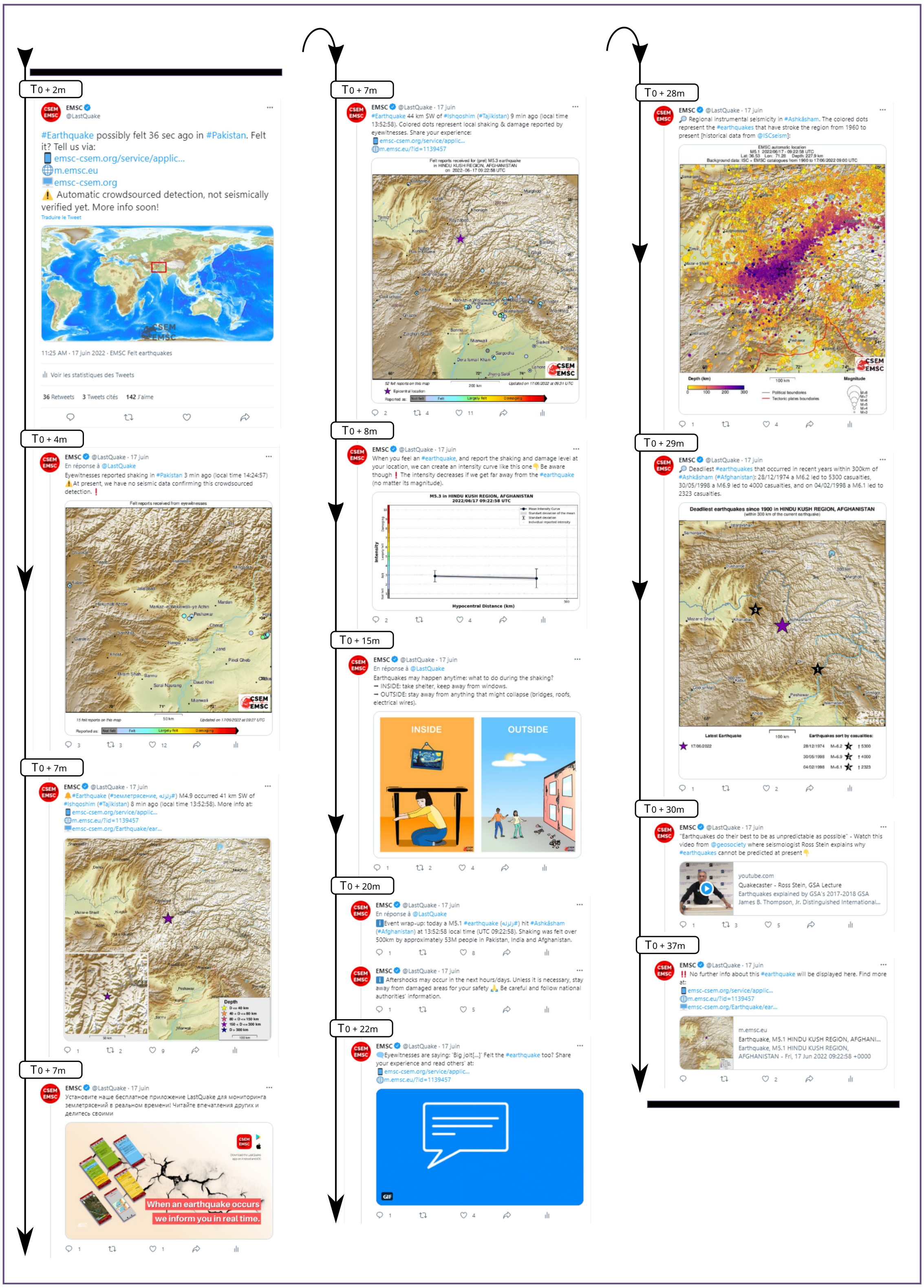

FIGURE 5
A thread of tweets automatically published in relation to the destructive M5.9 earthquake on 21 June 2022. Since the damage was not automatically detected, this event was placed in the category "large, with audience" (Figure 4). The publication time for each tweet is indicated with respect to the origin time.

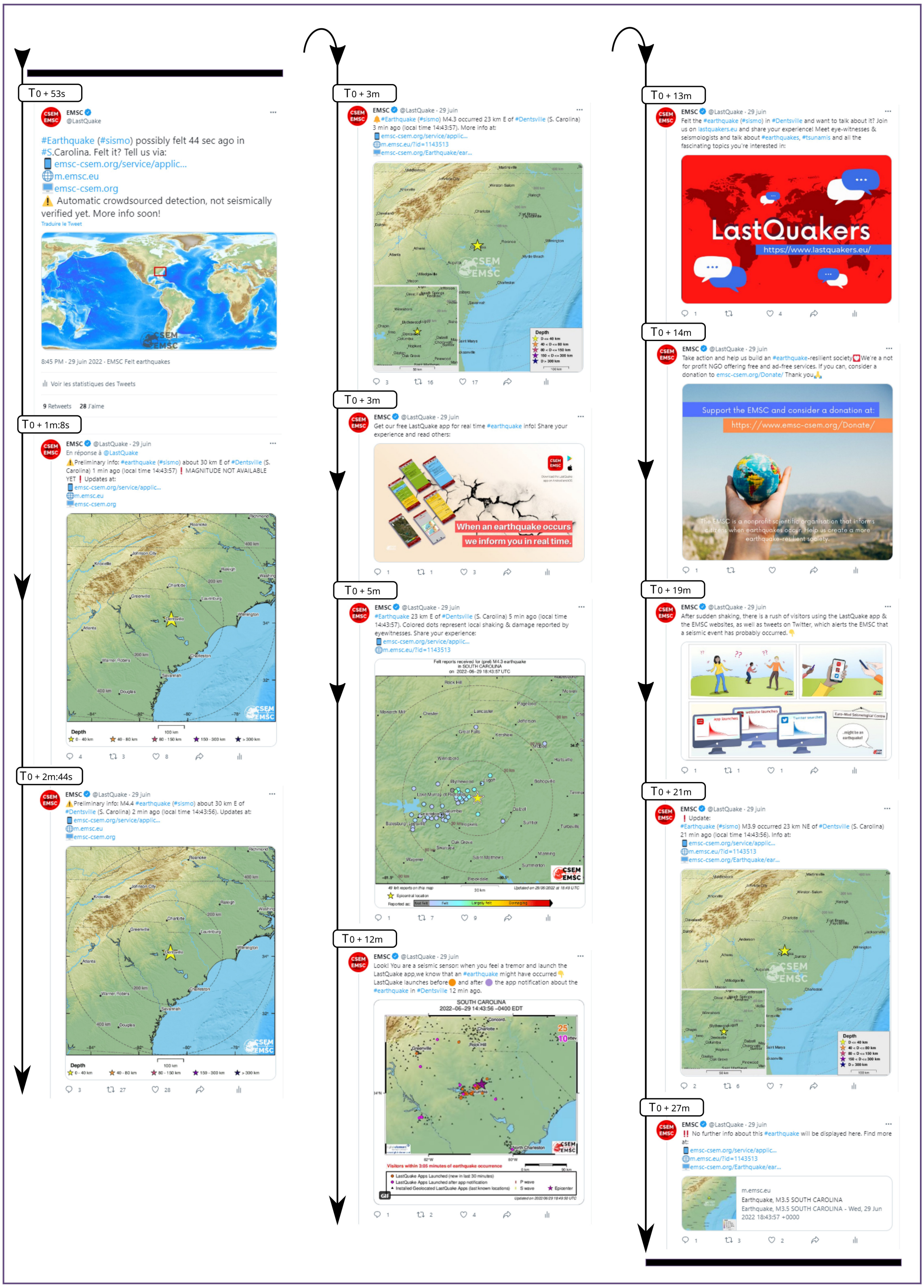

FIGURE 6
Threads of tweets automatically published in relation to South Carolina's M3.5 earthquake of 29 June 2022 and their publication times after earthquake occurrence. This earthquake was in the category "small with audience" (Figure 4). This category is considered to open a teachable moment and include in this case information on the system (tweet numbers 7 and 10). The second tweet presenting an epicentral location without magnitude estimate originated from the CsLoc method based on the combined analysis of crowdsourced and seismic data for the rapid location of felt earthquakes (Steed et al., 2019; Bondár et al., 2020).

TABLE 1 Number of views and unique visitors to the different components of the LastQuake system on 29 December 2020, the day of the damaging Petrinja (Croatia) earthquake.

December 29, 2020, M6.4 Petrinja Croatia earthquake		
	Views	Unique visitors
App	10M	320k
Twitter	9M	>200k
Website (mobile)	4M	260k
Website (desktop)	1.2M	110k

The number of unique visitors is not available on Twitter; it was assumed to be greater than the number of followers.

through the relay Twitter offers to the more traditional media. @LastQuake can contribute both to the dilution of the visibility of possible misinformation and to filling the information gap present immediately following a significant earthquake that is often exploited to spread misinformation (Fallou et al., 2020; Peng, 2020; Zhou et al., 2021). The positive users' feedback and the continuous increase of followership (210,000 in February 2022, 226,000 in November 2022, 272,000 in February 2023) are currently proxies providing qualitative support that @LastQuake is having an impact. A tool is presently in place to quantify whenever possible the bot's performance and whether its impact changes from one country to the next, while remembering that the @LastQuake bot remains a global service that does not take into account local cultural factors and social interactions affecting human behaviors and reactions (e.g., Oreskes, 2015).

Finally, although the @LastQuake bot strives to optimize the automatic delivery of timely, people-centered earthquake information and to limit human communication, such interactions remain essential and are highly appreciated on social media, contributing to limiting anxiety during crises as well as developing trust and credibility essential for an institute to provide effective communication during emergencies (Appleby-Arnold et al., 2019).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RB: initiation, supervision, funding, review of the project, and writing of the manuscript. MC: definition and preparation of the tweets, project management, figure preparation, and review of the manuscript. J-MC: technical implementation of the bot, development of the monitoring tool, and review of the manuscript. LF: review of the project and the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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USGS and social media user dialogue and sentiment during the 2018 eruption of Kīlauea Volcano, Hawai‘i

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Responsive and empathic communication by scientists is critical for building trust and engagement with communities, which, in turn, promotes receptiveness toward authoritative hazard information during times of crisis. The 2018 eruption of Hawai‘i's Kīlauea Volcano was the first volcanic crisis event in which communication via the U.S. Geological Survey (USGS) social media group, "USGS Volcanoes," played a major role in providing eruption information to publics. Providing a concrete assessment of the social media effort during the eruption is necessary for optimizing future social media hazard crisis communication. We present qualitative and quantitative analyses of USGS Volcanoes' Facebook posts and over 22,000 follow-on comments spanning the 2018 eruption. Our analyses reveal that, for the 16 posts with the highest user engagement, USGS Volcanoes and informed non-USGS users directly answered 73% of questions and directly corrected or called out inaccuracies in over 54% of comments containing misinformation. User sentiments were 66% positive on average per comment thread regarding eruption information, and user feedback toward USGS Volcanoes, USGS scientists, or the Hawaiian Volcano Observatory was 86% positive on average. Quantitative sentiment analysis reveals a 61% correlation between users' overall expressed sentiments and frequency of the word "thank," providing further evidence that social media engagement by USGS Volcanoes and informed users positively impacted collective user sentiment. Themes emerging from our qualitative thematic analysis illustrate how communication strategies employed by USGS Volcanoes successfully engaged and benefitted users, providing insights for communicating with publics on social media during crisis situations.

KEYWORDS

Kīlauea, social media, qualitative thematic analysis, mixed methods, *NVivo*, hazard communication, sentiment analysis, misinformation

1 Introduction

The U.S. Geological Survey (USGS) Volcano Hazards Program (VHP) is responsible for providing U.S. eruption-hazard-related information to a variety of stakeholders, including residents, emergency managers, media organizations, aviation industry, public health agencies, and broader publics (Dietterich and Neal, 2022). During periods of calm (i.e., when volcanoes are not in a state of heightened unrest), the VHP provides general scientific information about volcanoes, including potential hazards (Stovall et al., 2016). During significant volcanic eruptions, the VHP provides this information far more frequently, often hourly, through local, regional, and national communication channels (Brown et al., 2015; Williams et al., 2020).

The eruption of Hawai'i's Kīlauea Volcano from May through September 2018 was the largest of its kind in the last 200 years (Neal et al., 2019). Hazards were varied and impacted communities throughout the state. The Island of Hawai'i was most affected by lava flows, sulfur dioxide gas and volcanic smog (vog), volcanic ash, earthquakes, and the collapse of Kīlauea's summit caldera (Neal et al., 2019). Throughout the eruption, VHP scientists and staff provided regular eruption updates through in-person community meetings, daily interagency press briefings, answering individual questions via email, updates to the official USGS Hawaiian Volcano Observatory (HVO) webpage (Tsang and Lindsay, 2019; Goldman et al., 2023; Stovall et al., 2023), and official email and SMS messages through the USGS Volcano Notification System, consistent with previous eruption responses in Hawai'i (Brantley et al., 2019).

Unlike previous Hawai'i eruption responses, social media also played a significant role in the USGS VHP's public communication in 2018. The USGS VHP social media group (hereafter called USGS Volcanoes) used Facebook and Twitter accounts to share eruption information with media, impacted community members, and curious or vested users worldwide (Stovall et al., 2023). Here we assess the strengths and shortcomings of this tool to optimize future social media crisis communication efforts by the USGS VHP; findings may have relevance for social media crisis response planning for other hazard monitoring organizations.

One way of assessing the effectiveness of the USGS Volcanoes' 2018 eruption communication effort is to quantify the frequency of responses provided by USGS Volcanoes to questions posted by others on their page. This approach directly evaluates one of USGS Volcanoes' key goals: "answer all questions" about the 2018 eruption (Stovall et al., 2023). Similarly, we can quantify how often USGS Volcanoes responded to posts containing false information (i.e., misinformation) or rumors, a problem that commonly occurs during hazard crises (Starbird et al., 2016; Hagley, 2021).

Another way of assessing USGS Volcanoes' social media communication efficacy during the 2018 eruption response is to understand USGS Volcanoes' role in promoting or reinforcing users' trust in the USGS and HVO (Goldman et al., 2023; Stovall et al., 2023). Social media, like in-person community meetings and the "askHVO" email account, provide a means of personal engagement between social media users and official messengers that, when done effectively, can build the public's trust (Woods et al., 2017; McBride and Ball, 2022; Stovall et al., 2023). Expressions of gratitude are common and reliable indicators of user trust in authoritative sources on social media (Graham et al., 2023). Taken further, analyzing the full range of sentiments expressed by social media users in response to USGS Volcanoes' post content or comments can provide a more complete picture of users' perception of USGS Volcanoes as a credible source and messenger of eruption information (Tumpey et al., 2019; Goldman et al., 2023), especially when compared with users' sentiments expressed toward non-USGS sources or messengers on social media (Goldman et al., 2023).

Given the above considerations, we analyze USGS Volcanoes' social media communications by addressing the following two sets of questions:

1) How frequent and effective were USGS Volcanoes and informed users' responses to other non-USGS users' eruption-related questions or comments containing misinformation or rumors?
2) How positively did users respond to USGS Volcanoes' posts and comments? How does this compare with overall audience sentiment toward non-USGS users?

To answer these questions, we focus our investigation on USGS Volcanoes' Facebook page, as this was the social media platform that Hawai'i residents reported visiting most regularly for 2018 eruption information, according to interviews conducted by Goldman et al. (2023). Facebook is also the most widely used social media platform in both the United States (Pew Research Center, 2021) and worldwide (Cheng et al., 2022; Graham et al., 2023), making our findings broadly applicable to hazard communication using social media by scientists and government agencies around the world.

Additionally, we identify and explain patterns in misinformation occurring in users' comments on USGS Volcanoes' social media pages throughout the 2018 eruption. This complements our analysis of USGS Volcanoes' communication by comparing major misinformation topics, their distribution through time, USGS Volcanoes' strategies in response, and whether increased occurrences of misinformation within users' comments are correlated with increases in negative sentiments expressed by users.

2 Background

Over the past decade, social media platforms have become necessary for conveying hazard information to public audiences at local (Hagley, 2021), national (Stovall et al., 2023), and global (Eriksson, 2018) scales. Social media's overall popularity is explained by Uses and Gratifications Theory (UGT), which posits that people seek out certain media to satisfy their personal needs (Rubin, 2009; Griffin, 2012), such as seeing themselves reflected in those channels and the sources communicating through them (Severin and Tankard, 2000). UGT also helps explain social media's utility for hazard communication, since people commonly use social media to seek out information about an event, educate themselves about a topic, or easily share information with others (Whiting and Williams, 2013). These popular social media functions are also described by the theory of sensemaking, which asserts that people constantly seek out information to fill gaps in understanding or make sense of their circumstances (Dervin, 2003; Weick et al., 2005; Starbird et al., 2016).

Social media provide numerous hazard communication benefits, including rapid information feedback loops both to and from those at risk (Flew et al., 2014; Westerman et al., 2014), an ability to handle high volumes of communication traffic (Saroj and Pal, 2020), and maintaining communication if cell phone reception is lost due to local or regional power outages caused by natural hazards (Tang et al., 2021). Social media have been especially effective in communicating hazard information during travel restrictions implemented during the first 2 years of the COVID-19 pandemic (Graham et al., 2023).

More traditional broadcast media channels—including radio, television, telephone, and non-social-media webpages—tend to provide a unidirectional, top-down delivery of information from official sources to publics (Berlo, 1960). By contrast, social media platforms such as Facebook and Twitter allow for multidirectional communication threads between publics and official messengers of hazard information, and among publics themselves (Taylor et al., 2012; Simon et al., 2015; Goldman et al., 2023). This two-way communication can facilitate the development of trustworthy relationships between science agencies and the publics they seek to serve through informal and, where appropriate, potentially humorous exchanges (McBride and Ball, 2022).

Finally, the inherent informality and conversational culture of social media allows for open expression of emotion among users (Vongkusolkit and Huang, 2021), providing hazard communicators with a transparent and immediate understanding of users' attitudes that they can use to tailor responses during a crisis. Thus, scientists and emergency managers can leverage the unique benefits of social media to provide publics with accurate and timely hazard information that increases their situational awareness while providing comfort and resiliency through online community and connection (Taylor et al., 2012; Ruan et al., 2022; Graham et al., 2023).

However, the ability for anyone to produce and share information on social media also facilitates the creation and propagation of false information, particularly in response to crises that are rapidly changing or cannot be described with great certainty (Starbird et al., 2016; Hagley, 2021). In the absence of a clear, credible, or authoritative source of accurate information, social media users may rely on misinformation and rumors to satisfy their need to make sense of a highly uncertain and stressful situation (Oh et al., 2013). Rumors containing false information can increase users' anxiety, reduce their faith in official information sources, or inhibit their ability to properly assess the crisis situation and take appropriate actions for their safety (Weick, 1988; Hagley, 2021). Thus, successful hazard communication requires strategies that stop or reduce the occurrence of false information in favor of accurate and credibly sourced information (Stovall et al., 2023).

2.1 USGS volcano hazards communication on social media

Social media has been used for USGS hazard and volcano information communication since 2009, when the Alaska Volcano Observatory (AVO) and Alaska Division of Geological and Geophysical Surveys (ADGGS) created the first volcano alert social media account (@alaska_avo) on Twitter in response to public requests following volcanic unrest at Redoubt Volcano (Stovall et al., 2023). Public reception was so positive that AVO created Facebook and Instagram accounts in 2013 and 2015, respectively (Stovall et al., 2023). Following the 2014-15 Pāhoa lava flow crisis in Hawai‘i, the USGS VHP established a second major social media account, USGS Volcanoes, on Facebook and Twitter, to emulate the dedicated communication stream provided by @alaska_avo (Stovall et al., 2023).

Before 2018, the VHP provided public hazard communications related to Hawaiian volcanoes through Volcano Notification System alert email and SMS messages, HVO's website, the askHVO email account, HVO's "Volcano Watch" print and web articles, TV and radio broadcasts, and in-person community meetings (Goldman et al., 2023; Stovall et al., 2023). The 2018 eruption of Kılauea Volcano was the first time USGS Volcanoes provided regular eruption updates on their Facebook and Twitter pages to complement the VHP's existing communication network. This effort resulted in a steep rise in user engagement on USGS Volcanoes' social media accounts (Figure 1), particularly among users based in Hawai‘i (Stovall et al., 2023). Thus, in addition to its traditional communication channels, USGS Volcanoes' social media became important platforms for conveying reliable and timely information about the 2018 Kılauea eruption to Hawai‘i residents.

2.2 Research term definitions

A *post* is a publicly visible body of text, often accompanied by a photograph, diagram, or video, published by the group USGS Volcanoes on their social media page (Kaplan and Haenlein, 2010), specifically, for this study, Facebook. Throughout the 2018 eruption, USGS Volcanoes published nearly 700 eruption-related posts (Stovall et al., 2023). A *comment* refers to any publicly visible body of text other than a post that is published by any user, including USGS Volcanoes, on the USGS Volcanoes social media page (Kaplan and Haenlein, 2010); note that these comments may include statements, questions, or both, as well as photos, videos, or links to other social media posts or external webpages. We define top-level comments as those posted directly in response to the original post rather than as a reply to another comment. A *post comment thread* is the publicly visible collection of all user comments posted (e.g., Gómez et al., 2008) in response to a USGS Volcanoes post. *Users* or *publics* are defined in our study as anyone interacting on social media who is not the source of information (i.e., USGS Volcanoes; Grunig, 2013). *Informed users* are users who provide factually correct information in response to other users' questions or misinformative posts (Kuklinski et al., 2000). We define factually correct, or *accurate*, information as that which is consistent with official information (Ruokolainen et al., 2023) in our research study; this means information that is posted by USGS Volcanoes or the USGS more broadly. We define *reach* as the number of unique individuals who viewed a USGS Volcanoes post or the USGS Volcanoes social media page on their mobile devices or computers (Verzosa Hurley and Kimme Hea, 2014).

We define *misinformation* as factually incorrect information that may or may not be intended to deceive other users (Rosnow, 2001; Bordia and Difonzo, 2004; Vraga and Bode, 2020). We define a *rumor* as a piece of misinformation that repeatedly appears within a single post or across multiple posts and conveys an unverified danger or threat (Bordia and Difonzo, 2004; Oh

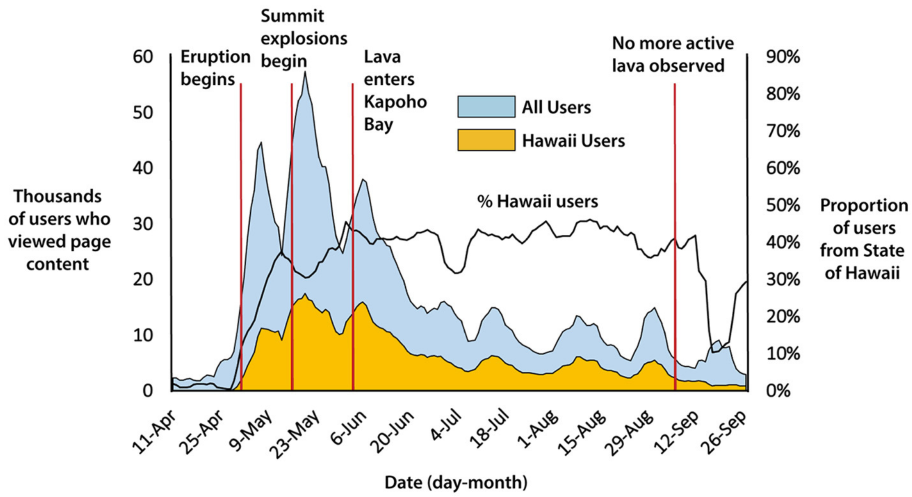

FIGURE 1
Plot of the 7-day running-average of USGS Volcanoes' reach, or the number of unique Facebook users who viewed at least one post from the USGS Volcanoes page, from April through September 2018. Adapted from Stovall et al. (2023).

et al., 2013). We note that this definition of rumor is limited to false information, unlike the broader, factually agnostic definition employed in the social psychology literature (Andrews et al., 2016; Starbird et al., 2016), because the rumors we analyzed for our study were all factually incorrect. Our definition also excludes recurring misinformation that does not convey danger or a threat, since we do not consider these comments in detail for this study. However, some of these rumors did promote distrust of USGS Volcanoes or other authoritative information sources, as explained by Stovall et al. (2023). We define *corrections* as comments that refute misinformation with facts, while *call-outs* are comments condemning a misinformative post without correcting it with facts (Lee and Lee, 2023). Finally, we define *trolling behavior* as dialogue that intends to "cause disruption and/or to trigger or exacerbate conflict for the purposes of their own amusement" (Hardaker, 2010). The concept of sentiment is also critical to our study; we use sentiment analysis to understand self-expressed emotions in users' comments. *Sentiment* is defined as the valence of a person's opinion or emotion (Colombetti, 2005; Tausczik and Pennebaker, 2010).

3 Methods

We use a mixed qualitative and quantitative approach to better understand the complex issues of trust, misinformation, and relationships between scientists and the publics they seek to serve. Our main methodology is a qualitative thematic analysis, or exploration of words and structures within a body of text to construct meaning (Crabtree and Miller, 1999), of 16 Facebook post comment threads with the highest recorded user reach during the 2018 eruption. We complement this qualitative analysis with keyword tallies and quantitative sentiment analyses of the text-based comment dataset available through Facebook's application programming interface (API). *Sentiment analysis* refers to the method of organizing written text by the polarity of emotions or sentiments reflected within it (Hutto and Gilbert, 2014). Our use of both quantitative and qualitative methods is known as triangulation, a process for gaining insight across multiple datasets (Creswell, 2009) and validating the study's findings (Webb et al., 1966; Johnson et al., 2007).

Qualitative thematic analysis focuses on identifying prevailing themes in content (Braun and Clarke, 2012). Specifically, we use interpretative thematic analysis, which involves immersing ourselves in the data and using multiple rounds of coding to determine dominant themes (Peterson, 2017). Our research focuses on conversational patterns in high-engagement post comment threads and interpreting how these patterns, or themes (defined further in Section 3.2 Qualitative and quantitative analyses of 16 post comment threads) inform our research questions, compared with recent qualitative or mixed methods investigations of USGS Volcanoes' 2018 social media hazard communications (Goldman et al., 2023; Stovall et al., 2023). Further, we used keyword tallies and sentiment analyses to complement our qualitative thematic analysis by providing numerical metrics that can be compared across the duration of the 2018 eruption and with similar studies of science communication on Facebook (Hagley, 2021; Lien and Wu, 2021; Graham et al., 2023).

3.1 Data collection

In October 2018, we downloaded bulk data for the @USGSVolcanoes account from April 7–October 1, 2018, using the Facebook analytics interface. This included numerical data for the @USGSVolcanoes account page (page likes, follows, and user location–city, state, country only) and its posts (individual post likes and shares, unique user views (reach), and comment counts). We ranked each post's impact (popularity) by tallying reach, which increases as posts are liked and shared through the social network. We identified 16 posts that reached over 100,000 users, contained threads with over 100 comments, and were posted

TABLE 1 List and metrics (through Oct. 2018) of qualitatively analyzed USGS Volcanoes Facebook posts.

"Post nickname" (Date, Time)	Total no. of comments	Daily user reach on post date	Lifetime reach (Oct. 2018)
"Kaupili street steaming cracks" (5/4/18, 12:57 p.m.)	157	48,802	152,172
"Overlook crater warning" (5/9/18, 11:24 a.m.)	211	59,743	217,490
"Overlook crater explosion" (5/9/18, 1:11 p.m.)	116	59,743	120,106
"Pohoiki road ground cracks" (5/17/18, 3:03 p.m.)	172	83,781	380,700
"Fissure 20 channelized lava flows" (5/19/18, 11:26 a.m.)	196	65,393	156,620
"Fissure 22 lava fountains" (5/21/18, 1:52 p.m.)	120	45,020	119,567
"Blue methane flames photo" (5/23/18, 9:58 a.m.)	234	53,327	218,061
"Blue methane flames video" (5/23/18, 1:52 p.m.)	217	53,327	271,726
"Fissure 22 UAS night video" (5/24/18, 2:11 p.m.)	115	56,864	152,622
"Kapoho bay lava entry" (6/4/18, 10:07 a.m.)	113	49,338	120,980
"Mid-June UAS caldera flight" (6/13/18, 3:04 p.m.)	205	29,177	121,538
"Helicopter view of fissure 8" (6/14/18, 12:15 p.m.)	170	30,285	196,645
"Late-June UAS caldera flight" (6/26/18, 11:18 a.m.)	104	20,150	101,155
"Fissure 8 lava whirlwind" (7/2/18, 1:49 p.m.)	121	21,353	186,752
"Kapoho lava island" (7/13/18, 7:32 p.m.)	130	16,594	149,222
"Late-August UAS caldera flight" (8/30/18, 4:13 p.m.)	173	19,427	254,026

Colors correspond with daily user reach (Figure 1) as follows: orange = first peak in reach (second highest overall), red = second peak in reach (highest overall), yellow = third peak in reach (third highest overall), blue = posts published after third peak.

between May 4th and August 30th, 2018 (Table 1), spanning the beginning of Kılauea eruption events through the end of significant activity at both the summit and lower East Rift Zone (Neal et al., 2019). We used the public-view Facebook interface to capture portable document format (pdf) files of the post comment threads (Figure 2) and imported them into *NVivo* (for Mac, Version 1.6.2; Bazeley and Jackson, 2013) to conduct both the interpretative thematic and quantitative analyses.

In June 2020, we extracted nearly 22,000 comments from Facebook's API that had been published on the USGS Volcanoes Facebook page between April 7 and October 1, 2018. This date range was chosen to include posts from roughly 1 month before the start of the eruption on May 3rd and 1 month after the last lava activity was observed on September 5th. We applied themes identified from our interpretative thematic analysis to quantitative analyses of rumors and user sentiment within the API comment dataset (henceforth "bulk comment dataset") to triangulate the data, as described in Fielding (2012). Triangulation allows for corroboration of the data, as well as identification of weaknesses or gaps within the analysis (Thurston et al., 2008).

3.2 Qualitative and quantitative analyses of 16 post comment threads

For our qualitative thematic analysis, we assigned labels, or "codes" (Miles and Huberman, 1994), to roughly 2,500 comments within the post comment threads of the 16 Facebook posts listed in Table 1. We used *NVivo,* a software package that is widely used for qualitative thematic analysis, to manually read, annotate, and classify (i.e., code) these comments over five distinct rounds, a process that provided us with a deeper understanding of prevalent themes within the text (Daymon and Holloway, 2010; McBride et al., 2020). While the terms, "theme" and "code," are often used interchangeably in qualitative studies (Miles and Huberman, 1994), we use "parent theme" for this study's top-level codes while using the term, "child code," to describe any of the codes embedded within each parent theme. A *primary child code* is a first-generation child code, located directly beneath its parent theme (Miles and Huberman, 1994). Likewise, a second-generation, or "grandchild" code, is referred to as a *secondary child code*, and so on. We summarize each parent theme below, while providing our codebook, or the complete list and definitions of all codes identified in this study, in the Supplementary material.

We identified two parent themes: *Eruption Sensemaking* and *Expressed Sentiments*. The theme *Eruption Sensemaking* contains questions asked by users regarding eruption events, as well as questions or statements alluding to misinformation or rumors. The name of this theme reflects that the comments we coded document users attempting to make sense of the highly uncertain nature of the 2018 Kılauea eruption (Weick et al., 2005; Starbird et al., 2016). The theme *Expressed Sentiments* contains comments in which users expressed positive, negative, and more nuanced emotions or sentiments (e.g., Liu, 2012) in response to eruption events or comments posted by other users.

Eruption Sensemaking is divided into two primary child codes: "Eruption Q & A," which contains users' questions and responses (including answers from USGS Volcanoes), and "Misinformation & Response," which includes comments with misinformation and users' responses to them (including from

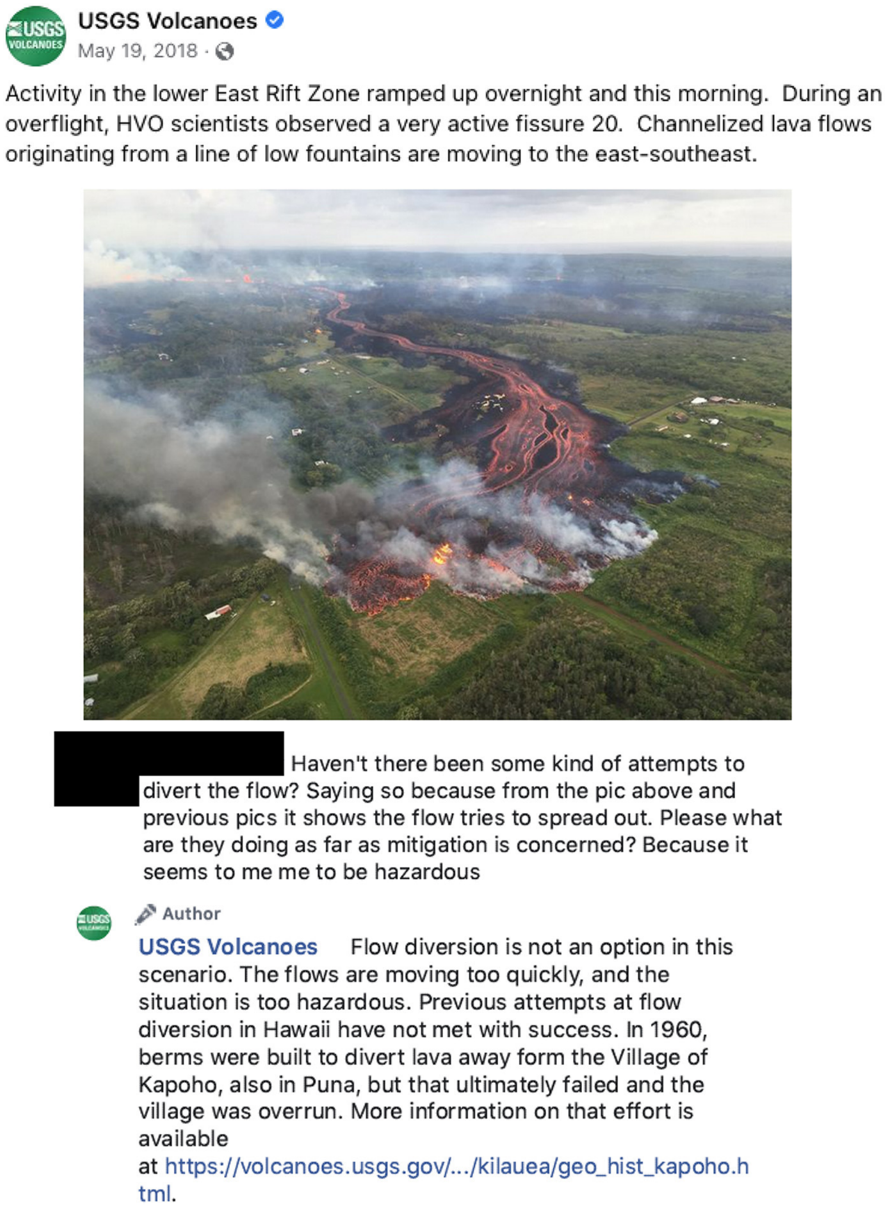

FIGURE 2
Example of a USGS Volcanoes Facebook post and underlying post comment thread regarding Kīlauea Volcano's 2018 eruption. User names and profile pictures have been omitted for privacy.

USGS Volcanoes), as well as the topics of each misinformative or rumoring comment. Comments that were either factually incorrect or inconsistent with information published by the USGS are coded as misinformation. We subdivide comments containing users' questions or misinformative statements into secondary child codes identifying whether these comments received direct responses, either from USGS Volcanoes or other users. We also further subdivide questions or misinformative comments that were not directly answered into "more relevant" and "less relevant" categories, with the latter including the most redundant, off-topic, or otherwise less appropriate comments for USGS Volcanoes or other users to respond to. These categories are further defined in the Results section. Topics coded under "Misinformation & Response" include: "Slump, Tsunami, or Catastrophic Eruption;" "PGV, Gases, Climate, or Weather;" and "Volcano or Tectonic Misinformation" (PGV refers to Puna Geothermal Venture, the geothermal energy power plant operating in the lower East Rift Zone). These three categories encompass major rumors or other forms of misinformation posted by users during the 2018 eruption, which are described in detail in Section 4.1 Eruption sensemaking: overview.

Primary child codes of *Expressed Sentiments* include: "Negative Sentiments Regarding," "Positive or Light-Hearted Sentiments Regarding," and "Mixed, Somber, or Sympathetic Sentiments Regarding." Comments coded within "Mixed, Somber, or Sympathetic Sentiments Regarding" contain a combination of comments in which users expressed multiple conflicting emotions, accepted negative events or outcomes, expressed interest for the wellbeing of people on the Island of Hawai'i, and defended the integrity or reputation of themselves or other people, entities, cultures, places, or customs. Each of these codes is subdivided based on the recipients of those sentiments: "Eruption or USGS Volcanoes Content" and "People, Entities, Places, or Customs." The code "People, Entities, Places, or Customs" is further subdivided into "USGS Volcanoes, Scientists, or HVO" and "Non-USGS People, Entities, Places, or Customs."

Following our qualitative analyses, we tallied the number of comments contained within several child codes to (1) quantify the responsiveness of USGS Volcanoes and its community of informed users to comments containing questions or misinformation and (2) quantify users' expressions of positive, negative, and mixed sentiments. Obtaining these frequency counts facilitated our determination of prevailing themes and sentiments within the post comment threads (Hennink and Kaiser, 2022). These tallies also provide a basis for comparison between our qualitative thematic analysis of the 16 post comment threads and quantitative analyses of the bulk comment dataset.

3.3 Quantitative analyses of bulk comment dataset

Our analyses of the bulk comment dataset included two components. First, we quantified and tracked the frequency of two categories of comments: those containing the most common rumor words, and comments containing the most common expressions of appreciation. We then conducted an automated sentiment analysis using the Valence Aware Dictionary for sEntiment Reasoning (VADER), as described in Hutto and Gilbert (2014). This open-source Python package uses a rule-based, human-tested sentiment model to identify and quantify both the polarity (i.e., positive or negative) and intensity (i.e., high or low) of sentiments expressed on social media (Hutto and Gilbert, 2014). We compared these results with the frequencies of our text searches to test for correlations between users' overall sentiments and (1) the occurrence of common rumors or (2) the prevalence of gratitude words in users' comments.

We chose VADER as our primary quantitative analysis package because its scores are tailored to social media communication, verified by multiple human evaluators, and found to perform more accurately than programs that are either more computationally intensive or closed source (Hutto and Gilbert, 2014). The sentiment analysis program VADER calculates four score types: positive, negative, neutral, and compound (Hutto and Gilbert, 2014). The compound score is the most comprehensive of the four, calculated from the three other scores while incorporating additional syntactic and semantic rules. Thus, we focused our sentiment analysis on the compound scores calculated for each comment in our bulk dataset. We binned these scores by comment publication date, focusing on the date range of May 1 through August 31, 2018, to avoid artifacts from the relatively low comment counts outside those dates, and calculated the average score for each binned day. The compound score ranges from −1.0 for text containing only negative sentiments to +1.0 for text containing only positive sentiments. A compound score of 0 indicates an overall neutral sentiment, though without differentiating between purely neutral sentiment and the existence of perfectly balanced negative and positive sentiments (Hutto and Gilbert, 2014).

We estimated the frequency of comments related to rumors and misinformation about the Hilina Slump, Yellowstone volcano, or an impending catastrophic eruption on Hawai'i by quantifying the occurrence of the words "hilina," "slump," "south flank" (in reference to Kılauea Volcano's southern slope, which lies above the Hilina Slump), "landslide," "catastroph" (to include both "catastrophe" and "catastrophic"), or "Yellowstone." The word "tsunami," while frequently associated with rumors about the Hilina Slump or a catastrophic eruption on Hawai'i, was excluded as a search term since it was often included in users' non-rumoring questions or comments about hazards posed by earthquakes during the 2018 eruption. Likewise, we estimated the frequency of conversations related to rumors related to geothermal energy production in the lower East Rift Zone by quantifying the appearance of the words "pgv," "methane," "sulfur," "sulphur," "geothermal," "wells," or "blue flame." These keywords capture (1) the unfounded assertion that the 2018 eruption was caused by geothermal utility operations in the lower East Rift Zone (explored in detail in Kauahikaua and Trusdell, 2020) or (2) that the blue flames observed in the lower East Rift Zone in late May 2018 were caused by sulfur gas, derived specifically from the utility, rather than methane produced from lava flows heating vegetation.[1] We note, however, that by quantifying frequencies of the above keywords, we include non-rumoring comments regarding these and all other topics included in our common 2018 eruption rumors. Thus, our keyword-based quantitative analyses of the bulk comment dataset only identify periods of time during the 2018 eruption when the appearance of the most common rumor topics was highest.

To estimate Facebook users' appreciation of eruption-related communications, we quantified the occurrence of comments with the words "thank" or "*mahalo*" (the Hawaiian word for "thank"), as well as comments containing both the words "USGS" and either "thank" or "mahalo," to differentiate gratitude expressed toward USGS Volcanoes' and other users. Results of each text query were plotted as a function of date to provide a broad picture of patterns in Facebook users' comments.

4 Results

We organize the results of our qualitative thematic analysis by the two parent themes that arose from our analysis—*Eruption Sensemaking* and *Expressed Sentiments*. For each theme, we first quantify the frequency of child codes that most directly address one or more of our research questions and then provide example conversation threads that address these questions in greater detail. We then plot the frequency of rumor words quantified from the bulk comment dataset and test the correlation between these frequencies and the daily average compound sentiment score

1 https://www.usgs.gov/media/images/k-lauea-volcano-methane-gas-flames

calculated with VADER. Finally, we plot the frequency of gratitude-based words from the bulk dataset and test the correlation between them and the daily average compound sentiment score.

4.1 Eruption sensemaking: overview

USGS Volcanoes and informed users provided direct, accurate answers to 73% of questions posed by other users. Of these answers, USGS Volcanoes provided 72% and non-USGS users provided 28% (Figure 3). Meanwhile, USGS Volcanoes and informed users directly corrected or called out 54% of all comments containing misinformation or rumors, with USGS Volcanoes providing 57% of these responses (Figure 3). When excluding comments coded as "less relevant," the percentage of comments with misinformation or rumors that were directly corrected or called out increases to 74%, comparable to the percentage of questions directly answered. All 16 of the post comment threads we analyzed contain questions and responses (Figure 4), while 14 of these posts also contain comments related to misinformation (Figure 5). Among the comment threads we analyzed, USGS Volcanoes always provided corrections in their responses to misinformative comments, with or without calling it out (Figures 3, Supplementary Figure 1). Non-USGS users provided corrections in most cases but sometimes called out misinformation without correcting it (Figures 3, Supplementary Figure 1).

There were several rumors or topics of misinformation that repeatedly appeared in USGS Volcanoes' post comment threads during Kılauea's 2018 eruption and correspond with several of the secondary child codes classified under "Misinformation & Response." One such rumor was that the Hilina Slump, the surface expression of an underground fault beneath the southern edge of the Island of Hawai'i (Lin and Okubo, 2020), was about to experience a catastrophic, tsunami-generating landslide due to the eruption of Kılauea Volcano. This rumor appears to have originated from a blog article published in early May that stated such a collapse was possible for Kılauea Volcano, though the article's concluding sentence clarifies that such an event was unlikely to happen in the near future.[2] A second common rumor was that Kılauea's eruption was linked to volcanic activity in Yellowstone National Park, whose caldera system is a frequent source of exaggerated concern regarding its potential to experience a super-eruption.[3] A third common rumor was that a catastrophic eruption was imminent from Kılauea Volcano and would impact the entire Island of Hawai'i. These rumors are grouped into the secondary child code "Slump, Tsunami, or Catastrophic Eruption." A fourth recurring rumor was that the 2018 eruption was triggered by geothermal energy production in the lower East Rift Zone. There is no evidence to support any human influence on eruptions of Kılauea Volcano (Kauahikaua and Trusdell, 2020), and the assertion that utility operations were the cause of the eruption may reflect longstanding debates about geothermal energy production in Hawai'i, which stem from a combination of cultural objections and health concerns.[4] This rumor was often accompanied by a separate rumor that blue flames observed in the lower East Rift Zone (see Table 1) were caused by sulfur dioxide emitted from Kılauea Volcano or that the gas responsible for the blue flames was produced by the utility rather than methane produced from the heating of vegetation by lava flows. Several users made comments that gases emitted from Kılauea's 2018 eruption–including the methane gas responsible for the blue flames–would contribute to global climate change or affect the island's long-term weather patterns. Given that all the rumors described in this paragraph have at least a loose association with the appearance of blue methane flames, we assign comments containing one or more of these rumors to the secondary child code "PGV, Gases, Climate, or Weather."

Finally, users posted comments containing misconceptions about other volcanic or tectonic processes that we include in our qualitative analysis (described below) solely for the purpose of distinguishing these factually incorrect comments from the aforementioned rumors, without analyzing their contents in depth. We assign all such comments to the secondary child code "Volcano or Tectonic Misinformation."

4.1.1 Eruption sensemaking: questions & answers (coded as "Eruption Q & A")

The proportion of directly answered questions varied across individual posts, with less than half of users' questions receiving direct answers in two out of three of the earliest posts we analyzed (Figure 4A). From mid-May through the end of August 2018, however, more than half of users' questions were directly answered. This may be attributable to the USGS Volcanoes social media team adding a staff member and developing specific staffing schedules, which allowed them to monitor posts more consistently for comments (Stovall et al., 2023). The proportion of questions directly answered remained consistently high after the May 9 posts (Figure 4A), even for those in which USGS Volcanoes provided relatively few direct answers to users' questions (Figure 4B). This demonstrates the role that informed users played in complementing USGS Volcanoes' effort to provide publics with accurate eruption information.

The complementary role observed between USGS Volcanoes and informed users is well-demonstrated in the following conversation thread from the post "Overlook crater warning" (Table 1), published on May 9:

> *"Dumb question, but why isn't, or how is, the water interacting with the heat *before* [sic] the water table drops? Where/how is the steam pressure being relieved in the far-left image?" (new top-level comment by User A, posted within "Overlook crater warning").*

After two other users posted direct and educated, but not entirely correct, replies, USGS Volcanoes posted the following answer, referring to the diagram included in their original post:

2 https://seismo.berkeley.edu/blog/2018/05/07/a-slow-emergency-and-a-sudden-slump.html

3 https://www.christytill.com/yellowstone.html

4 https://www.washingtonpost.com/news/powerpost/paloma/the-energy-202/2018/06/18/the-energy-202-kīlauea-s-eruption-reignites-debate-over-hawaii-s-geothermal-plant/5b2652f21b326b3967989b27/

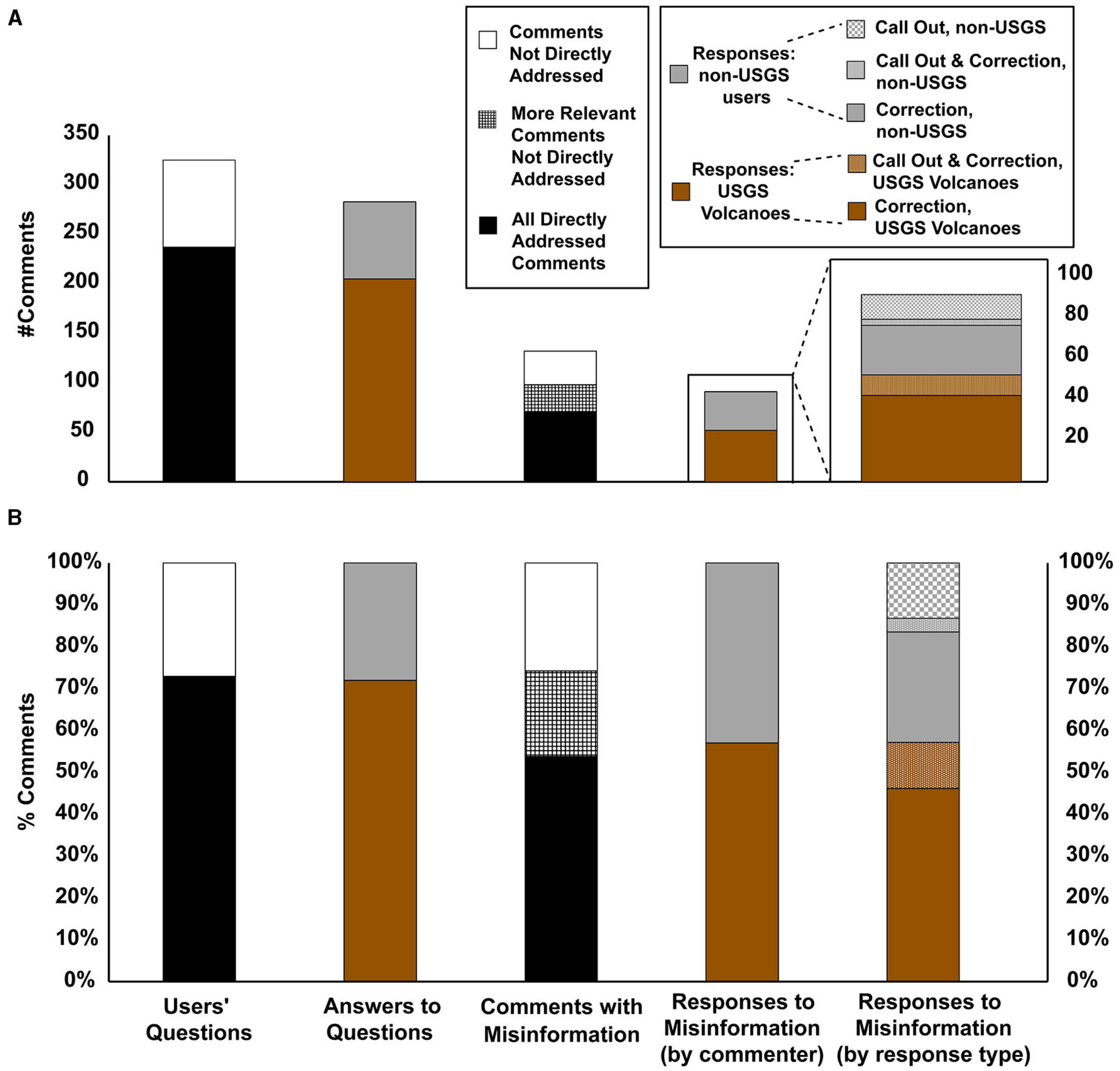

FIGURE 3
Quantitative overview of comments coded to theme "Eruption Sensemaking." **(A)** Comparing the number of comments coded as Users' Questions, Answers to Questions, Comments with Misinformation, and Responses to Misinformation. Fifth column is a zoomed-in inset of the fourth column for the purpose of illustrating response methods as indicated in the legend. **(B)** Plotting bar graphs from **(A)** in terms of percentages.

> *"In the first image, the area immediately around the conduit is basically boiled dry by the heat coming off the magma (like a pot that's been left on the stove for too long). When magma withdraws from the conduit, the rocks around it cool down and water can move into area [sic] around the top of the conduit" (USGS Volcanoes, in response to User A).*

Although User A did not post a reply to USGS Volcanoes' answer, three other users expressed their appreciation, one to USGS Volcanoes for their answer, another to both USGS Volcanoes and the two users who had provided educated responses, and a third to the person who posted the original question for asking it in the first place. Another user, who self-identified as a geologist, began their comment by stating that they too had "wondered the same thing," and thus the original comment was "not a dumb question at all," before adding, "thank you to our USGS team for answering, and for doing the best job keeping us informed." This conversation thread concluded with two additional users asking their own follow-up questions about water evaporation, both of which USGS Volcanoes directly answered, and one of these users posted "thank you" in response.

We employed context cues to determine that the original user was self-deprecating despite asking a good question. We also note that two users pitched in to provide the best answers they could, demonstrating how the social media thread promoted community participation and collaboration for sensemaking. USGS Volcanoes then provided a detailed explanation that made use of both the diagram in their post and an everyday analogy for users' ease of understanding (de Groot, 2009; Jee et al., 2010). Other users expressed their appreciation of the post that USGS Volcanoes

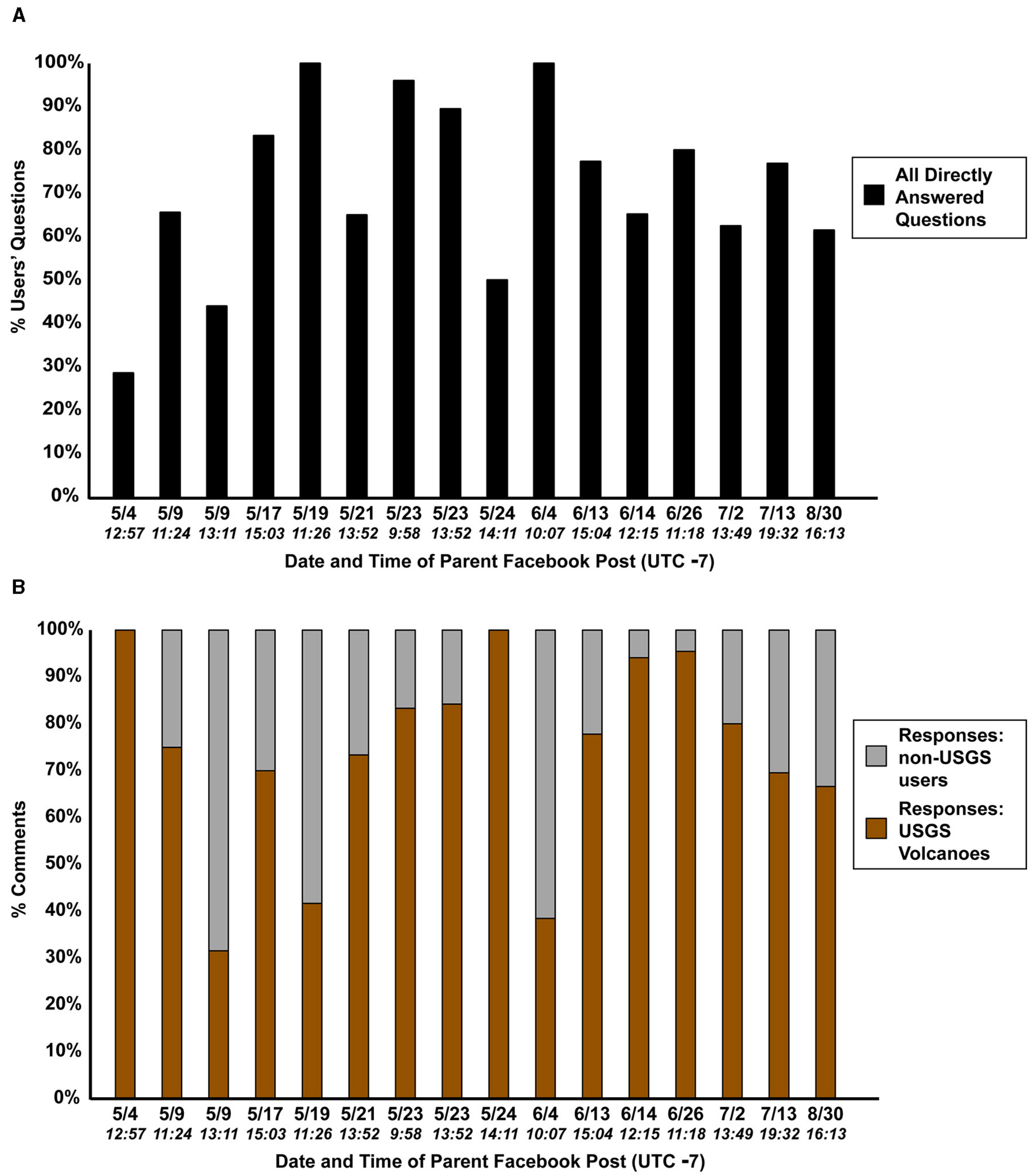

FIGURE 4
Plots of **(A)** Facebook users' directly answered questions and **(B)** direct responses to users' questions, organized by post comment thread and shaded by responding user (non-USGS or USGS Volcanoes). Each thread is indicated by the date and time the original post was published.

made, illustrating its usefulness to the broader audience of the post comment thread. One geologist outside of the USGS Volcanoes group even affirmed the legitimacy of the original question and gave praise to USGS Volcanoes. Moreover, USGS Volcanoes continued to answer users' questions posted within the same reply thread, illustrating their attentiveness.

Our qualitative thematic analysis also investigated potential explanations for the absence of direct answers to some users' questions (88 total). We coded all questions lacking direct responses into several non-mutually exclusive categories (Supplementary material: Codebook). The most common category of questions not directly answered was those already answered elsewhere in the same or a previous post (20 comments). Because the 16 post comment threads we analyzed were the most popular and had high comment counts, the USGS Volcanoes staff prioritized answering new or potentially controversial questions (Stovall et al., 2023). When dealing with high volumes of comments, several other categories of questions fell to

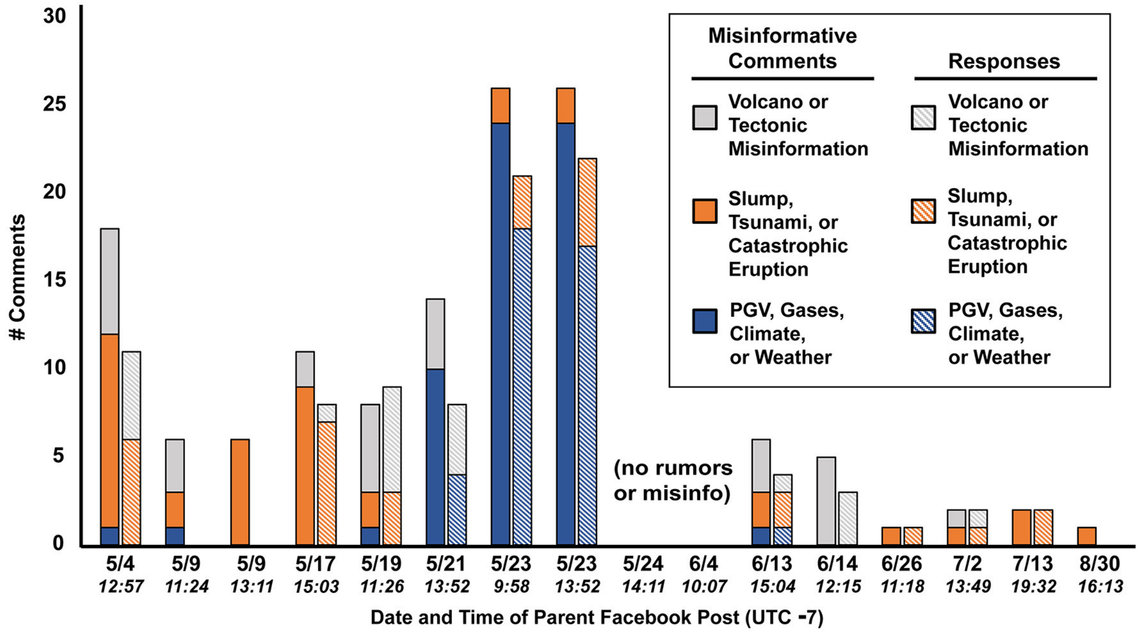

FIGURE 5
Plot comparing the frequencies of each category of misinformation across the 16 qualitatively analyzed post comment threads, labeled by the date and time each post was published. Each post contains a pair of bar charts: the left-hand chart (solid fill) quantifies comments containing an original question or statement related to misinformation, while the right-hand chart (faded/checkered fill) quantifies comments directly calling out or correcting misinformative comments, organized by misinformation topic. Posts labeled "no rumors or misinfo" had no comments containing misinformation or rumors.

a lower priority for USGS Volcanoes to address, including questions containing a request, recommendation, or offer to help USGS Volcanoes (14 comments), lengthy or unusually specific questions (9 comments), vague or tangential questions (9 comments), or a follow-up to a directly answered question (7 comments).

In contrast to the above, we consider one category of unanswered questions to have been important enough for USGS Volcanoes to have answered directly: those that were like questions USGS Volcanoes did answer directly (13 comments). With high comment volume, USGS Volcanoes staff occasionally missed some questions rather than intentionally passed them over. This is true for unanswered questions containing misinformation (19 comments), unless such questions involved controversial topics that USGS Volcanoes could not directly address because they were outside the USGS area of expertise (e.g., utility operations or risk associated with homes built in lava-flow hazard zones; Stovall et al., 2023).

We identify two key findings from comments coded to "Eruption Q & A." First, both USGS Volcanoes and informed users were responsive to most questions raised by other users, answering at least half of these questions in 14 of the 16 post comment threads we analyzed (Figure 4A). Second, USGS Volcanoes often used analogies to explain eruption phenomena that used illustrations and relatable examples to facilitate users' comprehension of new concepts (de Groot, 2009; Jee et al., 2010).

4.1.2 Eruption sensemaking: misinformation & response (quantitative results)

Although nearly half of all the misinformation-related comments we analyzed were related to "PGV, Gases, Climate, or Weather," this category only forms the majority of misinformation-related comments in three of the 14 comment post threads containing them (Figure 5). By contrast, while comments concerning the certainty of a Hilina Slump collapse, tsunamis, or a catastrophic eruption (related to Yellowstone volcano or Hawai'i) were the least common category of rumors, they comprise a majority of misinformation-related comments in six of the 14 posts (Figure 5). These results indicate that rumor frequency depended on the content of specific posts or post comment threads.

In looking across the 16 most popular posts, 71 misinformation-related questions or statements received direct responses (either corrections or call-outs), and 61 were not directly addressed. The three most common categories for the 61 misinformation-related comments that were not directly addressed include:

- Questions or statements concerning a contentious topic, such as the existence of residential areas on an active volcano or concerns regarding the power utility facility (23 total questions and comments).
- Questions or statements contained within a long thread of replies (17 total).
- Questions or statements answered or corrected elsewhere in the same or previous post (16 total).

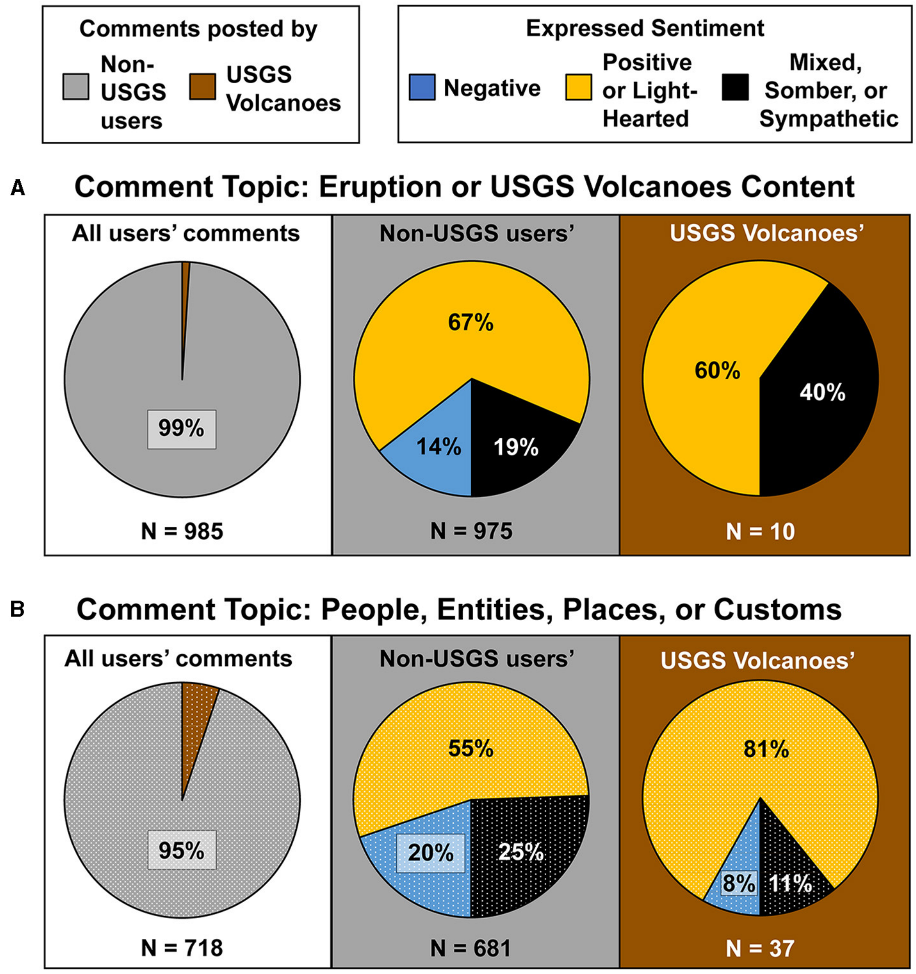

FIGURE 6
Plots comparing the frequencies of users' expressed sentiments regarding **(A)** Eruption or USGS Volcanoes Content, **(B)** People, Entities, Places, or Customs. First column compares proportion of non-USGS and USGS Volcanoes' comments, second column compares proportion of sentiments expressed only by non-USGS users, and third column compares proportion of sentiments expressed only by USGS Volcanoes. Background fill of second and third columns corresponds with the fill colors of pie charts in the first column.

The relatively high frequency of not-directly-addressed comments concerning contentious topics reflects USGS Volcanoes' commitment to remaining in their "communication lane" of expertise (Stovall et al., 2023). Additionally, by not engaging, USGS Volcanoes likely prevented conversations that might escalate users' feelings of frustration or distrust. Misinformation-related comments contained within a long reply thread may have been accidentally missed by USGS Volcanoes or informed non-USGS users. In contrast, questions or comments whose misinformation was addressed elsewhere in the same or previous post were deemed redundant (and therefore low priority) by USGS Volcanoes or other informed users and therefore left unanswered.

Other types of misinformation-related comments without direct responses include:

- Top-level questions (13 total),
- Top-level statements (11 total),
- Trolling, rumor-milling, or conspiracy-promoting comments or questions (11 total),
- Inside a short reply thread (10 total),
- Tagging a non-USGS user (10 total),
- Tagging USGS Volcanoes (excluding questions/comments coded as trolling; 5 total).

We consider top-level comments, as well as comments contained within a short reply thread or comments tagging USGS Volcanoes directly, to have been more easily visible to USGS Volcanoes staff than questions contained within long reply threads or comments that did not tag USGS Volcanoes. Thus, it seems less likely that USGS Volcanoes accidentally missed these comments. We provide several possible alternative reasons why these comments were missed:

- They were posted hours-to-days after the original post, which may have been too difficult for USGS Volcanoes or other informed users to locate the missed comments in the wake of more recent or pressing questions.

- They were answered in one or more USGS Volcanoes posts, including FAQs, that were not qualitatively analyzed in this study.
- They were posted when USGS Volcanoes staff were unavailable or had to address higher-priority communications (Stovall et al., 2023).

All but one of the misinformation-related comments that tagged non-USGS users confidently asserted the misinformed statement and did not ask those users to verify or refute it. Thus, it may not have been apparent to the tagged non-USGS users that they were being provided with misinformative commentary, and USGS Volcanoes may have missed these comments since they were part of a conversation explicitly directed at another user. By contrast, we consider that trolling, rumor-milling (as defined by Starbird et al., 2016), or conspiracy-promoting comments or questions were intentionally ignored by USGS Volcanoes and informed users to avoid counterproductive arguments.

Given the above considerations, we code the following categories of misinformation-related comments without direct responses as being "less relevant" for USGS Volcanoes or other users to respond to, which correspond with the unfilled white segments of the third column of bar charts in Figures 3A, B:

- Questions or statements concerning a contentious topic (1st most common category).
- Questions or statements answered or corrected elsewhere in the same or previous post (3rd most common).
- Trolling, rumor-milling or conspiracy-promoting comments or questions (5th most common).
- Tagging a non-USGS user (7th most common).

Accordingly, the remaining misinformation-related comment categories were coded as "more relevant," and correspond with the hatch-filled bars in Figures 3, Supplementary Figure 1A:

- Questions or statements contained within a long thread of replies (2nd most common).
- Top-level questions (4th most common).
- Top-level statements (5th most common, tied with "Trolling, rumor-milling,..." etc.).
- Inside a short reply thread (7th most common, tied with "Tagging a non-USGS user").
- Tagging USGS Volcanoes (8th and least common).

The proportion of misinformation-related comments that were directly corrected or called out varied across individual posts without a clear temporal pattern (Supplementary Figure 1). However, all comments that we coded as "more relevant" for USGS Volcanoes and other users to respond to only occurred in the first half of the 16 post comment threads we analyzed, as indicated by the presence of hatch-filled bars in threads dated through May 23rd but not afterward (Supplementary Figure 1A).

4.1.3 Eruption sensemaking: misinformation & response (qualitative examples)

Below we provide an example of a conversation thread in which a commonly occurring rumor or topic of misinformation was directly addressed or refuted. This conversation is about the Hilina Slump, a common rumor topic particularly early in the eruption (Figure 5) in which the user (User C) asks questions related to a rumor but without a clear intent to deceive:

> *"Has the hilina slump been affected by the recent activity? I've heard scattered reports of a major movement along the slip" (new top-level comment by User C, "Pohoiki Road Ground Cracks").*
>
> *"There was motion along the slump during the May 4 M6.9 earthquake, but that is expected. Otherwise, the slump's behavior is normal. There is some misinformation out there about an imminent catastrophic landslide, but this is not accurate. We posted some information in the "HVO News" section of the HVO website, just under the map, that explains what is happening with the Hilina slump" (response by USGS Volcanoes, who also included a URL to HVO's website).*
>
> *"USGS Volcanoes thank you!! Is there a risk percentage of the slump collapse? A lot of people are worried and it would help to have some solid numbers" (User C, responding to and directly tagging USGS Volcanoes).*

These comments were followed by a question from a second user ("User D") asking similar questions, but in a lengthy post that we interpret as the result of User D experiencing a high degree of anxiety. USGS Volcanoes responded to both Users C and D by providing well-established geologic evidence against a catastrophic landslide occurring. User D then posted two more comments of similar length and expressed similarly heightened anxiety to the first, with USGS Volcanoes providing direct responses each time. In their final response, USGS Volcanoes tagged User D and replied:

> *"We can certainly understand your concern, given the rumors that are swirling on line. Hopefully we addressed many of your points in the News item on HVO's home page (see the link in our initial reply). It is important to remember that this is not the first time a magmatic intrusion has been active this far down the East Rift Zone. It's relatively common, happening every few decades, but as this is the first time since 1960 it may seem like a unique event" (USGS Volcanoes).*

In the same comment as above, USGS Volcanoes also explained that there is no evidence in instrumental monitoring data, including GNSS or volcano deformation data, "that any sort of failure" of the integrity of Kılauea's southeastern slope "is imminent," adding that "there is no evidence in the geologic record that such a collapse has ever happened in the past (and Kılauea has been erupting above water for about 100,000 years!)."

This was followed by replies from both Users D and C:

> *"USGS Volcanoes Mahalo for taking the time to answer my questions" (User D).*
>
> *"USGS Volcanoes thank you!!" (User C).*

In this conversation thread, USGS Volcanoes directly addressed each user's concern through detailed and factual responses and also demonstrated empathy for User D's concerns. We interpret the final replies of both Users C and D, which convey sincerely articulated (User D) or enthusiastic (User C) appreciation, as evidence of the efficacy of USGS Volcanoes' factual, responsive, and empathic communication strategy.

The above conversation contrasts with instances whereby a user appears to intend to misinform or introduce a rumor. One prominent instance of this is a user (User B) introducing a rumor connecting Kılauea's eruption to Yellowstone National Park's geyser activity. Following a direct response by USGS Volcanoes in an effort debunk this rumor, User B engages in rumor-milling behavior (as defined by Starbird et al., 2016), making use of ellipses, word capitalization, and framing a rumor-related suggestion as a question. This resulted in several contentious exchanges between User B and other users calling out User B and their misinformative posts. User B exhibited behavior in these exchanges that insulted and provoked the other users. USGS Volcanoes did not provide additional replies to either User B or anyone else commenting in this thread. USGS Volcanoes provided a direct, succinct, factual reply that addresses the fallacy in User B's comment, while choosing not to engage them any further once the user demonstrated their intent to continue disseminating disinformation, which we define as factually incorrect information intended to deceive (following Starbird et al., 2016). However, several other users chose to call out User B's disinformation. This response demonstrates a strategy adopted by USGS Volcanoes to allow their page's "community of informed followers" to self-police the content of the page's comment threads (Stovall et al., 2023). This parallels a similar phenomenon during social media conversations concerning Australia's 2010-11 Queensland and Victorian floods in which both moderators and users of flood-related Facebook pages promptly corrected false rumors (Bird et al., 2012; Alexander, 2014).

Additionally, not all rumor-related conversations end with a satisfactory resolution. This is exemplified in the post "Fissure 22 Lava Fountains," whereby a user (User E) asks about the status of the geothermal energy power plant, summarizing the legitimate questions that several Hawai'i residents, including User E, had about the risks associated with lava inundation at this utility (Stovall et al., 2023). Despite USGS Volcanoes attempting to direct User E to the appropriate messenger—Hawai'i County Civil Defense—this user pressed USGS Volcanoes for an answer they could not accurately or honestly provide without stepping out of their communication lane (Stovall et al., 2023). The exchange ended with a comment by User E that we interpret as expressing exasperation, particularly evidenced by their selective use of all capital letters. This is reminiscent of the frustration expressed by a lower East Rift Zone resident interviewed by Goldman et al. (2023) that HVO "didn't know what was going to happen" regarding the specific timing, location, and severity of eruption hazards early in the crisis. Thus, we postulate that User E's comments were motivated, at least in part, by uncertainty (Starbird et al., 2016) regarding the future evolution of lower East Rift Zone eruption hazards and the potential for any issues of concern regarding the utility. To note, there were extensive efforts to understand and reduce risk at the utility's site during the eruption, including a supplemental emergency proclamation issued by Gov. David Ige in early May.

To summarize, comments coded to "Misinformation and Response" illustrate several key findings. First, USGS Volcanoes corrected misinformation by providing concrete facts and addressing users respectfully and empathically. This approach is useful for building publics' trust in and willingness to listen to messengers of scientific information (McBride, 2018; Goldman et al., 2023). However, USGS Volcanoes was selective in which misinformative comments they directly addressed because some topics were outside their expertise. The fact that "questions or statements concerning a contentious topic" were the most frequent category of comments not directly addressed [Section Eruption sensemaking: misinformation & response (quantitative results)] provides further evidence supporting USGS Volcanoes' use of discretion when responding to misinformation. Additionally, informed users (cf. Stovall et al., 2023) provided their own corrections to users who posted misinformative or rumoring content (Figures 3, Supplementary Figure 1) and also complemented USGS Volcanoes' tactful, emotionally restrained responses by emphatically calling out and condemning the users posting misinformation. These instances demonstrate the beneficial synergy between responses by USGS Volcanoes and the community of informed users.

The occurrence of misinformation and rumor topics differed among the analyzed post comment threads, with comments related to "PGV, Gases, Climate, or Weather" being heavily concentrated in three mid- to late-May post comment threads, while comments containing all other misinformation topics were more evenly distributed among the analyzed post comment threads (Figure 5). This concentration of utility-related misinformation and rumors in mid- to late-May corresponded with lava encroachment on the utility facility's location and preparations for possible lava inundation (Stovall et al., 2023). Although the other major rumor topics identified (Hilina Slump, Yellowstone volcano, or a catastrophic eruption) did not correspond with a single eruptive phase of the 2018 eruption, at least two (Hilina Slump and Yellowstone volcano) can be traced to online publications from early May: an academic blog post describing the possibility of a landslide along the Hilina Slump (see Section Eruption sensemaking: overview) and an online article describing recent eruptions of a Yellowstone National Park geyser (referenced by User B in the first rumor dialogue examined in this section).

4.2 Expressed sentiments: overview

In this section, we first present quantitative results of comments coded to the theme *Expressed Sentiments* to understand the most common sentiments expressed by non-USGS users and how those sentiments reflect the overall success of USGS Volcanoes' Facebook communications in promoting or reinforcing trust among their users. We then describe the types of commentary represented by each expressed sentiment.

4.2.1 Expressed sentiments: quantitative results

For the 985 comments coded as containing sentiments expressed in response to the "Eruption or USGS Volcanoes Content" in the 16 qualitatively analyzed post comment threads, 99% were posted by non-USGS users and 1% by USGS Volcanoes (Figure 6A). For the 718 comments containing sentiments in responses to "People, Entities, Places, or Customs," non-USGS users posted 95%, and 5% were posted by USGS Volcanoes (Figure 6B). Across both topic categories (i.e., the two primary child codes of *Expressed Sentiments*, as defined in the Methods and shown in Supplementary material: Codebook), non-USGS users' comments had a higher proportion of negative sentiments than comments by USGS Volcanoes, though most comments by both sets of users were positive (Figure 6). Non-USGS users' comments in the topic category "People, Entities, Places, or Customs" also contained a higher proportion of "mixed, somber, or sympathetic" (i.e., "mixed") sentiments than comments by USGS Volcanoes (Figure 6).

While most of the 16 post comment threads we analyzed contained a majority of positive expressed sentiments, several threads contained a majority of negative and mixed sentiments (Supplementary Figure 2). Regarding the "Eruption or USGS Volcanoes Content," three post comment threads contained <50% comments with positive sentiments, while for "People, Entities, Places, or Customs," seven post comment threads contained <50% positive comments. The highest proportions of negative and mixed sentiments (i.e., lowest percentage of positive sentiments) occurred as a result of one or more of the following causes: (1) users arguing over a topic of misinformation (applies to posts published on 5/4, 5/19, and both from 5/23), (2) users expressing blame or displeasure toward each other or external entities (applies to posts published on 5/17, 5/19, and both from 5/23), or (3) users expressing fear, shock, or sadness in response to the eruption event described in the original USGS Volcanoes post (applies to posts published on 5/19, both from 5/23, and 6/4).

When isolating non-USGS users' comments into those regarding "USGS Volcanoes, Scientists or HVO" vs. "Non-USGS users, People, or Entities," we find that all 16 of the highest-user-reach post comment threads contained at least 60% positive sentiments toward "USGS Volcanoes, Scientists or HVO" (i.e., USGS-oriented; Supplementary Figure 3A). Comment threads for the May 9th post "Overlook crater explosion" and the May 23rd post "Blue methane flames video" received the highest total percentage of negative and mixed sentiments that were USGS-oriented. By contrast, only four post comment threads contained more than 50% positive sentiments toward "Non-USGS users, People, or Entities" (i.e., non-USGS-oriented; Supplementary Figure 3B). These four posts include the May 9th "Overlook crater warning," May 24th "Fissure 22 UAS night video," July 13th "Kapoho lava island," and August 30th "Late-August UAS caldera flight."

4.2.2 Expressed sentiments: qualitative results

We found that users expressed several common negative sentiments throughout the course of the eruption in response to the "Eruption or USGS Volcanoes content": anxiety or fear that eruption hazards would escalate and endanger residents, frustration at the inconvenience caused by eruption hazards, shock or sadness at the destruction caused by the eruption, and sorrow on behalf of adversely impacted residents. Users expressed the following negative sentiments toward "USGS Volcanoes, Scientists, or HVO": frustration by what users perceived to be incorrect or missing information provided by USGS Volcanoes, or feelings of distrust toward USGS, USGS Volcanoes, HVO, or scientists more broadly. Finally, users expressed the following negative sentiments toward "Non-USGS People, Entities, Places, or Customs": blaming eruption survivors, local and state officials, or the power utility for endangering themselves, residents, or property; disparaging remarks toward Hawaiian landscapes or Native Hawaiian beliefs, language, or customs; criticizing other users for posting misinformation, spreading rumors, or asking "stupid" questions; exhibiting trolling behavior in response to other users' criticisms; making self-deprecating remarks; or criticizing other users for expressing negative comments toward USGS, USGS Volcanoes, scientists, or HVO.

In response to the "Eruption or USGS Volcanoes Content," non-USGS users (and occasionally, USGS Volcanoes) expressed the following positive sentiments: admiration of eruption phenomena, science, nature, or USGS Volcanoes' coverage of the eruption; intrigue or curiosity about eruption phenomena or USGS Volcanoes' activities; excitement without indications of anxiety, fear, or other negative emotions; or humor that was light-hearted or upbeat, as opposed to sardonic or cynical (with the latter being coded under "Negative Sentiments"). Non-USGS users expressed the following positive sentiments toward "USGS Volcanoes, Scientists, or HVO": gratitude for USGS Volcanoes answering their questions, alleviating their concerns about the eruption, or responding in a calm or empathic manner; complimenting USGS Volcanoes for their expertise or the content of their Facebook page; statements of increased knowledge from USGS Volcanoes' information; or affirmations of answers provided by USGS Volcanoes. Finally, non-USGS users and USGS Volcanoes expressed the following positive sentiments toward "Non-USGS People, Entities, Places, or Customs": reassurance that residents or visitors were safe, or that specific eruption hazards did not pose immediate threats to peoples' safety; empathy toward concerned or anxious users; compliments of non-USGS users for correctly answering or sincerely responding to eruption-related questions; supportive statements toward users whose questions were disparaged; or compliments of users' cleverness or humor.

Overall, comments coded to *Expressed Sentiments* demonstrate that a combination of USGS Volcanoes' original post content and their interactions with users elicited a high frequency of positive emotions from users, providing strong evidence that this Facebook page was a beneficial channel for communicating 2018 Kılauea eruption information to social media audiences. Conversely, comments containing negative or mixed sentiments were correlated far more often with major eruption events, the loss of property or a cherished landscape, or arguments between non-USGS users than by USGS Volcanoes' interactions with users.

4.3 Triangulation with bulk comment dataset

For each theme, we first present a plot comparing the daily frequency of several keywords throughout the eruption, followed by a plot of those same frequencies normalized to the total daily comment count and overlain by the sentiment analysis curve we calculated with VADER (Hutto and Gilbert, 2014). For the theme *Eruption Sensemaking*, we focus on the code "Misinformation and Rumors," and for the theme *Expressed Sentiments*, we focus on the code "Positive Sentiments Regarding... People, Entities, Places or Customs."

Within the code "Misinformation and Rumors," we focused our bulk quantitative analysis on the rumor words listed in the Methods Section. Rumor words about the Hilina Slump, Yellowstone volcano, or an impending catastrophic eruption persisted at moderate to high frequencies from May through the end of July, while rumor words related to geothermal utility operations were heavily concentrated in mid-May (Figure 7A). The contrasting timescales in frequency for these two major categories of rumor topics are consistent with the relative frequencies of these rumor topics identified in the comment threads of the 16 highest-user-reach posts (Figure 5). The quantitative results presented in Figure 7A complement our in-depth analysis of the 16 post comment threads by illustrating increased occurrences of rumor words about the Hilina Slump, Yellowstone volcano, or a catastrophic eruption throughout mid-June and mid- to late-July that are not captured in the three post comment threads published within those time periods (specifically, 6/13, 6/14, and 7/13).

The concentrated frequency of rumor words categorized as "PGV, Methane, Sulfur/Sulfur, Geothermal, Wells, or Blue Flames" (Figure 7A) in mid- to late-May aligns with the occurrence of specific eruption-related events. These events are captured, in part, in our qualitative results for secondary child code "PGV, Gases, Climate, or Weather" (Figure 5) for the high-reaching post comment threads that spanned the period of increased frequency: in the "Blue methane flames photo" and "Blue methane flames video" posts (both from May 23), discourse centered on whether burning of methane or sulfur gases was responsible for generating the blue flames presented in the posts by USGS Volcanoes; and, in the "Fissure 22 lava fountains" post (May 21), the preponderance of comments focused on clarifying hazards associated with potential lava inundation of the geothermal utility's facility. Our bulk quantitative analysis treats all mentions of the utility as rumoring, even though legitimate concerns regarding its vulnerability to inundation by lava flows existed and were addressed in the post comment threads. To note, both of these topics elicited strong negative emotions as expressed on social media. Thus, our triangulation provides a reminder of the importance of accounting for the needs and concerns of eruption-impacted communities when scientists or emergency responders communicate about an ongoing natural hazard crisis.

Within the code "Positive Sentiments Regarding... People, Entities, Places or Customs," we focused our text search on the gratitude words listed in the Methods, given their frequent appearance in comments coded to this subtheme. Occurrence of the words "thank" and both words "thank AND usgs" closely match the pattern of the total comments curve, while occurrences of the words "mahalo" and both words "mahalo AND usgs" partially correspond with the total comments curve (Figure 8A). This result strongly suggests that the rate at which USGS Volcanoes and informed users answered other users' questions, or provided information that users appreciated, kept pace with overall user engagement. In other words, Figure 8 provides evidence that USGS Volcanoes and informed users were responsive to other users' questions about the 2018 eruption. This finding also complements our qualitative results for the code *Eruption Sensemaking:* "Eruption Q & A" by providing an indirect measure of USGS Volcanoes' and informed users' responsiveness to other users' questions.

In contrast to the bulk text search results for common rumor words (Figure 7A), the frequency of gratitude words, particularly "thank,'" closely follows the overall frequency of users' comments. This suggests that the rate of user expressions of gratitude did not vary significantly throughout the duration of the 2018 eruption, similar to how USGS-oriented positive sentiment did not vary significantly among the 16 closely analyzed post comment threads (Supplementary Figure 3A).

We used the VADER sentiment analysis program to test for correlations between sentiments expressed in users' comments and the frequency of common rumor words. We also used VADER to test for correlations between users' overall expressed sentiments and the frequency of gratitude words. After calculating the average VADER compound score for each day of comments from May through August 2018, we took the 7-day running average of these scores and compared the shape of the resulting curve with normalized plots of rumor keyword frequency (Figure 7B) and gratitude keyword frequency (Figure 8B). We compared the VADER compound score with normalized, rather than absolute, bulk quantitative text search results because of the closer resemblance between our normalized results and the fairly stable VADER compound score curve. The 7-day running average of VADER's compound score for our bulk dataset ranges from 0.13 to 0.24, with an average score of 0.18 (see Supplementary material).

We quantified the resemblance of the 7-day running average of the VADER compound score to our keyword frequency curves by calculating correlation coefficients between them. The strongest correlation, 0.61, exists between the "thank" curve and VADER compound score, followed by a weaker correlation of 0.48 between the "mahalo" curve and compound score. Very low correlation values, indicating a lack of any correlation, are observed between the VADER compound score and normalized plots for all other gratitude keyword terms (Figure 8B) and all rumor keyword terms (Figure 7B). The correlation (61%) observed between users' overall expressed sentiments, as calculated by VADER, and the number of comments containing the word "thank" provides evidence that the ability of USGS Volcanoes and informed users to respond directly, accurately, and promptly to users' questions contributed directly to users' expressions of gratitude.

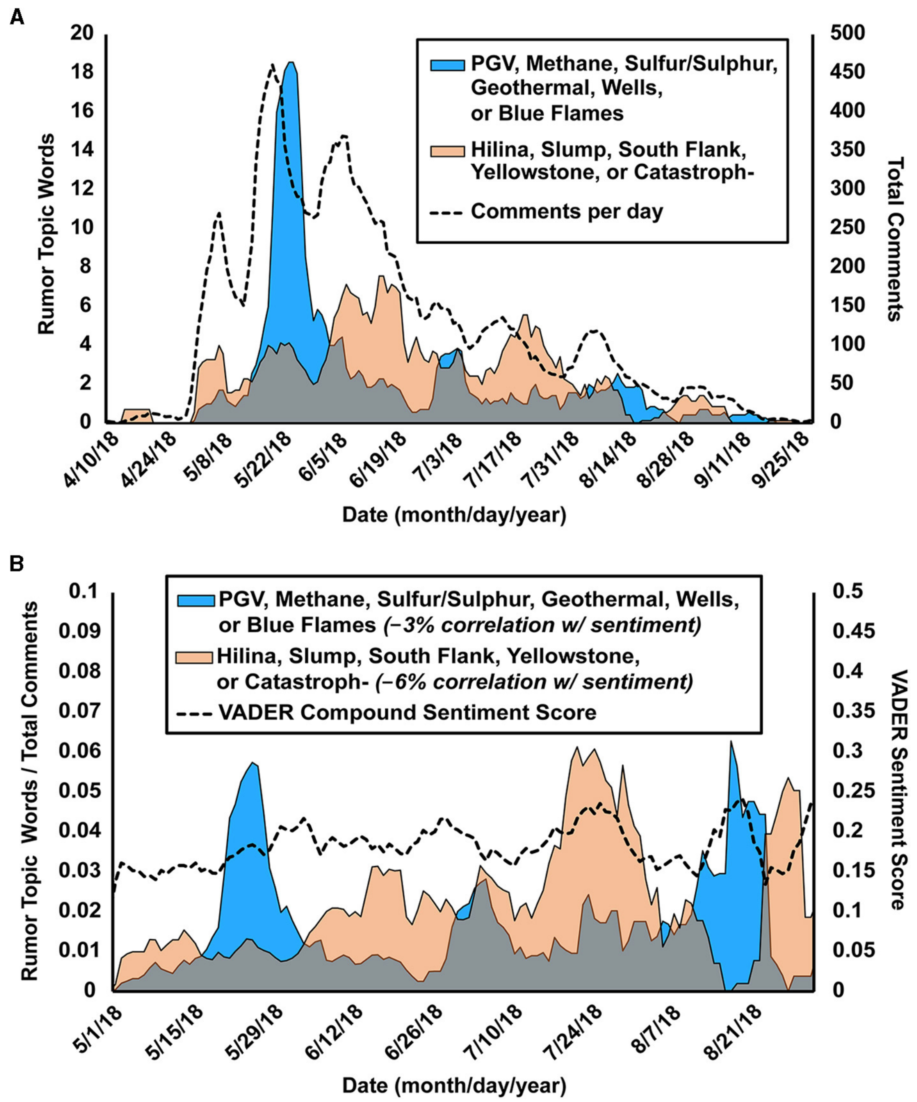

FIGURE 7
(A) Plot of rumor topic word frequencies from the bulk Facebook dataset (shaded line plots). Dashed black line indicates total user comments per day. **(B)** Plot of normalized rumor topic word frequencies from bulk Facebook dataset (shaded line plots), compared with compound VADER sentiment score (Hutto and Gilbert, 2014), presented as a dashed black line. Legend contains correlation scores of each shaded histogram with the VADER compound sentiment score, expressed as a percentage (0% = no correlation, 100% = perfect correlation, −100% = perfect anticorrelation).

5 Discussion

5.1 Benefits of USGS volcanoes' dialogues with social media users

Prior to the 2018 eruption, USGS Volcanoes' primary function was to share information about U.S. volcanic unrest and educate "volcano enthusiasts" and other users intrigued or excited by volcano knowledge, images, and videos (Stovall et al., 2023). This is consistent with UGT in that users were initially drawn to the page because it validated their sense of self—in this case, through their personal interests. Once the 2018 eruption began, two significant changes occurred: user reach increased more than 10-fold and the proportion of users who came from Hawai'i increased nearly 10-fold, from <5% of total users to 30–40% for most of the eruption (Figure 1; and see Stovall et al., 2023). These changes are also explained by UGT, in that social media users, particularly Hawai'i residents, sought out the USGS Volcanoes page in the hopes of finding accurate and prompt eruption information.

A concern commonly expressed by emergency managers and science communication planners is that providing official information on social media platforms would be counterproductive due to the prevalence of misinformation and rumors on those same channels (Hughes and Palen, 2012; Williams et al., 2020). However, increasing the visibility of official messengers on social media has been shown to decrease the prevalence of misinformation (Andrews et al., 2016) by filling what otherwise would be an "information void" (Bartel et al., 2019). Our study demonstrates that USGS Volcanoes' ability to attract attention and build trust among social media users minimized the "information void," at

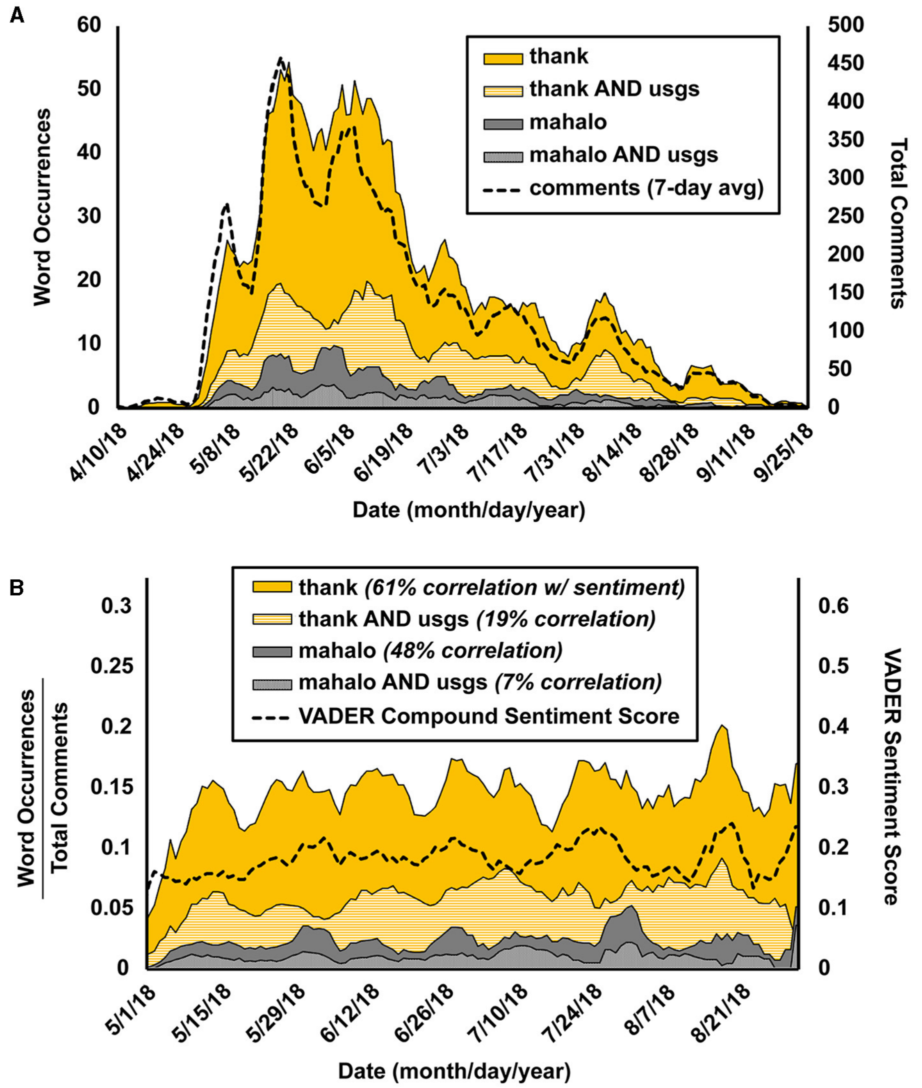

FIGURE 8
(A) Plot of gratitude word frequencies from the bulk Facebook dataset (shaded line plots). Dashed black line indicates total user comments per day. **(B)** Plot of normalized gratitude word frequencies from bulk Facebook dataset (shaded line plots), compared with compound VADER sentiment score (Hutto and Gilbert, 2014), presented as a dashed black line. Legend contains correlation scores of each shaded histogram with the VADER compound sentiment score, expressed as a percentage (0% = no correlation, 100% = perfect correlation, −100% = perfect anticorrelation).

least among the population of over 10 thousand users whom USGS Volcanoes' posts reached.

USGS Volcanoes' dialogues with users on social media were necessary for establishing themselves as a trusted, credible messenger of Kılauea eruption information to a broader online audience than previous eruptions in Hawai'i (Tumpey et al., 2019; Goldman et al., 2023). Our qualitative thematic analysis demonstrates that the educational, interactive, and sometimes humorous nature of the USGS Volcanoes social media page (McBride and Ball, 2022) positively contributed to at least some users' emotions, leading these users to tag their social media "friends" as a way of sharing their enthusiasm (Johnston et al., 2013). This tagging behavior, in turn, provided a wider audience for USGS Volcanoes' content and communications.

USGS Volcanoes' active engagement with their Facebook users contrasts with the USGS's Twitter communication response to the 2016 Bombay Beach earthquake swarm (McBride et al., 2020). Although misinformation was not found to be a significant problem by McBride et al. (2020) during this earthquake swarm, there were no two-way conversations between non-scientist Twitter users and USGS scientists monitoring and forecasting earthquake aftershocks. This prevented publics on Twitter from receiving an accurate picture of the most likely magnitude of aftershock earthquakes. Instead, these users received news media outlets' framing of earthquake forecasts that overemphasized the highest probability of large aftershocks occurring (McBride et al., 2020). The absence of USGS scientist engagement on social media also prevented users from better understanding those scientists' official language around earthquake forecasts, as well as building relationships with those scientists (Grunig, 1992).

Goldman et al. (2023) argued that, without preexisting relationships with publics, government officials are less likely to be viewed as trusted, credible messengers, increasing the likelihood that publics will turn to other sources and messengers of eruption information with whom they share a deeper mutual understanding (as outlined by Broom, 1977). Our study of USGS Volcanoes' 2018 Kılauea eruption dialogues with users on Facebook illustrates how government officials can be viewed as trusted, credible messengers on social media by demonstrating the ability of USGS scientists to convey accurate eruption information online to these users while building a relationship of trust with them.

A comment posted by a user ("User K") in response to the May 9th "Overlook Crater Warning" post illustrates the positivity that most users expressed toward USGS Volcanoes: "Thank you so much for posting this. Please post more videos! We value you, and know that it takes more than 5 min to share all of this in a way that informs, prepares and calms the public. maha[l]o nui loa!" This comment not only identifies USGS Volcanoes as a valuable messenger, but also explains why User K viewed them as one—USGS Volcanoes provided useful information in a timely yet comprehensive manner while conveying it in a calming way. These qualities are important not only for convincing publics to accept the information provided by an official messenger (Goldman et al., 2023), but also for encouraging those publics to continue seeking out information from that same messenger, as exemplified in User K's comment asking USGS Volcanoes to post additional content. The positive sentiment expressed by User K toward USGS Volcanoes is representative of the significant majority of positive sentiments that were USGS-oriented within the 16 highest-user-reach post comment threads (Supplementary Figure 3A).

5.2 Improving future social media hazard communication responses

Our study reveals that qualitatively analyzing social media discourse is valuable for evaluating the efficacy of a government agency's crisis communication response. Such assessments capture the emotional complexity in social media users' comments, the community values reflected among some people directly impacted by the crisis, and how both of those factors relate to the formation of certain types of misinformation. Our study also demonstrates the importance of performing complementary quantitative analyses of this discourse, providing a broader understanding of the frequency and temporal distribution of recurring rumors or sentiments expressed in users' comments.

Recent studies in hazard communication suggest that managers can adopt a qualitative process similar to the one used in our study to group users' questions or concerns into major themes, allowing those managers to prioritize their communication along those themes (Wukich, 2015; Dong et al., 2018; Ruan et al., 2022). This has previously been done by Williams et al. (2020) to identify successes and areas of improvement across all aspects of the USGS response to Kılauea's 2018 eruption, from hazard mapping and data collection to its public communication efforts.

Furthermore, subthemes identified from our coding process may serve as a framework for science agencies or emergency managers planning to communicate with users on social media platforms during a natural hazard crisis. For example, official science messengers may benefit from preparing a list of rumor typologies and listing effective responses to those rumors whenever they appear. Some of these responses may require interagency coordination to ensure consistent messaging and proper attribution of expert resources.

Finally, the results of our study can serve as a basis for comparison with more recent USGS Volcanoes' social media dialogues during various phases of Kılauea's more recent summit lava lake eruptions (Stovall et al., 2023). The first of these occurred from mid-December 2020 through May 2021 following the presence of a short-lived summit water lake (Nadeau et al., 2024). Studying how USGS Volcanoes' dialogues with users have evolved from 2018 to the present would provide an updated understanding of successes and potential lessons to apply to other social media hazard communication efforts in the United States and worldwide.

6 Researcher reflections and research limitations

The main limitation of this study's qualitative analysis is the relatively small body of text analyzed: 16 out of 694 posts relating to Kılauea Volcano from April 23rd, when the first Facebook posts about the overflowing Halemaʻumaʻu lava lake were published, through September 5th, the last day that active lava was observed at the surface of Kılauea.[5] The analyzed posts are not evenly spaced throughout the duration of the eruption, though our choice to focus on the 16 farthest reaching posts has the advantage of analyzing conversations that likely had the greatest impact on public users' understanding of the eruption. Working with a smaller sample of text enabled a detailed qualitative analysis to be performed, focusing on deep rather than broad understanding of the content. Additionally, we are only able to analyze the perceptions of people who interact with posts and not those who may have read but did not interact. This limitation prevents us from documenting and analyzing the full range of possible perceptions of users viewing USGS Volcanoes' social media posts. One further complexity is our inability, due to limitations of data collection, to determine locality of users to fully understand their relationship to the events in 2018. This information would have been useful to contextualize the users' experiences and concerns more fully.

Another limitation of our qualitative approach is that the comment threads that we imported as pdf files for analysis were ordered by "relevance" rather than chronology, limiting our ability to trace the full progression of users' questions and USGS Volcanoes' or informed users' responses over time. The percentage of direct responses that we report USGS Volcanoes provided to users' questions or misinformation-related comments is an underrepresentation of USGS Volcanoes' overall responsiveness, since our qualitative thematic analysis does not include USGS

5 https://www.usgs.gov/volcanoes/Kīlauea/2018-lower-east-rift-zone-eruption-and-summit-collapse

Volcanoes' use of FAQs to address common questions and rumors. We also do not provide a comparison of users' questions, sentiments, or comments containing misinformation or rumors between USGS Volcanoes' page and other social media outlets that Hawai'i residents reported following regularly during the 2018 eruption (Goldman et al., 2023). We also do not have the data for users' reactions in the post comment threads that we qualitatively analyzed, which would have provided additional context for how positively users reacted to comments from USGS Volcanoes and from informed non-USGS users. Moreover, a majority (60–70%) of viewers of the USGS Volcanoes' social media page came from outside the State of Hawaii (Stovall et al., 2023). We do not have full geographic data for individual users or their comments, meaning that, of the 30–40% of users located in the State of Hawaii, we could not quantify the percentage of users located on the Island of Hawai'i, particularly regions impacted by Kılauea's eruption.

There were also several limitations in our bulk quantitative methods. The bulk comment dataset exported from Facebook's API includes several sets of duplicate comments that we were unable to automatically isolate and remove based on the similar, and sometimes identical, wording with other comments that were not duplicates. Further, we found that the Facebook API dataset only contained roughly 80% of the comments that were manually visible on the social media posts, which we determined by comparing the total number of comments in the API dataset with the number of comments we manually counted on the USGS Volcanoes' social media page from the same period of time as of November 2020. Our method of performing simple text searches on the Facebook API dataset only captured one sentiment, gratitude, since other sentiments could not be reliably reduced to single words. Similarly, rumor-related text searches did not capture occurrences of misinformation that do not contain the keywords listed in the Methods and presented in the Results, nor did they distinguish rumors from non-rumor-related comments. Finally, the main limitation of performing a VADER quantitative sentiment analysis on the Facebook API dataset is that emojis in users' comments were converted into unrecognizable symbolic characters upon being exported to a comma separated vector (csv) format. Since VADER can read and interpret the sentiments expressed by specific emojis (Hutto and Gilbert, 2014), the loss of these data into unreadable characters equates to an artificial neutralization of the sentiment score for those emojis.

7 Conclusion

This study presents a mixed-methods investigation of dialogues between the social media group USGS Volcanoes and non-USGS-affiliated users on Facebook during the 2018 eruption of Hawai'i's Kılauea Volcano. Through our qualitative thematic analysis, we identified two key themes in the dialogues. The first—*Eruption Sensemaking*—describes the roles and strategies that USGS Volcanoes and informed non-USGS users assumed in answering other users' questions, or correcting or calling out comments containing misinformation or false rumors. The second theme—*Expressed Sentiments*—contains three categories of emotions expressed in users' comments: positive, negative, and a grouping of "mixed, somber, and sympathetic." Our quantitative analyses included tallying the codes identified from our qualitative analysis, performing text searches on a larger dataset of 22,000 comments exported from Facebook's API, and using the VADER sentiment analysis program to quantify the degree to which users' overall sentiments were positive or negative throughout the eruption.

We identified four main findings, two for each qualitative theme. The findings that correspond with *Eruption Sensemaking* include, (1) USGS Volcanoes and informed users directly answered more than 70% of users' questions and corrected over half of comments containing misinformation or rumors and (2) these same messengers responded to other users' comments in ways that exemplified best practices identified in the hazard communication literature. Our findings corresponding with *Expressed Sentiments* include (3) that users' emotions were overwhelmingly positive, with 70% of positive feedback being directed at USGS Volcanoes, its scientists, or HVO, and (4) the occurrence of the word "thank" roughly correlates with users' overall sentiment throughout the eruption, indicating the critical role that USGS Volcanoes' and informed users' interactions with other users had on users' overall sentiment.

We determined that USGS Volcanoes' social media communication was a critical part of the USGS VHP's 2018 Kılauea eruption response by analyzing publicly visible social media dialogues between USGS Volcanoes and non-USGS users. We also illustrate how USGS Volcanoes' frequent, two-way discussions with social media users in 2018 provided important benefits by broadening the scope of public user engagement compared to previous USGS hazard communication efforts. The methods and results of this study provide a useful framework for hazard monitoring agencies and officials in the U.S. and elsewhere to build on in planning the most effective communication with publics during future hazard crises. Additionally, our methodology lays the groundwork for tracking the evolution of social media communication from official science agency accounts, such as USGS Volcanoes, over the course of multiple natural hazard events.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RG performed all qualitative and quantitative analyses and led writing of the manuscript. SM supported qualitative analyses, co-wrote the manuscript, provided perspectives on prevailing social science concepts, guidance on how to perform a mixed methods study, including developing this study's codebook, and guidance on writing for an interdisciplinary audience. WS assumed the role of primary advisor for RTG's NSF GRIP fellowship at the USGS Cascades Volcano Observatory, provided access to USGS Volcanoes Facebook data, and curated the API bulk-comment dataset. WS and DD co-wrote the manuscript and provided perspectives on state-of-the-art volcanology literature, the 2018 eruption as well as the USGS social media response. All authors helped conceptualize the study and read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2024.986974/full#supplementary-material

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