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Bridging gaps in research and practice for early warning systems: new datasets for public response

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Early warning systems (EWSs) are essential for disaster and crisis response, applicable across a wide range of hazards and threats. They are increasingly recognized as pivotal in cross-disciplinary contexts, where diverse expertise is required to manage cascading, compound, and interconnected risks holistically. Despite their critical role, significant gaps persist in understanding the interplay between the technical, social, and organizational elements that underpin effective systems. Drawing on insights from the literature and our work on global datasets, such as the World Risk Poll, this comment paper highlights four key areas: (1) leveraging public behaviors and responses to enhance warning effectiveness; (2) understanding the role of trust in information sources and its influence on warning reception; (3) identifying limitations in existing analyses; and (4) addressing operational challenges such as data accessibility and harmonization. We propose a coherent approach that utilizes multi-country surveys to establish a common benchmark for addressing these issues, identifying shared patterns across diverse geographies, and improving the management of complex events and cross-border crises. This benchmarking effort could reveal actionable insights into regional drivers of EWS effectiveness, ultimately fostering greater international cooperation and advancing the socio-technical integration of disaster risk knowledge into operational resilience.

KEYWORDS

public alerting, early warning systems, public warning, disaster management, crisis management

1 Introduction

Climate change, interconnected networks, and geopolitical instabilities are increasingly complicating the operational environment for first responders, civil protection, and civil society. At the forefront of tools designed to address these challenges are Early Warning Systems (EWS), which are gaining prominence in both academic research and practice. EWS can be defined as "an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication, and preparedness activities that enables timely action to mitigate disaster risks ahead of hazardous events" (UNDRR, 2017). Effective EWS should address multiple hazards to enhance the efficiency and consistency of warnings (UNDRR, 2017).

EWS are recognized as "core operational functions" within the strategic doctrines of civil protection globally (Haddow et al., 2021; McEntire, 2022) and are foundational in addressing vulnerabilities associated with cascading, compound, and interconnected dynamics (Pescaroli and Alexander, 2018; Pescaroli et al., 2023). Evidence shows that a 24-h alert for storms or heatwaves, for example, can reduce damages by up to 30% [UNDRR (United Nations Office for Disaster Risk Reduction) and WMO (World Meteorological Organization), 2023]. However, despite the United Nations Secretary-General underscoring the need to protect everyone with EWS by 2027, the implementation of these systems faces numerous challenges. According to the UNDRR (United Nations Office for Disaster Risk Reduction) and WMO (World Meteorological Organization) (2023), less than half of developing countries possess multi-hazard EWS, and the percentage is even lower for small island states. While progress has been made, significant gaps remain in their implementation, particularly in Africa, the Americas, and the Caribbean.

According to Tupper and Fearnley (2023), developing multi-hazard early-warning systems requires renewed efforts to promote interdisciplinary collaborations and international cooperation, particularly in addressing less visible hazards and challenges related to interoperability. Building on these insights, this comment provides a brief overview of the key components of EWS, examining the dynamics that influence their success and the barriers to their effective implementation. We propose leveraging existing datasets on risk perceptions to strengthen emergency planning and management, offering new directions for cross-disciplinary research.

2 Key components of early warning systems

EWS are pivotal for emergency response and management, providing lead time to activate organizations and the public before adverse events (Lindell et al., 2007). Recognized as more than technical alert tools, EWS must integrate scientific, administrative, and social components to be effective (Alexander, 2016). Their success does not depend just on the release of a signal, but relies on the interplay between operational context, demographics, socio-economic factors, psychological traits, culture, and the characteristics of the information delivered (Mileti and Sorensen, 1990; Quarantelli, 1990). The checklist of the WMO (2018) identifies four key interrelated pillars that are essentials for developing EWS "disaster risk knowledge based on systematic collection of data and disaster risk assessments; detection, monitoring, analysis and forecasting of hazards and possible consequences; dissemination and communication; and preparedness at all levels to respond to the warnings received" (WMO, 2018). Similarly, Hemachandra et al. (2021) identify three core components that orient their effectiveness:

(a) Policy, legislative, and institutional arrangements, including governance, political recognition, integration into development planning, stakeholder collaboration, regular feedback, local authority empowerment, and resource provision;

(b) Social and cultural considerations, including training, awareness, preparedness, community engagement, and cultural diversity;

(c) Technological and scientific arrangements, including the integration of scientific knowledge, risk information, hazard communication, and systems for monitoring and forecasting.

Warning systems are closely interconnected with other emergency management practices, particularly evacuation. Research shows that the effectiveness of these systems improves when individuals observe their neighbors evacuating or receive communications from family and friends, highlighting the role of social influence in emergency responses (Basolo et al., 2009; Ploran et al., 2018). Additionally, compliance with protective actions increases when evacuation orders are issued by local authorities and when first responders provide guidance (Kyne et al., 2018; Ploran et al., 2018). The integration of these practices ties closely to the social and cultural considerations outlined above, particularly the need for community engagement and clear communication. The literature extensively highlights the central role of communication in synchronizing these components and translating them into effective practices. Effective warning messages should be clear, accurate, actionable, and consistent, while clearly identifying the geographic area involved and describing potential impacts (Quarantelli, 1990; Wallace et al., 2016; McEntire, 2022; Ploran et al., 2018; Dryhurst et al., 2021). Employing multiple communication channels is essential to reach diverse groups and ensure actionable responses, though researchers caution against "over-warning," which can undermine message credibility (Morss and Hayden, 2010; Strawderman et al., 2012; Schumann et al., 2018).

While communication strategies form the backbone of EWS, their effectiveness is ultimately shaped by socio-psychological influences on public engagement in protective and preparedness behaviors. Several broad drivers have been identified, including risk perception (an individual's assessment of the perceived likelihood and severity of a hazard), protective action perception (an individual's evaluation of the effectiveness of a proposed action and their capacity to perform it), and stakeholder perception (encompassing the perceived responsibility of stakeholders vs. individuals for protective actions, as well as public trust in stakeholders) (Lindell and Perry, 2012).

An increasing body of research has explored key influences on these drivers. For example, gender consistently emerges as a determinant, with women more likely than men to take appropriate protective actions (Schumann et al., 2018; Yang et al., 2016). Direct or indirect experience with a hazard is also a strong driver of preparedness behavior and responsiveness to warnings, with several studies finding a positive relationship (e.g., Silver and Andrey, 2014; Schumann et al., 2018; Becker et al., 2017, 2022). However, mild experiences with hazards can result in the opposite effect, where individuals perceive the impact of such events as typical, underestimate risks, and fail to recognize the potential severity of more extreme events (Mileti and O'Brien, 1992; Dryhurst et al., 2020a,b). For instance, someone who has experienced a mild earthquake may not fully grasp the dangers of a more severe one.

Public trust in the source and credibility of the message is another critical factor influencing preparedness behavior and warning responsiveness. Messages issued by credible sources, such as weather services or local authorities, are more likely to prompt protective actions (Bostrom et al., 2018; Folk et al., 2019; Lazo et al., 2015). Informal and trusted sources, such as friends and family, also play an essential role, especially when official information is lacking (Sorensen, 2000; Vihalemm et al., 2012). The consistency of some of these relationships, however, varies. For example, the relationship between age and protective actions differs across studies and hazards, sometimes showing no significant correlation (Folk et al., 2019). Similarly, the influence of education on warning responsiveness presents mixed findings; lower educational attainment is generally linked to lesser responsiveness, while higher education levels show variable impacts (Kyne et al., 2018; Meyer et al., 2018). These findings underline the importance of tailoring EWS strategies to diverse social and cultural contexts, as most studies to date focus on specific countries, raising questions about the transferability of these insights to other settings.

3 Open challenges in researching EWS

The technology for forecasting is well established, but there are limitations associated with siloed thinking and the effective integration of warnings into organizational and societal practices (Tupper and Fearnley, 2023). Scholarly discussions on EWS often demonstrate a limited scope, frequently constrained by the availability of data and cultural or language barriers (Pescaroli and Magni, 2015). Early research in the field of EWS was predominantly qualitative, focusing on the United States (Mileti and Sorensen, 1990; Quarantelli, 1990). More recent studies have adopted quantitative methods but remain confined to specific geographies, hazards, and events, such as New York City, Miami-Dade County, Rio Grande Valley, Texas (Kyne et al., 2018), and San Diego, California (Strawderman et al., 2012). International research is sparse and hindered by data limitations, with studies conducted in locations like Rome, Italy, Frankfurt, Germany (Appleby-Arnold et al., 2019), and Tallinn, Estonia (Vihalemm et al., 2012). This geographic and data limitation underscores the need for interdisciplinary collaboration and the integration of socio-technical frameworks discussed earlier. In other words, these gaps highlight the importance of adopting a holistic, multi-hazard perspective that prioritizes the alignment of technical and social systems. This limitation extends to studies on individual hazards (Garcia and Fearnley, 2016; Quansah et al., 2010), which have predominantly addressed hurricanes (Bostrom et al., 2018; Lazo et al., 2015; Jiang et al., 2019), floods (Horita et al., 2018), tornadoes (Durage et al., 2014; Schumann et al., 2018), wildfires (Folk et al., 2019), earthquakes (Velasquez et al., 2020; McBride et al., 2020), volcanoes (Potter et al., 2018), and droughts (Bhardwaj et al., 2023). Specific events such as Hurricanes Katrina, Rita, Ike, and Matthew, as well as the wildfires in Maui, Hawaii, and Mati, Greece, have also been focal points of research (Morss and Hayden, 2010; Synolakis and Karagiannis, 2024). The generalizability of findings from these focused studies to other locations and hazards requires further scrutiny, as there are differences in hypotheses, methodologies, questionnaires, sample sizes, and modeling approaches. This reinforces the need for global and multi-disciplinary initiatives, as emphasized in previous sections, to address these gaps. Recent projects and documentation incorporating a multi-country or multi-hazard perspective demonstrate progress in this direction [UNDRR (United Nations Office for Disaster Risk Reduction) and WMO (World Meteorological Organization), 2023].

At a more theoretical level, the emerging challenges associated with systemic risk—such as cascading, compound, concurrent, and interacting hazards—underscore the need for a holistic approach to complexity in early warning systems (EWSs). Identified as critical tools for mitigating crisis escalation and fostering cross-disciplinary research collaborations, EWSs must be framed within a socio-technical lens to address these complexities effectively (Pescaroli and Alexander, 2018). Despite progress, the interaction of EWSs with broader system dynamics within socio-technical frameworks remains insufficiently explored. Abbas and Michael (2023) emphasize that socio-technical theory offers valuable insights into system adaptability through iterative and flexible design processes. These processes highlight the risks of optimizing individual components in isolation, underscoring the importance of collaboration for achieving long-term system effectiveness. As integrated systems, EWSs rely on the alignment and functionality of interconnected social and technical components to reduce risks for vulnerable populations and assets. Understanding the interdependence of these components could provide actionable solutions for operational challenges in resource-constrained settings (Pescaroli et al., 2023).

The socio-technical nature of EWSs is well established in academic literature. Alexander (1993, p. 400) described warning creation and implementation as involving "complex interactions between physical, technological, and social systems whose operation must be carefully coordinated to achieve a satisfactory result." Basher (2006) expanded this perspective, advocating for a "systems" agenda that integrates natural and social sciences while strengthening scientific and institutional mechanisms. He argued for a people-centered approach that addresses vulnerable populations' needs through activities such as community risk mapping, response planning, local monitoring, tailored public information, and innovative media and education strategies. Key measures include establishing benchmarks for technical services, involving public representatives in oversight, conducting research on warning comprehension, and training technical experts in social factors. Simulations further enhance preparedness and system functionality. Empirical studies provide evidence for these socio-technical approaches, highlighting the interplay between individual perceptions and broader socio-cultural factors. Wu et al. (2008) demonstrated the socio-technical complexity of even simple technologies like SMS-based alerts, showing that adoption depends on individual perceptions (e.g., trust and risk awareness) and socio-cultural factors such as gender and community norms. Barriers such as socio-cultural misalignment often hinder adoption, while tailoring systems to user needs and fostering engagement enhance their effectiveness. To improve emergency communication, future research should explore the interplay between contextual factors, psychological drivers, and operational requirements, incorporating stakeholder insights. Integrating new datasets, such as real-time social media analytics, participatory mapping, and geospatial risk data, could reveal patterns in trust-building, information dissemination, and community engagement, offering innovative approaches to strengthening EWSs.

Trust in information sources is another vital factor influencing EWS efficacy. Research has shown that trust significantly impacts the likelihood of acting on warnings, and demographic and socio-economic factors shape perceptions of trustworthy sources (Lindell and Perry, 2012; Siegrist and Cvetkovich, 2000; Kotthaus et al., 2016; Appleby-Arnold et al., 2019). Investigating these dynamics and their interaction with socio-technical systems using diverse datasets, including demographic surveys and behavioral analytics, could enhance global understanding and inform adaptive warning strategies.

Alcántara-Ayala and Oliver-Smith (2017) argue that despite advancements, current EWSs fail to integrate adequately within broader socio-technical frameworks required for effective disaster prevention. They call for solutions that combine technical processes with sustained partnerships among communities, scientists, authorities, and stakeholders. These systems should prioritize multi-directional risk communication, fostering preparedness and addressing the root causes of disaster risks, including social vulnerabilities and resilience. Far from being merely response tools, EWSs are integral to capacity-building efforts that improve individual and collective preparedness through risk perception, scenario planning, and response strategies.

Finally, Velasquez et al. (2020) and Pescaroli et al. (2022) highlight persistent challenges in translating technological components into effective organizational practices. These include gaps in governance and accountability, standardization of plans and procedures, and training. Addressing these challenges requires targeted actions within social, political, behavioral, and operational frameworks, ensuring EWSs remain effective and resilient. Future research could leverage large-scale datasets from disaster response simulations, public engagement platforms, and hazard-specific risk assessments to enhance the operational relevance and scalability of socio-technical solutions.

4 Open challenges in translating disaster risk knowledge into operational practices

The potential use of datasets in enhancing EWS is rapidly expanding, supporting the development of risk knowledge and operational practices. The availability of planetary-scale geospatial datasets is growing, with repositories such as UNEP Grid and GFDRR ThinkHazard providing valuable resources (Lindersson et al., 2020). For example, EWS for droughts can now integrate seasonal rainfall forecasts with data on precipitation, soil moisture, and evapotranspiration across various timescales (Bhardwaj et al., 2023). However, limitations persist, affecting the operationalization of EWS. On the one hand, global datasets often provide low-resolution data, which is insufficient for detailed, project-level assessments. This limits the understanding of exposure and its implications for EWS. Dynamic exposure data for early warnings are rare, with risk managers and weather services frequently relying on personal knowledge for issuing warnings. On the other hand, many countries continue to use outdated or inaccessible basic census data, asset inventories, and city plans. Effective planning processes should include considerations such as the relationship between monitoring stations and local communities, the quantity and quality of monitoring devices, available human resources, capacity development needs, communication options, and necessary maintenance. As noted, "The instruments to monitor hazards should be simple and practical, ensuring people (not only technically trained ones) can use them effectively" (United Nations Office for Disaster Risk Reduction et al., 2024, p. 25). Socio-economic indicators can sometimes serve as proxies for estimating exposure when full inventories are unavailable (Šakić Trogrlić et al., 2022). While addressing these data and planning gaps is essential, the success of EWS ultimately hinges on their ability to translate this knowledge into actionable public responses.

Despite advances in information technology and the availability of GIS, a critical gap remains in developing a cross-national understanding of diverse population needs to synchronize EWS deployment effectively and enhance long-term resilience. This challenge is particularly relevant for complex events, such as low-probability, high-impact events and concurrent hazards, where cascading and interconnected risks highlight the urgency of developing interoperable datasets to enable real-time cross-sector coordination and mitigate escalation points during complex disasters. The Words into Action (WiA) Guide to Multi-Hazard Early Warning Systems (United Nations Office for Disaster Risk Reduction et al., 2024) emphasize that the transboundary dynamics of such events demand interoperable data as a baseline for effective multi-hazard early-warning systems. This includes the development of a governance architecture to support efficient implementation.

One major challenge to the effective operationalization of EWS is public responsiveness to issued warnings. It is not enough for citizens to receive a warning; they must trust the warning and its communicator and act upon it for it to be effective. Despite advancements in understanding risk perceptions and behavioral responses to warnings (e.g., Lindell and Perry, 2012), critical knowledge gaps persist. Specifically, how findings from one country or culture might apply to another remains unclear, potentially compromising the effective implementation of EWS into operational practices for organizations (Velasquez et al., 2020; Pescaroli et al., 2022, 2023). Neußner (2021) highlights the growing shift from hazard-based to impact-based warnings, which include details of the hazard, its impact, and recommended actions. Action-oriented warnings, using clear directives such as "prepare," "act," or "evacuate," can enhance comprehension and support global harmonization. A standardized three-tier system, akin to traffic lights, could simplify understanding, though cultural differences and local needs require redundancy through formats such as colors, symbols, and concise messages. However, progress toward international standardization has been slow. For example, the Cancun 2017 conference on early warning overlooked global harmonization and the specific needs of vulnerable groups, such as migrants and tourists. These concerns have been included in the recommendations of United Nations Office for Disaster Risk Reduction et al. (2024), which stress the importance of translating public understanding of warnings into actionable knowledge and well-developed contingency planning. To sum up, the literature suggests that integrating interoperable datasets, actionable warnings, and culturally adaptive strategies, EWS can bridge the gap between disaster risk knowledge and operational resilience, ultimately fostering more effective preparedness and response.

5 Conclusion: a way forward

It could be argued that no one wants to reinvent the wheel, but often the solution to existing problems lies in applying lateral thinking to use available resources differently. A starting point to advance in the direction suggested in documents such as United Nations Office for Disaster Risk Reduction et al. (2024) and UNDRR (United Nations Office for Disaster Risk Reduction) and WMO (World Meteorological Organization) (2023) is leveraging existing datasets from multi-country surveys. While these datasets may not be specifically designed for EWS, they can provide a universal benchmark, helping to overcome the limitations of disparate study designs. Considering the theoretical understanding discussed in the previous sections, this approach enables the formulation of targeted hypotheses and research questions on EWS components. These can explore the interlinkages between hazard, vulnerability, and exposure, offering a comprehensive understanding of the factors influencing EWS effectiveness across countries.

In the last year, our team applied this methodology to the World Risk Poll (https://wrp.lrfoundation.org.uk/), "the first and only global study of worry about, and harm from, risks to people's safety," covering 147,000 people in over 140 countries. Compared to existing studies in the literature, the World Risk Poll enables the systematic testing of variables influencing EWS, covering often-neglected areas and highlighting regional drivers and differences between hazards. This dataset allows for an analysis of the social factors influencing where people source information about potential disasters, the organizations they trust, and the motivations behind individual and family disaster preparedness behaviors. Additionally, it examines how demographic, socio-economic, experiential, or psychological factors affect warning information sources across different countries. Key variables analyzed include age, educational attainment, household size and income, prior disaster experiences, and exposure to warnings. Examples of research questions proposed include: "How do socio-economic factors influence trust in EWS across different countries?" and "What are the behavioral patterns in response to EWS in regions with low infrastructure resilience?" This global perspective is refined through detailed, country-specific statistical analysis, allowing for a nuanced understanding of local conditions, which will be further discussed with project stakeholders.

Building on these initial insights, our project has identified several challenges that must be addressed to maximize the potential of cross-border datasets for EWS. The early results of this approach are encouraging. We expect to generate new knowledge targeted at designing better EWS, offering concrete recommendations to support training organizations, public warning systems, and educational initiatives aimed at resilience practitioners and policymakers. Methodologically, our project demonstrates that the World Risk Poll and similar multi-country surveys can be analyzed through a regression modeling approach, employing statistical methods developed during the coronavirus pandemic (Dryhurst et al., 2021). This analysis provides valuable insights into the correlations between demographic, socio-economic, experiential, and psychological factors that influence people's choices and trust in disaster information sources. It also identifies the relative importance of these factors and assesses the consistency of these predictors across diverse geographies. These insights are particularly valuable in addressing cascading risks, where interoperable data can help anticipate how interconnected vulnerabilities propagate across regions.

However, we consider this only a first step toward a more consistent approach to leveraging cross-border datasets for developing effective EWS. During the project's development, we have identified three core challenges:

1. The World Risk Poll is designed to be cross-cutting, and our current use represents just one possible application. It may be worth considering the creation of a similar dataset focused on specific, compatible topics, such as EWS and emergency response, to build directly on targeted data collection.
2. While the World Risk Poll represents substantial innovation, the international community should prioritize developing new cross-country datasets that specifically address perceptions of risk and preparedness at organizational levels—local, regional, and national—focusing on the intersection between business continuity management and emergency management (see Pescaroli et al., 2023).
3. There is a pressing need for new methodological approaches that integrate qualitative and quantitative data. Mixed methods approaches (e.g., Plano Clark, 2017) leveraging focus groups or semi-structured interviews could complement cross-country datasets designed for statistical analysis.

By leveraging cross-border datasets and refining methodologies, the international community can advance the development of EWS that are not only effective but also contextually adaptive and inclusive.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://storage.googleapis.com/wrp_shares/site_live/23_wrp.zip.

Author contributions

GP: Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology. SD: Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology. GK: Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration.

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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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