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Global Safety Evidence Centre

Effectiveness of disaster early warning systems in reducing the impact of extreme weather- and climate-related events: a systematic review



Safety Science

Evidence Review

Technical Report

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Executive summary

Introduction

Extreme weather and climate-related events are increasing in frequency and intensity, causing substantial loss of life, injuries, displacement, livelihood disruption and economic damage. Early warning systems have been widely used for mitigating the impact of extreme weather events, and several individual studies have assessed their effectiveness in improving outcomes. However, there is very limited comprehensive synthesis of evidence from these studies to establish whether existing early warning systems work, for whom, at what cost, and the conditions that facilitate their successful implementation.

We conducted a comprehensive systematic review of the available literature to assess the effectiveness of existing early warning systems, their cost-effectiveness, the barriers and enablers to their successful implementation, and the views of target populations regarding their usefulness. The research was guided by a consultation group of experts in systematic review methods as well as practitioners and researchers in disaster risk management, to ensure that the findings are relevant to policy and practice.

Research questions

The research questions were:

1. **What works and for whom**: What is the effectiveness of early warning systems in reducing the impact of extreme weather- and climate-related events?
    a. What are the different types of early warning systems that have been used to reduce the impact of extreme weather- and climate-related events?
    b. What is the effectiveness of different types of early warning systems in reducing the impact of extreme weather- and climate-related events?
    c. What are the demographics and characteristics of communities served by these early warning systems? Which early warning systems are more or less effective for different populations, communities, and regions?
2. **How**: What elements or components of these early warning systems are associated with reductions in loss of life and assets?
3. **At what cost**: What is the cost-effectiveness of adopting early warning systems for reducing the impact of extreme weather- and climate-related events?
4. **Implementation:** What are the enablers and barriers to successful implementation of early warning systems?
5. **User perspectives**: What are the views and experiences of target populations, organisations and governments regarding the acceptability and usefulness of early warning systems?

Findings from this review will inform the development of an evidence toolkit on effective disaster early warning systems.

Methods

A comprehensive protocol was developed and registered on Open Science Framework before commencing literature searches for the review. We searched seven academic databases, several organisational websites, Google and Google Scholar for research published from 1990 onwards. Additional studies were identified through reference checking, stakeholder engagement and a public call for evidence. Both academic publications and grey literature were considered, without geographical restrictions; however, only English-language reports were included for analysis due to unavailable language translation support.

Literature screening, quality assessment and data extraction were conducted in Covidence (a web-based systematic review software). Two reviewers assessed each potentially eligible paper. Information on study methods, early warning systems, populations and findings was extracted by one reviewer and checked by another. Studies were assessed for methodological quality, and confidence in the review findings was evaluated using appropriate tools.

Key findings

The review included 111 studies spanning 54 countries, covering floods, cyclones, extreme heat, droughts and other hazards. Most of the included studies examined nationally operated systems, but community-based systems were particularly common in lower-income settings and were mostly focused on mitigating the impact of flooding.

Key findings from the review include:

- Early warning systems can reduce the impact of extreme weather and climate events, but the strength of evidence varies by outcome, hazard type and implementation context.
- Effectiveness depends less on the level at which the system is operated – that is whether it is a national, community-based/local, regional, or global system – and more on whether warnings are trusted, timely, actionable, locally appropriate and accessible to the populations or communities that are most at risk.
- Evidence on the effect of early warning systems in reducing deaths was mixed or unclear. We found only one study – on tsunami early warning systems – that showed reduction in deaths.
- For reduction in illnesses or injuries, the evidence shows targeted benefits, such as fewer cardiac-related ambulance call-outs during extreme heat events or fewer typhoon-related injuries, but findings were inconsistent across studies.

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- For reduction in asset losses, there was strong positive effect of early warning systems, particularly for flood-related losses. The evidence shows that warning lead time of one-hour or more, improved preparedness knowledge and early action can reduce building content damages and economic losses.
- There were limited impact evaluations which have looked at the effect of early warning systems on outcomes such as loss of livelihood, and most studies used less robust research methods to assess effectiveness.
- The evidence was evenly distributed between middle-income and high-income economies, with a much smaller number from low-income countries. Evidence on the effectiveness of early warning systems from low-resource settings was more limited compared with evidence on implementation of early warning systems, which mostly originated from those settings.
- Evidence on the benefit of early warning systems for different populations and settings was limited. Many studies did not consistently report participant characteristics, but where reported, the evidence shows that gender, age, education, language, disability, occupation and trust in institutions can shape access to and understanding of early warnings and related preparedness action.
- Early warnings were more likely to lead to improved outcomes when they were delivered through multiple channels, in local languages, by trusted intermediaries, and included clear instructions on what people should do to protect themselves.
- Receiving a warning does not guarantee protective action. Systems are more likely to reduce harm when warnings are connected to household and community plans, evacuation routes, accessible shelters, support for people who need assistance, and pre-agreed roles and resources.
- Implementation barriers included limited infrastructure, poor communication channels, low trust, lack of local ownership, insufficient preparedness capacity and weak institutional coordination.
- Only a small number of studies assessed cost-effectiveness of early warning systems, but evidence from these studies shows that the benefits of adopting an early warning system far outweigh investment costs, with consistent evidence of cost-effectiveness seen across different hazards and income settings.

How up-to-date is this review?

This systematic review considered studies published from 1990 onwards. Academic database searches were conducted between 23 December 2025 and 16 January 2026. Website searches were completed on 31 January 2026, and the call for evidence closed on 31 March 2026.

Recommendations and next steps

Early warning systems are important disaster risk reduction tools, but warning coverage alone is not sufficient. Their benefits depend on whether warnings are received, trusted and understood, and whether people have the knowledge, resources, authority and practical support to act. The findings reinforce the need for people-centred, end-to-end systems across the four Early Warnings for All pillars: disaster risk knowledge; detection, observation, monitoring and forecasting; warning dissemination and communication; and preparedness and response capability. Investment should connect timely alerts to practical guidance, inclusive and locally appropriate communication, household and community preparedness, evacuation support, local capacity and anticipatory action.

Future research should use robust designs for evaluating effectiveness where feasible, report outcomes and population characteristics consistently, and include analyses of the differential effectiveness across diverse population groups to understand who benefits from early warning systems, who is missed and why. More impact evaluations are needed from low- and middle-income countries on the effectiveness of early warning systems, particularly for mortality, morbidity and livelihood outcomes.

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List of abbreviations and acronyms

Abbreviation / acronym / terms	Description
FAO	Food and Agriculture Organisation
WMO	World Meteorological Organisation
WRP	World Risk Poll
CRI	Climate Risk Index
UN	United Nations
UNDRR	United Nations Disaster Risk Reduction
ROBINS-I	Risk of Bias In Non-randomised Studies – of Intervention
RCT	Randomised Controlled Trial
RoB-2	Cochrane Risk of Bias tool version 2
MMAT	Mixed-Methods Appraisal Tool
UNDRR-ISC	United Nations Disaster Risk Reduction – International Science Council
FEWSNET	Famine Early Warning System Network
WHO	World Health Organisation
IRR	Incidence Rate Ratio
CI	Confidence Interval
GDPC	Global Disaster Preparedness Center
USA	United States of America
UK	United Kingdom
UKRI	United Kingdom Research Innovation
UN-SPIDER	United Nations Platform for Space-based Information for Disaster Management and Emergency Response
SWiM	Synthesis Without Meta-analysis
GRADE	Grading of Recommendations Assessment, Development and Evaluation
GRADE-CERQual	Grading of Recommendations Assessment, Development and Evaluation – Confidence in the Evidence from Reviews of Qualitative Research

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1. Introduction

1.1 Project background and rationale

Extreme weather and climate events – including heavy rainfall/floods, tsunamis, earthquakes, wildfires, heatwaves, and storms – have become increasingly common globally, and their frequency and intensity continue to rise. The 2025 World Risk Poll shows that one out of every twenty people globally viewed extreme weather events as their greatest source of risk, with heavy rain or flooding being the most cited cause of disaster experience, followed by hurricanes or cyclones (World Risk Poll, 2025). Estimates from the Climate Risk Index (CRI) indicate that over 9,400 extreme weather events were recorded globally from 1993 to 2022, resulting in over 765,000 fatalities and about US$4.2 trillion in direct economic losses (Adil et al., 2025). The evidence shows that the most fatalities were caused by storms (35%), heatwaves (30%), and floods (27%), with storms causing the most significant economic losses (56%), followed by floods (32%). In 2024 alone, a total of 605 extreme weather events occurred globally, leading to about 1,700 fatalities, 824,500 displacements, and about 1.1 million people reported as injured (World Meteorological Organisation, 2024).

Extreme weather and climate events affect all countries and continents. The 2022 Climate Risk Index ranks Pakistan as the country most affected by extreme weather events, followed by Belize, Italy, Greece, Spain, Puerto Rico, the United States of America (US), Nigeria, Portugal, and Bulgaria (Adil et al., 2025), with seven of these countries belonging to the high-income country group. However, the evidence shows that, over the long term, the impact of extreme weather events is particularly high in low- and middle-income countries (Adil et al., 2025; Ghosh et al., 2023). This is especially true in countries where extreme weather- and climate-related risks intersect with pronounced vulnerabilities and significantly lower adaptive capacities. For example, coastal communities are usually affected by disasters that are either slow in their occurrence (e.g., sea-level floods) or rapid-onset (e.g., storm- and cyclone-induced floods) (Adger et al., 2005), and due to the repetitive nature of such disasters, these communities remain at constant risk.

1.2 Early warning systems: why do they matter?

Early warning systems are mechanisms that have been used to mitigate the impact of extreme weather and climate events. The United Nations Office for Disaster Risk Reduction (UNDRR) defines an early warning system as an integrated system for hazard monitoring, forecasting, risk assessment and communication that enables communities, individuals, and governments to take timely action to reduce the impact of impending hazardous events (UNDRR, 2017). The 2019 Global Commission on Adaptation report identified that issuing a warning just 24 hours ahead of an impending hazard can reduce losses by 30 percent. The report also indicated that investing US$800 million in early warning systems in developing countries would prevent losses of up to US$16 billion per year (Global Commission on Adaptation, 2019).

Early warning systems are not disaster prevention mechanisms; rather, they are important components of disaster risk reduction and management (Alcantara-Ayala and Oliver-Smith, 2017). People-centred, impact-based, multi-hazard early warning systems, supported by appropriate emergency preparedness strategies, are effective in preventing disaster risk and reducing losses caused by extreme weather- and climate-related hazards at both national and local levels (UNDRR and WMO, 2022; Cuevas, 2012; Fakhruddin and Schick, 2019). An effective early warning system involves four key elements: a) risk knowledge: systematically collecting data and undertaking risk assessment to identify and understand risks, hazards, vulnerabilities and exposure patterns; b) detection, monitoring and forecasting: predicting and monitoring the intensity and occurrence of hazards; c) warning dissemination and communication: communicating accurate and timely early warnings to populations identified as at risk; and d) preparedness and response capabilities: building national and community response capabilities (UN-ISDR, 2006; Cazorzi et al., 2023; Khankeh et al., 2019).

A range of factors need to be taken into consideration when designing early warning systems. These include well-developed governance and institutional arrangements, involvement of local communities, consideration of cultural diversity and gender perspectives, and the use of a multi-hazard approach that links all hazard warning systems. It is also important that early warning systems are well implemented, accurate in their estimation of impending disasters, clearly communicated, and incorporate educational initiatives aimed at raising awareness among communities (Akhand, 2003).

Technological advancements play a key role in the design and communication of early warning systems. Technologies such as sensor detectors, smart devices, and automated monitoring systems are beneficial for hazard detection (Mustofa et al., 2023; Hassan et al., 2023). Moreover, social media platforms (e.g., X, LinkedIn) and instant messaging apps (e.g., WhatsApp, Short Message Service (SMS)) are useful for disseminating and communicating information about impending hazards (Budimir et al., 2019). The 2025 World Risk Poll suggests that, of the people affected by a disaster, more than half (58%) were warned through the internet (including social media and websites) and television, or through SMS/text message (54%) (World Risk Poll, 2025). This highlights the increasing role of digital technologies in disaster early warnings. While global internet use continues to increase, disparities in access remain, with only 27% of people in low- and middle-income countries having internet access compared with 93% in high-income countries.

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1.3 How effective are early warning systems?

Several studies have assessed the effectiveness of early warning systems in mitigating extreme weather- and climate-related hazards. Fakhruddin and Schick (2019) assessed the benefits of implementing early warning systems and their cost-effectiveness through a case study of the Cyclone Evan disaster that occurred in Samoa in 2012. Key findings indicate that adopting an enhanced early warning system could yield about US$6.74 million over a ten-year period, assuming a return period of five years for such a cyclone event and a 10% forecast error probability. Similarly, a joint study by the World Bank and the United Nations examining the economic benefits of adopting disaster early warning systems in Bangladesh found that, for every US$1 invested in early warning systems, there was a return of US$40.85 in benefits over a ten-year period (World Bank and United Nations, 2010). Teisberg and Weiher (2009) reported a 3:1 benefit-to-cost ratio for adopting hurricane early warning systems in the United States, meaning that every US$1 spent on implementing early warning systems resulted in US$3 in benefits.

A recent cross-sectional survey by Kalogiannidis et al. (2025) evaluated the effectiveness of early warning systems in reducing losses associated with natural hazards in Greece. The study focused on the effects of four key components of early warning systems: a) timeliness in issuing alerts, b) accuracy of hazard prediction, c) public awareness and education programmes incorporated into early warning systems, and d) technological advancement in improving the efficiency of early warning systems. The findings showed that early warning systems with these components had a strong positive influence on the reduction of loss of lives during disasters associated with natural hazards (R = 0.79, R^2 = 0.69). A similar study conducted in India found that households that received timely warning messages – at least 24 hours before the disaster – had less damage to their houses, assets, and livestock (Sahana et al., 2023). The results showed that households that received early warnings within 12 hours of the disaster suffered the most losses. In addition, households that received early warnings only through relatives and neighbours were more likely to suffer livestock deaths and land losses. These findings indicate that the timeliness of issuing early warning messages and the communication sources used are vital in reducing loss of life and assets during disasters.

1.4 Why it is important to do this systematic review

While several primary studies have assessed the effectiveness of early warning systems in reducing loss of life and assets in disasters, there is an existing evidence gap regarding systematic reviews that have synthesised the collective evidence on early warning systems to provide a robust summary of their effectiveness. Systematic reviews in this area have mostly focused on assessing a) the challenges and opportunities in cloud-computing early warning systems (Agbehadji et al., 2023), b) community engagement in disaster early warning systems (Sufri et al., 2020), c) flood early warning systems (Hammood et al., 2020), or d) the use of early warning systems in the detection of infectious disease outbreaks (Meckawy et al., 2022). The current research is unique because it uses robust systematic review methodology to comprehensively assess the effectiveness of disaster early warning systems and how best they can be implemented to improve outcomes.

Specifically, unlike previous reviews in this area, this systematic review: 1) collates and synthesises evidence on the effectiveness of early warning systems, the barriers and enablers to their successful implementation, and the experiences and views of communities regarding their usefulness and acceptability; 2) assesses the components of early warning systems that are associated with improved outcomes; and 3) explores 'for whom' early warning systems are effective by assessing variations in effectiveness for different populations, communities, or regions.

1.5 Research objectives

The objective of this systematic review was to collate existing early warning systems and assess their effectiveness in reducing the impact of extreme weather and climate events. This review also aimed to explore the factors involved in the successful implementation of early warning systems. It is intended to support the identification of effective disaster early warning interventions, policies and practices globally, and to contribute to the evidence on disaster risk management.

Findings from this systematic review will be used to develop an evidence toolkit that will summarise existing global evidence on the different early warning systems used to reduce the impact of extreme weather and climate events.

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1.6 Research questions

The research questions were:

1. **What works and for whom**: What is the effectiveness of early warning systems in reducing the impact of extreme weather- and climate-related events?
    a. What are the different types of early warning systems that have been used to reduce the impact of extreme weather- and climate-related events?
    b. What is the effectiveness of different types of early warning systems in reducing the impact of extreme weather- and climate-related events?
    c. What are the demographics and characteristics of communities served by these early warning systems? Which early warning systems are more or less effective for different populations, communities, and regions?
2. **How**: What elements or components of these early warning systems are associated with reductions in loss of life and assets?
3. **At what cost**: What is the cost-effectiveness of adopting early warning systems for reducing the impact of extreme weather- and climate-related events?
4. **Implementation:** What are the enablers and barriers to successful implementation of early warning systems?
5. **User perspectives**: What are the views and experiences of target populations, organisations and governments regarding the acceptability and usefulness of early warning systems?

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2. Methods

2.1 Project consultation group

The conduct and reporting of this systematic review were guided by a project consultation group assembled by the Lloyd's Register Foundation Global Safety Evidence Centre, with the aim of ensuring that the review findings are relevant to policy and practice. The group was made up of systematic review methods experts, as well as practitioners and researchers with expertise in disaster early warning systems. Group members were consulted three times during the project – at protocol development, interim findings, and final reporting.

The research team worked collaboratively with the consultation group to ensure appropriate use of language and terminology, and to co-produce recommendations from the review findings.

2.2 Protocol registration

The protocol for this systematic review was registered on the Open Science Framework on 11 December 2025 (Registration DOI: *10.17605/OSF.IO/78VPY*) and published on the website of the Lloyd's Register Foundation Global Safety Evidence Centre[1].

To ensure transparency, this systematic review was guided by established guidance, including the PRISMA guidelines for reporting systematic reviews (Page et al., 2020) and the PRISMA-Equity checklist (Welch et al., 2012), the Cochrane Handbook for Systematic Reviews (Higgins et al., 2024), and the GRADE and GRADE-CERQual frameworks.

2.3 Protocol deviations

At the quality assessment stage, minor deviations from the protocol were necessary due to the highly heterogeneous designs of the included studies, which made it unsuitable to critically appraise some of them using ROBINS-I, the Risk of Bias (RoB-2) tool, or the Critical Appraisal Skills Programme (CASP) qualitative checklist.

We used the Mixed Methods Appraisal Tool (MMAT) for quantitative non-randomised studies, quantitative descriptive studies, and mixed methods studies. Specifically, the MMAT checklist for non-randomised designs was used to appraise studies that employed a cross-sectional analytic design to evaluate the effectiveness of early warning systems. We used the MMAT quantitative descriptive checklist for studies that used structured, closed-ended survey questionnaires to quantitatively assess people's perceptions of early warning systems; and the MMAT mixed methods checklist was used to appraise studies that integrated closed-ended survey questionnaires and interviews (including one-to-one interviews and/or focus group discussions) to collect data on relevant outcomes and phenomena of interest. The CASP Economic Evaluation checklist was used to appraise studies that incorporated cost-effectiveness or cost-benefit analyses.

Studies that used a randomised controlled trial, quasi-experimental, or qualitative design were appraised using RoB-2, ROBINS-I, and the CASP qualitative tool, respectively.

The protocol registration record on Open Science Framework (available here: *10.17605/OSF.IO/78VPY*) has been updated to include these changes.

1 See a blog post on the systematic review protocol: *https://www.lrfoundation.org.uk/news/building-the-evidence-on-effective-early-warning-systems*

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2.4 Eligibility criteria

The inclusion and exclusion criteria applied in this systematic review are presented in Table 1 (for research questions 1–3) and Table 2 (for research questions 4 and 5).

Table 1. Inclusion and exclusion criteria for studies to answer research questions 1–3

PICOS domains	Inclusion criteria	Exclusion criteria
Population	• Studies focused on countries, communities, or regions which have been involved in disasters associated with extreme weather or climate events. • Studies focused on communities or individuals who have not been involved in disasters associated with a natural hazard but have participated in a simulation programme aimed at improving the effectiveness of early warning systems.	Studies that do not have any of the characteristics listed.
Intervention	• Early warning systems aimed at empowering communities and individuals threatened by disasters associated with a natural hazard to act in a timely and appropriate manner to reduce loss of life, personal injury, and damage to the environment and property. • Early warning systems for preventing disaster risk and reducing losses caused by weather- and climate-related hazards at both national and local levels. • Any mechanisms or measures used to detect, disseminate, and communicate early warnings of weather- and climate-related hazards such as floods, cyclones, storms, tsunamis, wildfires, droughts, heatwaves, sand and dust storms, earthquakes, and volcanic eruptions.	• Studies focused solely on risk knowledge and/or the detection, monitoring, performance and forecasting of early warnings. • Studies that are not specifically focused on early warning systems or do not meet any of the inclusion criteria.
Comparison	• Studies that used any statistical method – such as difference-in-differences, propensity score matching/weighting, or case studies with varied exposure levels – to mimic an experimental setting and ensure comparability between groups. • Where applicable, studies with active control groups (i.e., another intervention). • Studies with an inactive control (i.e., no intervention, business as usual, or minimal intervention).	Studies that do not meet any of these inclusion criteria.
Outcomes	*Primary outcomes* • Reduction or prevention of mortality (deaths) and morbidity (injuries/illnesses) • Reduction in loss of livelihood • Reduction in loss of assets, including both tangible and intangible items of financial value, such as land, houses, vehicles, work-related assets (e.g., fishing boats, factories), and critical infrastructure (e.g., transportation networks, water supplies, and telecommunications). • Cost of adopting an early warning system *Performance metric* • Timely issuance of warning alerts • Accuracy of alerts	• Studies that did not specifically assess the impact of early warning systems on protecting lives, livelihoods, the environment, or assets were excluded.

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PICOS domains	Inclusion criteria	Exclusion criteria
Study designs	Primary research studies that used designs aimed at capturing both the long-term and immediate impacts of early warning systems across various outcomes. Examples include: • Quasi-experimental studies • Randomised controlled trials • Longitudinal studies • Interrupted time series studies • Mixed methods studies • Studies with economic evaluations of early warning systems • Studies with information about the implementation cost of early warning systems	Studies that did not meet any of the inclusion criteria.

Table 2. Inclusion and exclusion criteria for studies to answer research questions 4 and 5

SPIDER domain	Inclusion criteria	Exclusion criteria
Sample	• Countries, regions, communities, or individuals that have experienced an extreme weather/climate hazard. • Individuals involved in the design or implementation of early warning systems.	Those who have not been affected by an extreme weather or climate hazard, as well as those who are not involved in the design or implementation of early warning systems.
Phenomenon of interest	Experiences of early warning systems from a beneficiary and deliverer/practitioner perspective.	Other phenomena, for example perceptions of disaster risk management in general, risk communication, or resilience.
Design	Any methods used to understand the experiences and perspectives of populations and communities affected by extreme weather or climate hazards. Examples include: • Implementation and process evaluations • Interviews • Surveys	
Evaluation	• Enablers and barriers to the successful implementation of early warning systems. • Experiences and views of populations and communities regarding the usefulness and acceptability of existing early warning systems.	
Research type	Any methods that reflect experiences and perspectives of early warning systems, including, but not limited to: • Phenomenology • Grounded theory • Case studies • Mixed methods studies	

In this review, we define early warning systems as timely and actionable measures put in place to identify, analyse, and warn communities of impending climate- and weather-related hazards (World Meteorological Organisation, 2025). We included early warning systems for the detection and communication of all weather- and climate-related hazards, including, but not limited to, flooding or heavy rainfall, cyclones, storms, tsunamis, wildfires, droughts, heatwaves, sand and dust storms, earthquakes, and volcanic eruptions.

2.5 Publication restrictions

In addition to the criteria above, the following eligibility criteria were applied:

- **Publication date**: studies published from 1990 onwards were considered for inclusion.
- **Geographical coverage**: there were no limits on study location; all eligible studies were included, regardless of country of publication.
- **Language of publication**: We considered all studies for inclusion regardless of their language of publication. However, at the full text screening stage, only eligible studies published in the English language were included due to difficulties with language translation.
- **Publication type**: both peer-reviewed studies and grey literature were considered for inclusion.

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2.6 Information sources

The following databases were searched for studies published from 1990 to January 2026.

- Scopus
- Web of Science
- PubMed
- Engineering Village
- MEDLINE
- Cochrane Library
- Campbell Collaboration's Library

In addition to the database searches, we conducted a search of the following sources for relevant grey literature:

1. **Search engines**: Google and Google Scholar
2. **Organisational websites**:
    a. Global Disaster Preparedness Centre: *https://preparecenter.org/search/*
    b. United Nations Office for Disaster Risk Reduction: *https://www.undrr.org/*
    c. PreventionWeb: *https://www.preventionweb.net/*
    d. World Meteorological Organisation: *https://wmo.int/topics/early-warning-system*
    e. UN Environnement Programme: *https://climate-action-and-early-warning-systems*
    f. Global Disaster Awareness and Coordination Systems: *https://gdacs.org/*
    g. Famine Early Warning Systems Network (FEWS NET): *https://fews.net/*
    h. Climate ADAPT: *https://climate-adapt.eea.europa.eu/en*
    i. Evidence Library of the Lloyd's Register Foundation Global Safety Evidence Centre: *https://www.lrfoundation.org.uk/evidence-library*
    j. ALNAP Help Library: *https://alnap.org/help-library/*

The above websites were selected based on expertise within the review team and discussions with the project consultation group.

1. **Call for evidence and stakeholder engagement**: we published a call for relevant studies on the Foundation website and social media channels, as well as presented the review protocol at relevant conferences to obtain eligible published and unpublished literature. The consultation group were also instrumental in identifying relevant grey literature.
2. We screened the references of relevant systematic reviews, key peer reviewed primary research, and grey literature identified during the searches for any additional eligible studies.

2.7 Search strategy

A comprehensive search strategy was developed to ensure that the literature searches capture both relevant peer-reviewed and grey literature.

One overarching literature search that includes terms related to both the quantitative and qualitative research questions was conducted, after which the inclusion and exclusion criteria relevant to the two sets of questions were applied at the screening stage. An example search in the MEDLINE database is presented in Appendix A. The database searches were conducted from 23 December 2025 to 16 January 2026, website searches were completed on 31 January 2026, and the call for evidence closed on 31st March 2026.

2.8 Search terms

In conducting the database searches, we used a combination of key terms and keywords associated with the intervention (early warning systems), context (extreme weather and climate events) and study designs. This was to ensure we identified relevant quantitative studies for research questions 1-3 and qualitative or mixed methods studies for questions 4 and 5.

Search terms were combined with the Boolean operators 'AND' and 'OR'. The following key terms were used:

1. Search terms related to the intervention (early warning systems), relevant to questions 1-5:

- "Early warning system*"
- "Early warning advi*"
- "System of early warning*"
- "Rapid response system*"
- "Early warning*" or ews or "Early action*"
- "Warning system*"

2. Search terms related to the context (extreme weather and climate events), relevant to questions 1-5:

- "Natural disaster*"
- "Natural hazard*"
- "Climate* related hazard*"
- "Weather* related hazard*" or "Climate*related effect*"
- Flood*
- Cyclone* or hurricane* or typhoon*
- Landslide*
- Storm*
- Tsunami*
- eruption*
- Drought*
- Wildfire*
- heat wave or extreme heat or prolonged heat or heatwave

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3. Search terms related to quantitative design, relevant to questions 1-3:
   - Comparison group*
   - Experiment*
   - Impact*
   - QED or quasi-experimental or quasi-experimental
   - RCT or random or random* control* trial
   - Effect* or affect*
   - longitudinal study
   - Cohort study
4. Search terms related to qualitative design, relevant to questions 4 and 5:
   - Interview* or focus group*
   - Qualitative
   - Questionnaire
   - Survey
   - Process evaluation

2.9 Selection process

Titles and abstracts and full text screening were conducted by three reviewers (EAK, MM, BO), with each paper screened by two reviewers. Conflicts were resolved through discussion among reviewers, and if unresolved, the lead reviewer (EAK) made the final decision.

To expedite literature screening, we used the following as guide:

1. At the title and abstract screening stage, we first looked out for relevant key words related to the intervention (early warning systems). Studies whose abstracts/titles contained 'early warning systems' and another intervention were considered for inclusion. However, we excluded papers whose abstracts/titles focus on interventions other than 'early warning systems'.
2. Where the intervention was not clearly defined in the abstract or title, the paper was put through full text review for a final decision.

The Covidence software (a web-based evidence synthesis collaboration software) was used for deduplication and literature screening.

2.10 Data collection process

A customised extraction template was created in Covidence to conduct data extraction on all five research questions. The extraction template included sections on study details (including the study title, aims/research questions, year of publication, funder, location, design, and type of hazard assessed); the population; intervention; and outcomes or phenomena of interest. There were separate sections for capturing quantitative outcomes and qualitative phenomena of interests.

The Cochrane POGRESS-Plus framework was used as guide for extracting data on equity-related demographic characteristics including place of residence, race/ethnicity/language/culture, occupation, gender/sex, religion, education, socio-economic status, age, and disability. To assess the elements or components of early warning systems, we extracted data on key elements of the early warning system and implementation techniques, where available in the included paper. Due to time constraints, we were unable to review secondary sources (e.g., websites, study protocols, intervention manuals) for missing information on the components of early warning systems.

The extraction template was pilot tested on ten of the included studies, and the template was revised before commencing formal data extraction. Data extraction was done independently by one reviewer (MM, BO, or CO) and checked by another (EAK). Prior to commencing the data extraction process, the lead reviewer (EAK) offered training and answered queries around the extractions. The lead reviewer also provided continuous support to reviewers throughout data extraction and quality-assured all extracted data.

2.11 Data items

Appendix B presents the data items that were extracted to answer research questions 1-5. This includes items on study details, participant characteristics, features of the early warning system, analysis methods, quantitative outcomes and qualitative phenomena of interests, and differential impacts. Studies with insufficient data on relevant outcomes or phenomena of interests were excluded from the review.

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2.12 Data management and processing

Papers identified from the database searches and searching of existing systematic reviews were imported into Covidence for deduplication, literature screening, data extraction and risk of bias assessment.

Papers identified through organisational website searches and the call for evidence were screened in Excel, and eligible papers were then imported into Covidence for data extraction and quality assessment. The Endnote 2025 software was used for reference management.

2.13 Risk of bias assessment

Risk of bias assessment is essential to determine the validity of the results of individual studies and how much they can be trusted. It ensures transparency, directly informs the strength of evidence in systematic reviews, and prevents misleading policy and practice recommendations due to flawed study design or conduct.

In this review, all included studies were critically appraised to assess the quality of the evidence and the viability of conducting meta-analysis of included quantitative studies.

For quasi-experimental studies, we used the Risk of Bias In Non-randomised studies – of Intervention (ROBINS-I) tool (Sterne et al., 2016) to assess risk of bias across domains such as confounding, outcome assessment and participants' selection. The ROBINS-I was also used for other non-randomised studies of intervention, such as longitudinal studies and interrupted time series studies. Randomised controlled trails (RCTs) were critically appraised using the Cochrane Risk of Bias (RoB-2) tool (Sterne et al., 2019). The RoB2 assesses bias across domains such as the process for randomisation, deviations from intended interventions, missing outcome data, measurement of outcomes, and selective reporting.

The Mixed Methods Appraisal Tool (MMAT) domains (Hong et al., 2018) for quantitative non-randomised studies, quantitative descriptive studies, and mixed-methods studies were used to critically appraise studies that use cross-sectional designs, surveys, and mixed methods approaches, respectively. The MMAT is a validated appraisal tool for assessing the methodological quality of a wide range of study designs. The tool includes seven domains each for different study designs including randomised controlled trials, non-randomised studies, quantitative descriptive studies and mixed methods studies. As described previously, the MMAT tool was only used for: a) studies that use cross-sectional designs to assess effectiveness of early warning systems, b) those that employ closed-ended survey questionnaires to assess perceptions, and c) mixed methods studies that combine quantitative surveys and interviews (including one-to-one interviews and/or focus group discussions) for data collection.

The Critical Appraisal Skills Programme (CASP) checklist for qualitative studies was used to assess methodological rigour, transferability, and trustworthiness of included qualitative studies, and the CASP Economic Evaluation checklist was used for appraising studies with cost-benefit analysis.

Risk of bias assessment was conducted independently by one reviewer (MM, BO, or CO) and checked by another (EAK). Discrepancies were resolved through discussion. The RoB-2 and ROBINS-I tools were used to assess risk of bias at the outcome level, and all the other appraisal tools were applied at the study level.

2.14 Effect measures

Due to the heterogeneity (diversity) of outcome metrics, effect measures are reported as presented in the included studies. This includes measures such as Risk Ratio (RR), Incidence Rate Ratio (IRR), Odds Ratio (OR), absolute/mean differences, percent/relative change, correlation coefficients, and economic evaluation metrics (including benefit-cost ratios, financial internal rate of return, and net present value).

2.15 Synthesis methods

In this review, meta-analysis was not viable due to the heterogenous designs of included quantitative studies, differences in populations, and inconsistent outcome measures, and comparators. Therefore, quantitative study findings were synthesised and described narratively, using reporting guidance from the Synthesis Without Meta-analysis (SWiM) guideline (Campbell et al., 2020). The SWiM guideline is a nine-item checklist aimed at promoting transparent reporting of systematic reviews of intervention that employ alternative synthesis methods when meta-analysis of effect estimates is not possible. The checklist covers reporting items, including a description of: 1) the rationale for grouping studies for synthesis, 2) the standardised metric for each outcome, 3) the synthesis methods, 4) the criteria used to prioritise results for summary and synthesis, 5) the methods used to examine heterogeneity in reported effects, 6) the methods used to assess certainty of the synthesis findings, 7) the graphical and tabular methods used to present effects, 8) the synthesised findings and the certainty of findings, and 9) the limitations of the synthesis methods used. The completed SWiM checklist is presented in Appendix C.

Data from each included study was used to produce evidence tables/summary of findings, including an overall description of included studies. Included studies were grouped by hazard type, and results were synthesised by the type of outcome, stratified by study design, type of early warning system, and geographical location of the study. A harvest plot[1] (Ogilvie et al., 2008) was used to display the direction of effects, methodological quality, and overall patterns across included studies that have assessed the differential effects of early warning systems.

1 A harvest plot is a data visualisation matrix used to display synthesis findings from systematic reviews of interventions where standard statistical meta-analysis is inappropriate. It is a useful method for displaying the effects of interventions by incorporating all relevant data.

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Qualitative data was synthesised using thematic synthesis (Braun and Clarke, 2006) and managed in Excel. Qualitative synthesis was conducted inductively by exploring the data to identify key quotes, themes, and insights reported by participants. Findings reported by the papers were analysed using line by line coding and then descriptive (main- and sub-) themes were developed. The themes were then developed into finding statements.

Interim findings were discussed with the project consultation group for feedback, which helped to re-structure reporting of findings, such as categorisation of the different types of disaster early warning systems.

2.16 Reporting bias assessment in the synthesis

As meta-analysis was not performed in this review, publication bias arising due to missing results was assessed by examining asymmetry in the harvest plot pattern. We also ensured a comprehensive literature search process by:

- Including both peer-reviewed and grey literature. Specifically, in addition to academic database searches, we conducted a comprehensive search of organisational websites and put out a call for grey literature.
- Targeting studies published from 1990 in any language.

2.17 Sensitivity analyses/robustness checks

We planned to conduct sensitivity analysis as part of meta-analysis, by removing low-quality studies or those with high risk of bias. However, as meta-analysis was not viable, sensitivity analysis was conducted qualitatively by examining whether the findings remain consistent after removing studies judged to have high risk of bias or low methodological quality.

2.18 Certainty assessment

Certainty of qualitative findings was assessed using the GRADE-CERQual (Confidence in the Evidence from Reviews of Qualitative research) framework. This included assessing the methodological limitations of included qualitative studies, coherence of the findings, adequacy of the data contributing to each finding, and the relevance of included studies to the review findings (Lewin et al., 2018).

The GRADE framework was used to assess confidence in findings from quantitative narrative synthesis, with adaptations where needed. Certainty of the evidence was assessed across six domains (Schünemann et al., 2013):

1. **Risk of bias**: potential flaws in the design or execution of studies that lower confidence. This domain was assessed by examining the proportion of the studies that fall into 'low' or 'moderate' risk of bias ratings using the following as guide: 70% or more low/moderate (no/minor concern), 69%-40% (serious concern), and <40% (very serious concern)
2. **Inconsistency**: unexplained diversity or heterogeneity in the findings across different studies. This domain was only assessed for studies that reported statistically tested findings (i.e., an effect size, confidence interval, and/or an explicit statement of effect). We assessed the proportion of studies that share the single most common direction of effect (i.e., Positive, negative, no effect, or mixed). Where there are 75% or more studies reporting the same direction of effect, we applied a rating of 'no/minor concern'; where there are 74%-50% studies, we applied a rated of 'serious concern'; and for <50% studies, we assigned a rating of 'very serious concern'.
3. **Indirectness**: variations in populations, interventions, or outcomes from those of interest. This was assessed based on the proportion of contributing studies that used a proxy or an indirect outcome measure (e.g., self-reported perception of effectiveness as a proxy for an objectively verified outcome). We applied the following guidance: no/minor concern (for 20% or less contributing studies); serious concern (for 21%-60% studies); and very serious concern (for >60% studies).
4. **Imprecision**: the level of uncertainty of effect estimates, for example, wide confidence intervals or small sample sizes. This domain was assessed based on the total number of contributing studies for an outcome: 10 or more studies (no/minor concern); 5-9 studies (serious concern), and <5 studies (very serious concern).
5. **Publication bias**: assessment of missing data or selective reporting. Due to the heterogeneous designs of included studies, quantitative assessment methods (e.g., funnel plot, Egger's test, trim-an-fill) were not feasible. Therefore, other methods for assessing publication bias were applied, including assessing the comprehensiveness of the search strategy, the spread of included studies' publication year, and assessment of the direction of effect.
6. **Upgrading evidence**: factors that may result in upgrading evidence from observational studies, such as large effect sizes and plausible residual confounding that may increase observational study certainty. In line with the GRADE guidance, evidence from observational studies was started at 'low confidence'.

Certainty of qualitative and quantitative evidence was rated as high, moderate, low, and very low.

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2.19 Equity considerations

This systematic review incorporates the principles of equity throughout – in the design, literature searches, data collection, synthesis, and reporting – guided by the PRISMA-Equity checklist.

As described above, there were no restrictions on geographical location of studies, and our search strategy aimed to capture studies published in all languages. We included eligible peer-reviewed and grey literature, with publication dates of database searches set from 1990 onwards.

Data extraction was guided by the Cochrane PROGRESS-Plus framework, which helped to identify the population/communities targeted by existing early warning systems and the differential effects across different populations, communities, and regions. A harvest plot was used to display findings on the differential effects of existing early warning systems by population characteristics such as age, gender, setting, occupation, and race/ethnicity/language.

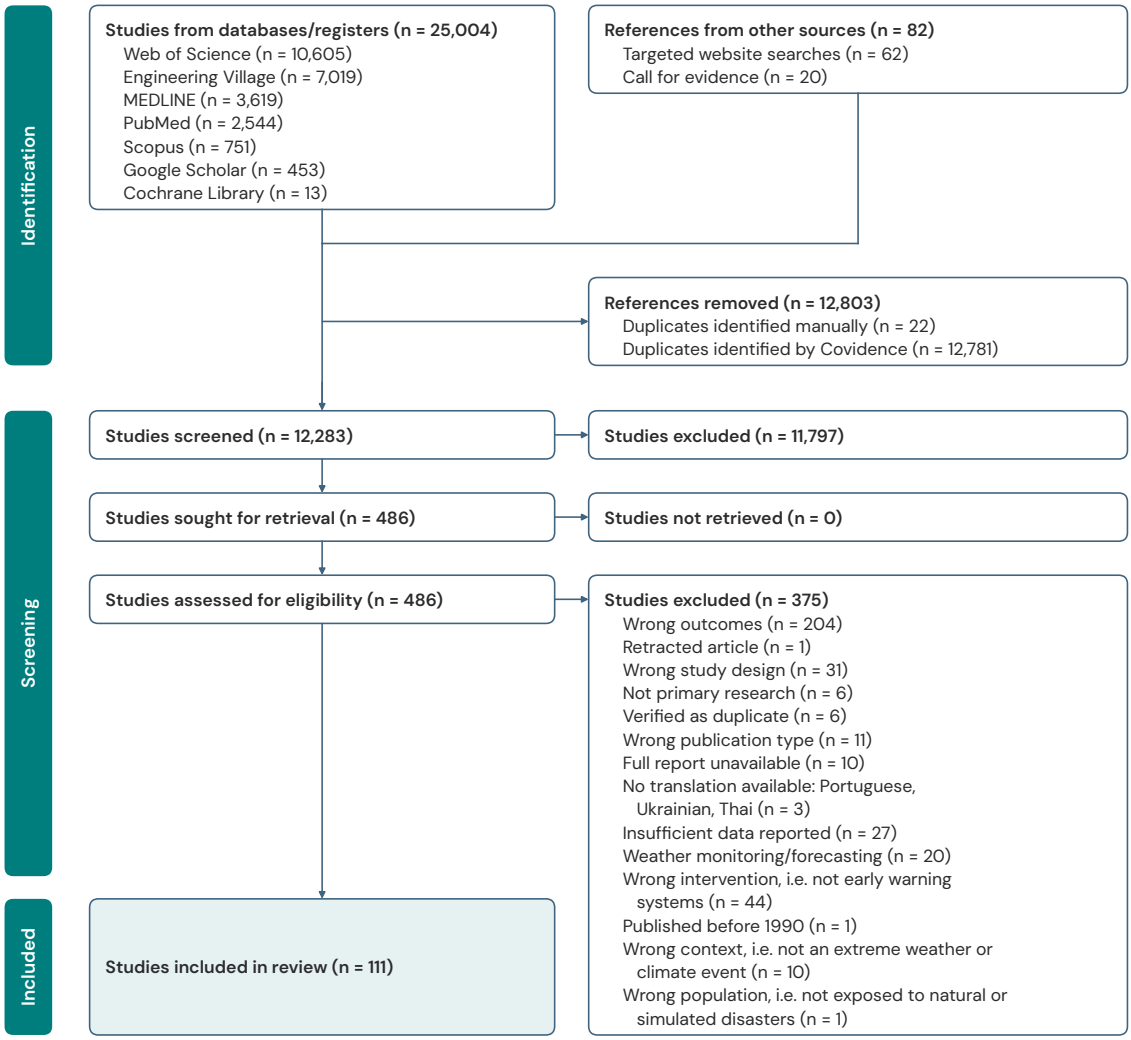
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3. Key findings

3.1 Study selection

The database and grey literature searches (including search of relevant organisational websites and the call for evidence) resulted in a total of 25,086 records. Following deduplication, we screened the titles and abstracts of 12,283 records, of which 11,797 were excluded and 486 were screened at the full text stage. Of the 486 full text reports screened, 375 were excluded for several reasons, the majority of which was related to irrelevant outcomes (n = 204), wrong interventions (n = 44), wrong study designs (n = 31), and insufficient/missing data (n = 27). Three studies were excluded due to unavailable language translators in Portuguese, Thai, and Ukrainian. Following full text screening, a total of 111 eligible studies were included in the review for synthesis. The processes for selecting studies and exclusion reasons are presented in Figure 1 (PRISMA flow diagram).

Figure 1. PRISMA flow diagram



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3.2 Characteristics of included studies

Of the 111 included studies, 55 provided evidence to answer quantitative research questions 1-3, 78 studies provided evidence on qualitative research questions 4 and 5, and 22 studies had evidence on both quantitative and qualitative research questions. An overview of the included studies for research questions 1-3 and research questions 4&5 can be found in Appendices E and F, respectively.

Sample size of included studies

Sample sizes of included studies ranged very widely, from 3 to 4,000,000, mainly driven by six large-scale studies that draw on population-level administrative data, survey population data, and social media user data. These include: 1) 4,000,000 twitter users (Chatfield et al., 2013), 2) 3,207,260 households flood-warning survey conducted in Thailand (Prathumchai and Bhula-or, 2020), 3) 1,731,269 all-cause deaths data obtained from 15 German cities (Feldbusch et al., 2025), 4) 1,555,006 users of a smartphone earthquake-detection app (Allen et al., 2025), 5) 1,549,376 birth records used in a Korean yellow dust exposure study (Altindag et al., 2017), and 6) 104,346 non-accidental deaths population-level data used for a heat health warning impact evaluation (Chen et al., 2023). The remaining studies were small to moderate scale, with sample sizes ranging from 3 to 50,002 (median = 146; Interquartile range = 77-569). Table 3 below presents a breakdown of sample size by studies that addressed research questions 1-3 and questions 4&5, as well as studies addressing questions from each group.

Table 3. Sample size of included studies

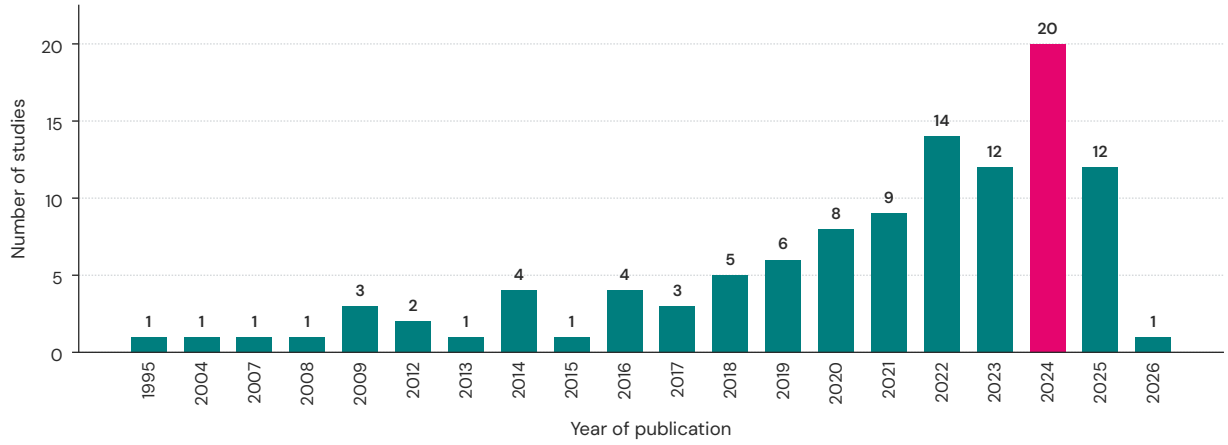
Group	Studies (n)	Range (min–max)	Median
All included studies	111	3–4,000,000	217
Studies providing evidence for questions 1-3	55	8–4,000,000	427
Studies providing evidence for questions 4&5	78	3–1,555,006	116
Studies addressing questions from each group	22	44–1,555,006	261

***Note**: Studies addressing questions from each group are also included within the qualitative and quantitative rows. Median is used instead of the mean as a small number of studies (six studies) report very large sample sizes that would otherwise dominate an average.*

Year of publication of included studies

The included studies were published between 1995 and 2026, with the majority of them (n = 76) published from 2020 onwards, and 2024 recording the most publications (see Figure 2).

Figure 2. Year of publication of included studies



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Type of publication and study design

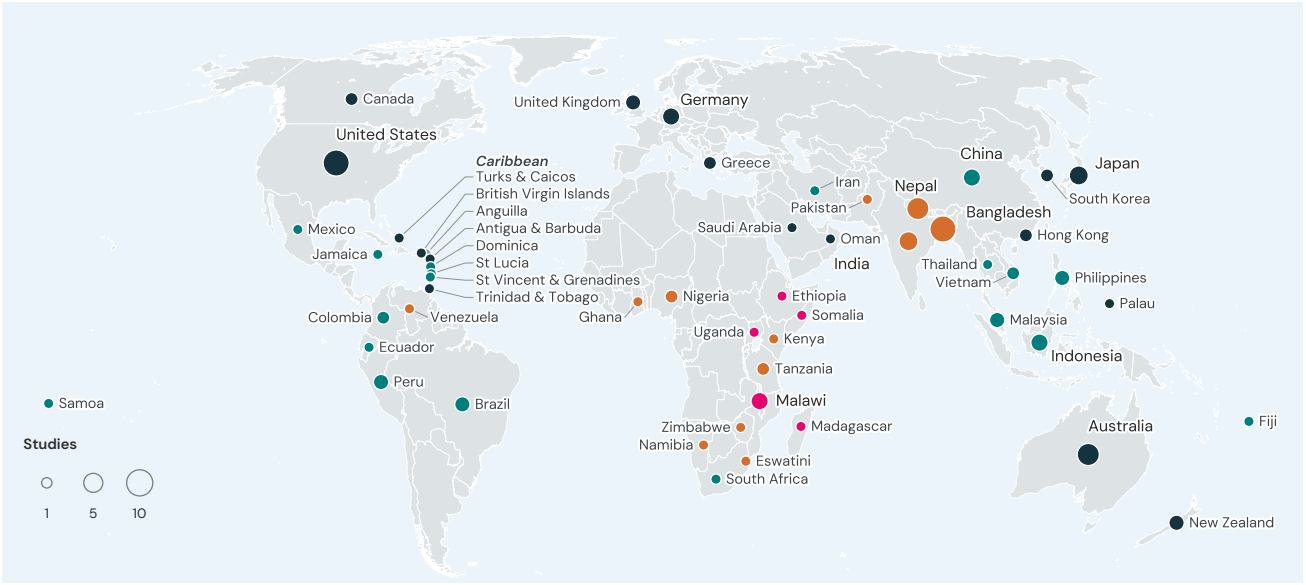
Of the 111 included studies, there were 90 peer-reviewed journal articles, 18 grey literature reports, two book chapters, and one conference paper. Most of the studies (n = 88) used designs that are best suited for exploring perceptions, experiences and associations rather than evaluating the causal impact of early warning systems. The majority of the studies used a cross-sectional/survey-based design (n = 34), followed by qualitative research (n = 31) and mixed methods designs (n = 24). Studies designed to test cause-and-effect were only few, with 11 quasi-experimental studies, one longitudinal study, two ecological studies, and one randomised controlled trial. There was also one simulation-based study, and six economic evaluations.

Study location

The included studies span 54 distinct countries, with 8 studies originating from multiple countries. The most represented countries include the United States (n = 10), Bangladesh (n = 10), Australia (n = 7), Nepal (n = 7), Japan (n = 5), China (n = 4), India (n = 4), Indonesia (n = 4), and Malawi (n = 4), with one study covering 98 countries globally.

When categorised by World Bank income level (World Bank, 2026), included studies were evenly distributed between middle-income and high-income economies, with a much smaller number from low-income countries. In particular, methodologically robust quantitative studies were more focused in high-income countries compared to qualitative studies, which mostly originated from lower-middle and low-income countries. Thus, evidence on the effectiveness of early warning systems from low-resource settings was more limited compared with evidence on implementation of early warning systems, which mostly originated from those settings. Figure 3 presents the geographic distribution of included studies, showing the countries in which studies were conducted and the World Bank income group of the countries.

Figure 3. Geographic distribution of included studies



High income 17 countries

United States	10
Australia	7
Japan	5
Germany	4
New Zealand	3
United Kingdom	3
Canada	2
Greece	2
Hong Kong	2
South Korea	2
Antigua and Barbuda	1
British Virgin Islands	1
Oman	1
Palau	1
Saudi Arabia	1
Trinidad and Tobago	1
Turks and Caicos Islands	1

Upper-middle income 19 countries

China	4
Indonesia	4
Brazil	3
Malaysia	3
Peru	3
Philippines	3
Colombia	2
Vietnam	2
Dominica	1
Ecuador	1
Fiji	1
Iran	1
Jamaica	1
Mexico	1
Samoa	1
South Africa	1
St Lucia	1
St Vincent & Grenadines	1
Thailand	1

Lower-middle income 12 countries

Bangladesh	10
Nepal	7
India	5
Nigeria	2
Tanzania	2
Eswatini	1
Ghana	1
Kenya	1
Namibia	1
Pakistan	1
Venezuela	1
Zimbabwe	1

Low income 5 countries

Malawi	4
Ethiopia	1
Madagascar	1
Somalia	1
Uganda	1

Not classified 1 territory

Anguilla	1

***Note**: 54 countries and territories from 111 studies; bubble size and the bars show the number of studies in each. Studies conducted in more than one country are counted once for each country. Income groups follow the World Bank FY2027 classification; Anguilla is not classified.*

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Hazard type

Hazard types researched in included studies were grouped based on the hazard classification profile recommended by the United Nations Office for Disaster Risk Reduction, and the International Science Council (UNDRR-ISC, 2025). Across included studies, the most studied hazard type was hydrometeorological (n = 87), followed by geological (n = 28), environmental (n = 4), and biological hazards (n = 1). Table 4 shows the different types of hazards that were reported in included studies.

Table 4. Hazard type by study

UNDRR-ISC hazard category	Studies	Includes
Hydrometeorological	87	Flood/heavy rain, hurricane/cyclone/typhoon, drought, extreme heat, storm, tornado, cold/snow, yellow dust
Geological	29	Earthquake, tsunami, landslide, volcanic activity
Environmental	4	Wildfire
Biological	1	Locust invasion (alongside other hazards in the same study)
Multi-hazard (not attributable to a single category)	1	Study describes a multi-hazard programme without specifying individual hazards

Across hydrometeorological hazards, flooding/heavy rain was the most researched hazard (n=55), followed by hurricane, cyclone or typhoons (n = 30), and extreme heat/heatwave (n = 21). Of the studies focusing on geological hazards, earthquake (n = 24), landslide (n = 11), and tsunamis (n = 4) were the most studied. Several of the included studies researched more than one hazard type. Table 5 shows the different hazards researched and the countries in which they were studied.

Table 5. Hazard type by country

Hazard type	Studies	Number of Countries	Countries studied (with study count where >1)
Flooding or heavy rains	55	31	Nepal (7), Bangladesh (6), Malawi (3), Malaysia (3), Philippines (3), United Kingdom (3), Australia (2), Brazil (2), Germany (2), Tanzania (2), Viet Nam (2), Colombia, Ghana, Greece, India, Jamaica, Japan, Kenya, Madagascar, Namibia, Nigeria, Pakistan, Peru, Saudi Arabia, Somalia, South Africa, St. Lucia, St. Vincent and the Grenadines, Thailand, Trinidad and Tobago, Zimbabwe
Hurricane, cyclones or typhoons	30	22	India (4), Bangladesh (3), Malawi (3), Viet Nam (2), Anguilla, Antigua and Barbuda, British Virgin Islands, China, Dominica, Jamaica, Madagascar, Oman, Palau, Philippines, Samoa, Somalia, St. Lucia, St. Vincent and the Grenadines, Tanzania, Trinidad and Tobago, Turks and Caicos Islands, Zimbabwe
Extreme heat (heatwave)	21	14	Australia (3), United States (3), Canada (2), China (2), Germany (2), Brazil, Hong Kong SAR, China, India, Korea, Rep., Madagascar, Malawi, Nigeria, Tanzania, Zimbabwe
Earthquake	24	15	United States (5), Japan (4), New Zealand (2), Peru (2), Brazil, Colombia, Ecuador, Indonesia, Jamaica, Mexico, Philippines, St. Lucia, St. Vincent and the Grenadines, Trinidad and Tobago, Venezuela, RB
Drought	17	16	Australia (2), Brazil, China, Eswatini, Ethiopia, Iran, Islamic Rep., Jamaica, Madagascar, Malawi, Somalia, St. Lucia, St. Vincent and the Grenadines, Tanzania, Trinidad and Tobago, Uganda, Zimbabwe
Tsunami	7	4	Indonesia (4), Greece, Japan, United States
Landslide	11	10	Brazil (2), Bangladesh, Hong Kong SAR, China, Indonesia, Jamaica, Philippines, St. Lucia, St. Vincent and the Grenadines, Trinidad and Tobago, Viet Nam
Wildfire	4	3	Australia (2), Philippines, United States
Yellow dust	1	1	Korea

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Funding landscape of early warning systems research

Funding source of early warning systems research was reported in 79 of the 111 included studies. Funding sources varied across the 79 studies, with government and national research funding agencies emerging as the most common funders (n = 29), followed by university/academic funding agencies (n = 20), and international organisations (e.g., World Bank, United Nations, the European Union) (n = 14).

When we looked at the breakdown of government/national research funding agencies, the United Kingdom (UK) government – through the Foreign, Commonwealth, and Development Office (FCDO), UK Aid, and UK Research and Innovation (UKRI) – provided the most funding by a slight margin (n = 6), followed by the US National Science Foundation (n = 4), the Chinese National Science/Research Funding (n = 4), and New Zealand research funders (n = 4). Appendix D presents more details on the funding source reported in included studies.

3.3 Risk of bias in studies

Risk of bias of the included studies was conducted to inform understanding of the strength of evidence, as well as to inform assessment of the confidence in the evidence using GRADE and GRADE-CERQual.

In all, seven critical appraisal tools were used for risk of bias assessment due to the diverse nature of study designs in this review. The Cochrane RoB-2 tool was applied to the only randomised controlled trial study in this review (Mehiriz et al., 2018), and this resulted in an overall rating of 'some concerns'. This was mainly due to lack of a pre-specified analysis plan, resulting in a rating of 'some concerns' for domain 5 (selection of the reported results) of the appraisal tool.

Fifteen (15) of the included studies were critically appraised using the ROBINS-I, with the majority showing a rating of low-to-moderate risk of bias and a few with serious-to-critical risk of bias ratings. Specifically, there were four studies rated as 'low risk except for concerns about confounding', eight studies with moderate risk of bias, two with serious risk of bias, and one with critical risk of bias.

The CASP qualitative tool was used for appraising 31 included studies, with most of the studies showing strong methodological quality. In all, 27 of the 31 studies were rated positive/methodologically sound and the remaining four were rated negative /relatively poor methodologically. The rationale for a 'low quality' rating of qualitative studies primarily included lack of ethical considerations; no or unclear description of the target population, sample size, analysis plan and researcher reflexibility/positionality.

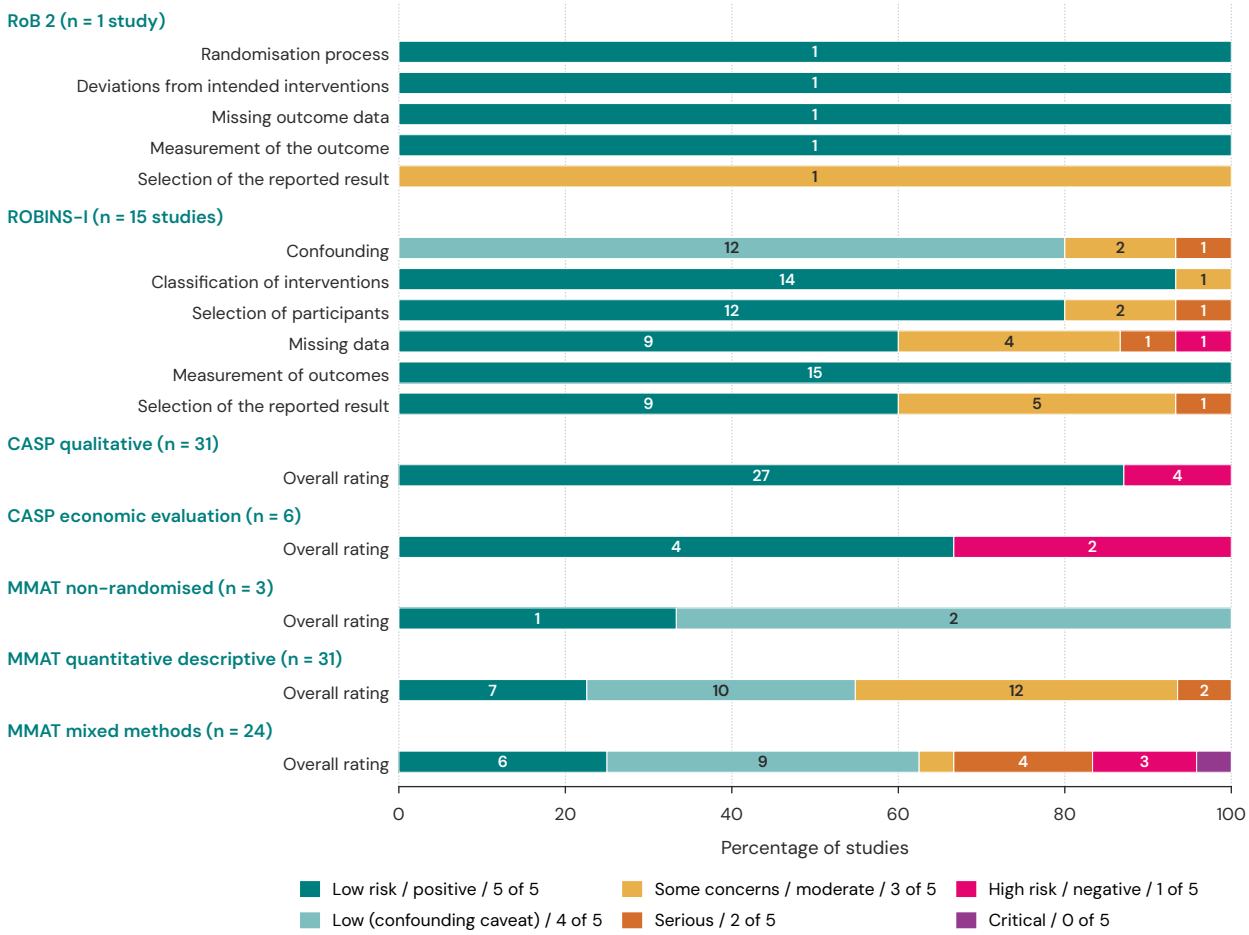
Included economic evaluations (n = 6 studies) were critically appraised using the CASP framework for Economic Evaluations. The results show that four of the six studies were positive/methodologically sound, and the remaining two were negative/relatively poor methodologically, with methodological weaknesses primarily clustered around analytical rigour.

The MMAT checklists were applied to three non-randomised studies, 31 quantitative descriptive studies, and 24 mixed methods studies. Across the three non-randomised studies, appraisal scores ranged between 4/5 and 5/5, and twenty-nine (29) of the 31 quantitative descriptive studies met three of five MMAT criteria, indicating high numbers of methodologically sound non-randomised and quantitative descriptive studies. Mixed methods studies, on the other hand, were more variable in quality, with a considerable number showing significant methodological limitations related to how well the qualitative and quantitative components were integrated and how well divergencies were addressed. Of the 24 mixed methods studies, six met all five MMAT criteria, nine met four of the criteria and eight met two of the assessment criteria.

Figure 4 below shows the distribution of risk of bias ratings by the various appraisal tools used in this review. Appendices G-K show the risk of bias ratings for each of the included studies by the different appraisal tools used.

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Figure 4. Distribution of risk of bias ratings by appraisal tool



Note: RoB-2 and ROBINS-I rating shown by domain; other appraisal tools show overall rating

3.4 Findings from evaluation of early warning systems

This section addresses the following research questions (RQs):

RQ1. What works and for whom: What is the effectiveness of early warning systems in reducing the impact of extreme weather- and climate-related events?

RQ1a What are the different types of early warning systems that have been used to reduce the impact of extreme weather- and climate-related events?

RQ1b. What is the effectiveness of different types of early warning systems in reducing the impact of extreme weather- and climate-related events?

RQ1c. What are the demographics and characteristics of communities served by these early warning systems? Which early warning systems are more or less effective for different populations, communities, and regions?

RQ2. How: What elements or components of these early warning systems are associated with reductions in loss of life and assets?

RQ3. At what cost: What is the cost-effectiveness of adopting early warning systems for reducing the impact of extreme weather- and climate-related events?

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RQ1a. What different types of early warning systems have been evaluated?

In addition to categorising the included early warning systems by hazard type (see previous section on 'Characteristics of included studies'), the different types of early warning systems that were evaluated in included studies have been categorised by the level at which the system was operated, using guidance from UN-SPIDER[1]:

- **Community/people-centred early warning systems**: warning systems operated at a local level by community members or municipal governments.
- **National early warning systems**: operated at the national level by government agencies such as a meteorological department, a geological observatory, an agricultural or a health ministry.
- **Regional early warning systems**: operated at a more regional level, for example, the Famine Early Warning System Network (FEWSBNET) that is operated in various regions within the United States.
- **Global early warning systems**: operated at the international level by international organisations such as the Food and Agricultural Organisation (FAO) and the World Health Organisation (WHO).

Of the 111 included studies, the majority (n = 83) examined a national-level early warning system. This was typically run by a national hydrological, meteorological or disaster management department. Community/local early warning systems accounted for 17 of the included studies, most of which were community-based flood early warning systems and were mostly evaluated in Southern/East Africa and South/Southeast Asia. There were only six studies that examined a regional early warning system, and five evaluated a global system – all of which focused on evaluating a crowdsourced smartphone earthquake-detection network (for example, the Earthquake Network app, and the Android Earthquake Alert system).

When we looked at the hazard types covered by the different early warning systems, we found two clear patterns across included studies. First, nationally operated early warning systems have been applied across all hazard categories reported in this review, and hydrometeorological hazards (65 of the 86 studies that researched hydrometeorological hazards) were covered by most nationally operated systems. Secondly, all globally operated systems evaluated in this review focused on earthquake early warning systems, and regional systems only covered hydrometeorological (n = 5) and geological hazards (n = 3). Table 6 presents the hazard type by operational level, and Appendix L shows the different types of early warning systems that were evaluated in included studies and their operational level.

Table 6. Hazard type by operational level of early warning systems

Hazard type	Community/local	National	Regional	Global
Hydrometeorological	16	65	5	0
Geological	3	17	3	5
Forest fires	1	3	0	0
Health	0	1	0	0
Biological	0	0	1	0
Multi-hazard (unspecified)	0	0	1	0
Total (hazards)	20	86	10	5
Actual studies at this level	17	83	6	5

In terms of the settings where these early warning systems were implemented, national-level systems (n = 83) were evenly distributed across country income groups, with 43% of them implemented in high-income countries, 28% in lower-middle income countries, and 25% in upper middle-income countries.

Community/locally operated early warning systems skewed clearly toward lower-income settings, with 15 of the 17 studies implemented in lower-middle or low-income countries and only two studies conducted in high-income countries. Regionally operated systems were mainly implemented in the Caribbean and small island states (Anguilla, Antigua and Barbuda, British Virgin Islands, Turks and Caicos), and Southern African countries (Madagascar, Malawi, Zimbabwe) through donor-funded programmes. Globally-implemented systems spanned high-income (New Zealand) to upper middle-income countries – including Ecuador, Colombia, and Peru.

1 See UN-SPIDER early warning systems classification here: *https://un-spider.org/risks-and-disasters/early-warning-systems#no-back*

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RQ1b. What is the effectiveness of different types of early warning systems in reducing the impact of extreme weather- and climate-related events?

Findings on effectiveness have been grouped by outcome (mortality, morbidity, loss of assets, loss of livelihood) and performance metric (timely issuance of alerts and accuracy of alerts), and within each of these, by hazard type and the operational level of the early warning system (community/local, national, regional, global). Findings are reported using the vote counting method – in line with guidance from SWiM (Campbell et al., 2020) – based on the direction of effect. Effectiveness results for a given outcome are grouped into one of four categories:

- **Positive effect**: results showing that the early warning system was associated with improved outcome.
- **Negative effect**: results showing that the early warning system was associated with an undesirable outcome than the comparator.
- **No effect**: the study found no difference between groups that received early warning (i.e., the intervention group) and those that did not (i.e., the comparator).
- **Mixed effect**: positive, negative and/or no effect results reported across sub-groups, sub-analysis, or multiple measures within the same outcome.

Consistent with guidance from the Cochrane handbook for systematic reviews of interventions (Schünemann et al., 2019), throughout this section, we have not used thresholds for P values or described findings as 'statistically significant' or 'not significant'. Rather, we have reported effect estimates alongside confidence intervals, where available. Where P values are presented alongside effect estimates, only the exact values are reported.

Confidence in the evidence is assessed and reported for each outcome based on the GRADE framework.

Effectiveness by hazard type

Effect on mortality

The impact of early warning systems on mortality outcomes was evaluated in 18 of the included studies, of which eight reported statistically tested findings (including an effect size, confidence interval, and/or an explicit statement of effect), while 10 studies used descriptive approaches. Of the eight studies that reported statistically tested findings, two (Escalera and Register, 2008; and Song and Li, 2024) were rated critical and serious risk of bias, respectively. This was due to inadequate classification of the intervention, missing data, and bias in the selection of the reported results. The remaining studies were rated low to moderate risk of bias. Table 7 provides a summary of the direction of effect of the eight studies that tested findings statistically.

Table 7. Summary of findings (showing the direction of effect) for studies that evaluated the effect on mortality

Hazard type	Studies	Positive effect	Negative effect	No effect	Mixed effect
Flooding	1	0	0	1	0
Cyclone/hurricane/typhoon	1	0	0	1	0
Extreme heat	4	0	0	2	2
Tsunami	1	1	0	0	0

Extreme heat

Extreme heat was researched in four of the included studies that reported on mortality outcomes, with effectiveness spanning mixed (n = 2) and no effect (n = 2). Study designs used for evaluating effectiveness include ecological design, quasi-experimental design (difference-in-difference approach), case-crossover, mixed methods, and longitudinal study designs.

In an ecological before-and-after study comparing two extreme heat events in Adelaide, Australia, Nitschke et al. (2016) found that the heat warning system was not associated with reduction in deaths, with about 3.7 extra deaths (p=0.04) reported in 2014 when the early warning system was implemented (Incidence Rate Ratio (IRR) = 1.01; 0.86-1.17; 95% Confidence Interval (CI) -45.3-52.6), compared to the pre-warning system in 2009 (IRR = 1.11, 95% CI 1.00-1.24). However, there are internal inconsistencies in the reported observed deaths: the 2009 daily reported heatwave-related average deaths of 28.6 recorded over 13 days implies a total of about 372 deaths (i.e., 28.6 x 13), which is more than the observed deaths of 364 (i.e., 28.0 deaths x 13 days) recorded post-implementation of the early warning systems. Therefore, this finding needs to be interpreted with caution.

Weinberger et al. (2018) reported mixed effects of a heat warning system implemented in 20 cities in the United States, with findings showing that extreme heat alerts were not associated with lower deaths overall (- 0.5% change in rate, 95% CI -2.8 to 1.9). However, there was a significant reduction in heat-related deaths specifically in Philadelphia – one of the implementing cities (4.4% lower deaths, 95% CI -8.3 to -0.3). In a study conducted in Germany, Heudorf and Schade (2014) found significant excess deaths during the 2010 heatwave (22.7% more deaths, p<0.01). However, they found an increase in heat-related deaths during the 2006 (mean death = 20.6 deaths/day; excess mortality = 4%) and the 2013 heatwaves (mean deaths = 19.1 deaths/day; excess mortality = 12%) compared to baseline. In older adults aged 80 years old and over, the findings show significant excess deaths in both the 2006 (33.3% excess mortality) and 2010 (37.6% excess) heatwaves, and a decrease (-15.3%) in excess mortality during the 2013 heatwave for that age group.

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Ebi et al. (2004) evaluated a heat warning system in Philadelphia and reported an estimated 2.6 lives saved per warning day (p = 0.08).

Flooding/heavy rains, tsunami, and typhoon

For flooding/heavy rains, a mixed methods study conducted in Malawi by the Global Disaster Preparedness Centre (GDPC) found a positive effect on mortality (p = 0.358), with 97.1% of households reporting no flood-related deaths.

Escaleras and Register (2008) analysed 146 tsunami events that occurred globally (including data from Asia, the Americas, Africa and Europe) between 1966 and 2004 and found that issuing a tsunami early warning was associated with significantly fewer deaths (15.3% mortality reduction; warning coefficient = -2.24, Standard Error = 0.665, p = 0.05). In a longitudinal study conducted in China by Song and Li (2024), the authors reported no significant effect of a rural typhoon loudspeaker early warning system on mortality.

Table 8 below provides a summary of the 10 studies that reported on mortality but without a formal statistical test.

Table 8. Summary of studies with descriptive findings on the effect of early warning systems on mortality outcomes

Study	Hazard	Setting	Findings (not statistically tested)
Agyei 2020	Flooding	Philippines	0.30 (out of 1) reduction in mortality.
Chau 2009	Extreme heat	Hong Kong	Days with VHWW: Number of deaths from IHD per day: 5.5 Number of deaths from Stroke per day: 6.4 (excludes outliers)
Feldbusch 2025	Extreme heat	Germany	Pre-HHWS (1993–2004): median 31.1 all-cause deaths/day on eligible hot days (IQR 17.0–31.0). Post-HHWS (2005–2020): median 30.5 deaths/day (IQR 18.0–33.0), despite more eligible hot days per year (143.5 vs 111.6).
Hasan 2024	Flooding	Bangladesh	Composite mortality-reduction effectiveness score: 0.5 (Kaijuri, weighted 0.167) and 0.3 (Thutia, weighted 0.100). Sub-score specifically for timing of the message: 0.434 (Kaijuri), 0.167 (Thutia).
Heo 2019	Extreme heat	Korea	[Mean mortality on true heat-wave days] = 3.752 deaths/day
Huy 2009	Flooding	Vietnam	1985 typhoon (pre-EWS): 14 deaths; 2006 typhoon (post-EWS): 2 deaths (fishermen at sea)
Norkhairi 2022	Flooding	Malaysia	Simulation: no warning ~13,500 fatalities (~90% of population at risk); fatalities fall with earlier/faster siren activation, from ~8,000 (siren at breach, 60-min delay) to 0 fatalities with a siren activated 2+ hours before breach and under a 60-min delay.
Rai 2020	Flooding	Nepal	93% of respondents stated a preference for mortality reduction. Annual WTP per household: NPR 123.70 (USD 1.14). Total annual WTP across all beneficiary households: NPR 1,088,038 (USD 10,074).
Ringo 2024	Flooding	Tanzania	65.59% agreed and 26.88% strongly agreed that their response actions to flood warnings helped reduce human deaths (mean 4.13/5, SD 0.76); 3.49% neutral, 4.03% disagreed or strongly disagreed.
Wu 2020	Extreme heat	China (Shanghai)	58.2% of heat-related deaths in Shanghai occurred on days with no heat warning in place; 41.7% occurred on warning days. 66.7% of heat-related deaths occurred in the summers of 2014 and 2015.

***Confidence in the evidence on mortality reduction*: Low** due to inconsistency in the reported effects (see the full ratings in Appendix M)

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Effect on morbidity

Morbidity outcomes were assessed in nine studies, of which five reported statistically tested findings (including an effect size, confidence interval, or an explicit statement of effect), and four provided descriptive summaries of effect. Of the five studies with statistically tested findings, one (Song and Li, 2024) was rated serious risk of bias due to inadequate classification of the interventions and missing data. The remaining studies were rated low to moderate risk of bias. Table 9 provides a summary of the direction of effect of the five studies.

Table 9. Summary of findings (showing the direction of effect) for studies that evaluated the effect on morbidity

Hazard type	Studies	Positive effect	Negative effect	No effect	Mixed effect
Flooding	1	0	0	1	0
Cyclone/hurricane/typhoon	1	1	0	0	0
Extreme heat	3	0	0	1	2

Extreme heat

Extreme heat was covered in three of the five studies (Nitschke et al., 2016, Mehiriz et al., 2018, Clemens et al., 2022), with study designs including a randomised controlled trial, an ecological study design, and an interrupted time series. Two studies (Nitschke et al., 2016, Mehiriz et al., 2018) found mixed effect of heat early warnings and one study (Clemens et al., 2022) reported no effect.

In an ecological study conducted in Australia, Nitschke et al. (2016) found a significant reduction in cardiac-related ambulance call-outs (IRR = 0.46, 95% CI 0.36-0.60) but reported an increase in total ambulance call-outs (IRR = 1.05, 95% CI 0.99-1.12, p = 0.04) during the same extreme heat period. Mehiriz et al. (2018) evaluated the effect of an automated phone heat warning system in Canada using a randomised controlled trial design and found no change in heat-related symptoms (p = 0.60) or overall health care use (p = 0.48). However, a sub-group analysis revealed that among women with chronic illness, those who received the automated heat health advisory phone call were significantly less likely (54% less likely, p = 0.04) to use health services (such as emergency services) during extreme heat.

Clemens et al. (2022) conducted an interrupted time-series of emergency department visits during extreme heat events from 2012 to 2018 and found no significant change in the rate of visits following implementation of the harmonised heat warning and information system (rate of change = 0.04; 95%CI -0.03 to 0.10, p = 0.278).

Typhoon and Flooding/heavy rains

For Typhoons, Song and Li (2024) found that the rural loudspeaker early warning system was significantly associated with fewer injuries/illnesses (IRR = 0.97, p = 0.000). They reported that for every 1 percentage-point increase in loudspeaker early warning system coverage, there was a 3% reduction in typhoon-related injuries, showing the importance of the loudspeaker system as a tool for warning communities and promoting protective behaviours during typhoon events.

The flood early warning system evaluated in Malawi (GDPC, 2025) showed a difference in household injuries among those who took early action (mean injuries = 0.08 per household, SD = 0.294) and those that did not take early action (mean injuries = 0.13 per household, SD = 0.426, p = 0.167).

Table 10 provides a summary of the four studies that reported descriptive evidence on the effect of early warning systems on morbidity outcomes.

Table 10. Summary of studies with descriptive findings on the effect of early warning systems on morbidity outcomes

Study	Hazard	Setting	Findings (not statistically tested)
Agyei 2020	Flooding	Philippines	0.30 (out of 1) reduction in injuries/illnesses. Note: Likert scale rating converted to a 0-1 ratio
Ringo 2024	Flooding	Tanzania	75.41% agreed and 19.46% strongly agreed that their response actions to flood warnings helped reduce injuries (mean 4.10/5, SD 0.64); 2.70% neutral, 2.43% disagreed or strongly disagreed.
Williams 2022	Extreme heat	Australia	Estimated cost savings (derived from Nitschke 2016's reported morbidity reductions, 2014 heatwave, 9-day HHWS activation): 297 fewer ambulance call-outs (~$310,000 saved), 119 fewer renal admissions (~$643,000), 141 fewer heat-related admissions (~$750,000), 279 fewer ED presentations (~$302,000). Total estimated savings: AU$1,498,000–2,513,000.

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Study	Hazard	Setting	Findings (not statistically tested)
Wu 2020	Extreme heat	China (Shanghai)	50% of heat-related illnesses in Shanghai occurred on days with no heat warning in place. Warning coverage varied by source: NOAA warnings covered 96.4% of illness records versus 29.5% for the GB (national) system. 60.5% of illnesses occurred in the summers of 2014 and 2015.

***Confidence in the evidence on morbidity reduction*: Very Low** due to inconsistency in the reported effects and imprecision (small evidence base). See the full GRADE ratings in Appendix N.

Effect on loss of livelihoods

Loss of livelihood was examined in only one of the included studies (Hasan and Islam, 2024), and this was not statistically tested (see description below).

Flooding/heavy rains

Hasan and Islam (2024) conducted an evaluation of the flood early warning system in two communities (Kaijuri and Thutia) in Bangladesh, using community members' ratings of the effectiveness of the early warning system in reducing crop and livestock damage. Ratings were done on a 0-1 multi-criteria analysis scale, running from 'not effective' to 'extremely effective', with Kaijuri's flood early warning system rated 0.3 (moderately effective) and Thutia's rated 0.1 (not effective).

***Confidence in the evidence on loss of livelihoods*: Very low** due to inconsistency (descriptive assessment of effectiveness), indirectness (study uses a proxy measure for loss of livelihood), and imprecision (very small evidence base). See Appendix O for the full GRADE ratings.

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Effect on loss of assets

Fourteen (14) of the included studies addressed loss of assets, of which five reported statistically tested findings (see Table 11 below) and nine provided descriptive summaries of effectiveness. Of the five studies that reported statistically tested findings, one (Song and Li, 2024) was rated serious risk of bias, and the remaining had low to moderate risk of bias ratings.

Table 11. Summary of findings (showing the direction of effect) for studies that evaluated effect of early warning systems on loss of assets

Hazard type	Studies	Positive effect	Negative effect	No effect	Mixed effect
Flooding	2	2	0	0	0
Cyclone/hurricane/typhoon	2	0	1	1	0
Drought	1	0	0	0	1

Flooding/heavy rains

Flooding/heavy rains was covered by two quasi-experimental studies (Kreibich et al., 2021, Aguirre et al., 2019) that evaluated impact on loss of assets, and both studies reported positive effects of flood early warning systems.

Kreibich et al. (2021) evaluated a flood early warning system in Germany and found a significant reduction in loss of assets when households received one hour or more warning lead time and knew what protective actions to take. The authors found a 4% reduction in building content loss (€3,800 less absolute building content loss) and a 2% reduction in house damages (€10,000 less absolute building loss) following implementation of the warning system.

Aguirre et al. (2019) evaluated an anticipatory (early) action programme ahead of a flooding event in Peru and assessed the programme's effectiveness in reducing damage to houses. The findings revealed that households that participated in the programme were significantly less likely to have damaged houses, with 72.6% of them reporting no damages compared with 21% of the control group (i.e., households that did not participate in the early action programme).

Cyclone, typhoon and drought

For typhoon, Song and Li (2024) found that rural loudspeaker warning systems were effective at informing individuals and promoting the adoption of protective behaviours. However, for fixed assets such as houses, there was no differences in losses following implementation of the rural loudspeaker warning system (IRR = 1.004)., The authors found that the extent of house damage was more correlated with the severity of the typhoon warning signal level, with all four signal levels reported to be associated with damages (i.e., Extreme signal level: IRR = 1.57; Severe IRR = 1.25; Moderate signal: IRR = 1.20; Minor signal: IRR = 1.35). The extreme level warning was found to be associated with 20% more house damages.

Sahana et al. (2023)'s evaluation of a cyclone early warning system in India found improvement in preparedness for cyclones following the Aila cyclone of 2009 when the early warning system was introduced. However, the findings show that subsequent cyclone events, including Komen (2015), Fani (2019) and Bulbul (2019), resulted in substantial losses among the households surveyed. Almost 39% of households had lost all or some of their assets during cyclone-induced flooding, with more than 60% reporting loss of livestock, and 87.7% experiencing at least one home damage over the past decade. The authors assessed the impact of warning source and warning lead time on losses and found that households that received early warning messages through relatives, neighbours and the village assembly (rather than through radio, newspaper, or TV) had significantly worse outcomes across every loss category, including a) house damages (village assembly: coefficient (B) = 0.497, Standard Error (SE) = 0.192; relatives: B = 0.247, SE = 0.247, SE 0.196; neighbours: B = 0.263, SE = 0.181); b) livestock deaths (village assembly: B = 0.946, SE = 0.435; relatives: B = 1.508, SE = 0.513; neighbours: B = 1.241, SE = 0.410); and c) land losses (village assembly: B = 0.582, SE = 0.159; relatives: B = 0.887, SE = 0.215; neighbours: B = 0.452, SE = 0.140). The findings show that most of the surveyed households mainly received early warning information through word of mouth – from neighbours, the village assembly, and relatives. Therefore, it is unsurprising that there were substantial losses associated with the cyclone event.

For drought, Tang et al. (2023) evaluated a drought early warning system among pastoral herder households in China, to assess its impact on economic losses. The authors found that receiving the cyclone early warning was associated with a lower probability of households experiencing any economic losses at all (B = -0.051, SE = 0.131). However, receipt of the early warning was found to be associated with reduction in the extent of economic losses by 22,882 Yuan (B = -0.538, SE = 0.141).

Table 12 below provides a summary of the nine studies that reported descriptive evidence on the effect of early warning systems on loss of assets.

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Table 12. Summary of studies with descriptive findings on the effect of early warning systems on loss of assets

Study	Hazard	Setting	Findings (not statistically tested)
Agyei 2020	Flooding	Philippines	0.17 (out of 1)
Fakhruddin 2019	Cyclone/hurricane/typhoon	Samoa	Total SAT 19.23 million (USD 8.43 million) in avoided damages across agriculture, livestock, manufacturing, tourism, schools, housing and household possessions; researchers estimate 81.45% of losses from Cyclone Evan could have been avoided with efficient early warning.
Hasan 2024	Flooding	Bangladesh	Composite effectiveness score for asset losses (Kaijuri) 0.5 (out of 1); weighted score: 0.167 (Thutia) 0.1; weighted score: 0.033
Huy 2009	Flooding	Vietnam	1985 typhoon (pre-EWS): 87 fishing boats and 210 houses destroyed, ~50 of 80 ha of crops destroyed, 80% of livestock seriously affected. 2006 typhoon (post-EWS): 86 houses damaged (6 completely destroyed), 6 fishing boats destroyed.
Rai 2020	Flooding	Nepal	96% reported saving property due to the flood EWS; mean savings NPR 117,027 (USD 1,083) per household, mostly cash/jewellery, transport, livestock and cereals.
Ringo 2024	Flooding	Tanzania	34.85% disagreed/strongly disagreed that response actions reduced destruction of movable house assets (31.10% agreed; mean 2.60/5, SD 1.42); 41.55% agreed response actions reduced livestock loss (mean 3.20/5, SD 1.22).
Shah 2012	Flooding	Bangladesh	Average total flood damage per household (2007 flood) ~US$200, similar in high- and low-flood-prone areas. Crop damage: US$111 (high-prone) vs US$91 (low-prone). House/inventory damage: US$76 (low-prone) vs US$26 (high-prone).
Shrestha 2025	Flooding	Nepal	Total economic impact: buildings USD 15.48 million, agricultural crops USD 4.72 million, across three municipalities (Rapti Sonari, Duduwa, Narainapur).
Thieken 2007	Flooding	Germany	Mean damage to household contents €16,335; mean damage to residential building €42,093 (varying by region: Elbe €20,770/€57,829, Elbe tributaries €13,088/€45,820, Danube €13,536/€16,834). Damage correlated most strongly with flood water level (ρ≈0.47–0.66) and duration of clean-up (up to 0.45).

***Confidence in the evidence on loss of livelihoods*: Very low** due to inconsistency in the reported effects and indirectness (use of an indirect/proxy measure for loss of assets). See Appendix P for the full GRADE rating for this outcome.

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Timely issuance of warning alerts

Timely issuance of early warning alerts was assessed by whether it is associated with reduced losses or that the warning led recipients to take protective action. This was addressed by five of the included studies, of which two reported statistically tested findings (see Table 13 below) and the remaining three provided descriptive summaries of effectiveness.

Table 13. Summary of findings (showing the direction of effect) for studies that evaluated the effect of timely issuance of warning alerts

Hazard type	Studies	Positive effect	Negative effect	No effect	Mixed effect
Flooding	1	0	0	1	0
Cyclone/hurricane/typhoon	1	0	0	0	1

Flooding

Kreibich et al. (2021) found that longer warning lead time is only effective at reducing losses when there is complementary preparedness knowledge. They found that a warning lead time of 1 hour or more, without also knowing what preparedness actions to take, did not lead to reduction in flood-related losses.

Cyclone

For cyclones, Sahana et al. (2023) reported an association between early warning lead time and cyclone-related losses – including house damages, livestock deaths and land losses. They found that for house damages, shorter warning lead time was associated with worse outcomes (within 12 hours: coefficient (B) = 0.1745, SE = 0.219; within 1 day: coefficient (B) = 0.134, SE = 0.222). However, for livestock deaths, shorter lead times were associated with positive outcomes (within 12 hours: B = -0.0213, SE = 0.7589; within 1 day: B = -0.2454, SE = 0.7338). There was no association between lead time and land losses across the five reported lead-time categories (i.e., within 12 hours: B = -0.1613, SE = 0.4591; within 1 day: B = -0.2515, SE = 0.4863; before 2 days: p≥ 0.1 = -0.4797, SE = 0.4640; before 5 days: B = -0.3134, SE = 0.5301; before a week: B = +0.6667, SE = 0.6871).

Table 14 below provides a summary of the three studies that reported descriptive evidence on the effect of timely issuance of alerts

Table 14. Summary of studies with descriptive findings on the effect of timely issuance of alerts

Study	Hazard	Setting	Findings (not statistically tested)
Allen 2025	Earthquake	Global study (98 Countries, not including the USA)	36% received the alert before shaking, 28% during, 23% after, 13% did not know. The BeAware alert type reached 44% of recipients before shaking versus 14% for TakeAction; helpfulness ratings were higher when the alert arrived before shaking (93% rated it 'very helpful') than after (75%).
Ochoa-Rodríguez 2018	Flooding	United Kingdom	Hypothetical localised warnings: at 0.5h/80% probability, 42% would notify the public and 64% place resources on standby; at 1h/80% probability, 42% notify public and 70% standby; at 2h/60% probability, 36% notify public and 64% standby.
Rai 2020	Flooding	Nepal	Average lead time 2.75h (range 30min–6h). 97% of households who saved property said they could save more with 1 additional hour of lead time (expected 1.83× current savings; 2h more would yield 2.56×).

Confidence in the evidence on timely issuance of alert: Very low due to a small evidence base (imprecision), use of an indirect/proxy measure for timely issuance of alert (indirectness), and inconsistency in the reported effect (see Appendix Q for the full GRADE ratings).

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Accuracy of alerts

Two of the included studies addressed the effect of accuracy of alert messages in improving outcomes, both of which reported descriptive summaries of effectiveness. These are summarised in Table 15 below.

Table 15. Summary of descriptive findings on the effect of accuracy of alert messages

Study	Hazard	Setting	Findings (not statistically tested)
Malawi Red Cross Society 2024	Cyclone/hurricane/typhoon	Malawi	Total n=807: 64% (n=569) found the warning message accurate and believed it immediately; 12% (n=110) believed the warning message with doubts, and 14% did not believe (n=128) it.
Shah 2012	Flooding	Bangladesh	About 70% said forecasted water levels were 'not always accurate' versus the Flood Forecasting and Warning Centre's own claimed accuracy of 'more than 85%'; about 50% believed the forecast trend (rising/falling) matched the local situation.

Confidence in the evidence on accuracy of alert: **Very low** due to a small evidence base, use of a self-reported measure for accuracy of alerts, and findings not statistically tested.

Effectiveness by operational level

Of the 20 studies that provided statistically tested findings on effectiveness, 17 evaluated national-level early warning systems, two focused on community/local level systems and one assessed a regional early warning system. Table 16 below provides a summary of the direction of effect by operational level, and Appendix R presents details of the direction of effect for all the 20 studies with statistically tested findings, organised by outcome, hazard type and operational level.

Table 16. Summary of findings (showing the direction of effect) on effectiveness by operational level

Operational level	Studies	Positive effect	Negative effect	No effect	Mixed effect
Community/local	2	0	0	2	0
National	17	3	3	6	5
Regional	1	1	0	0	0

RQ1ci. What are the demographics and characteristics of communities served by these early warning systems?

This section specifically looks at the demographics of populations and communities targeted by the early warning systems reported in the sections above.

Across the included studies, participants' demographics such as age, gender, disability, occupation, ethnicity/language/culture, occupation, and educational level were very rarely reported.

Age was reported in 59 (53%) of the 111 included studies, but in inconsistent formats (e.g., mean age with or without standard deviations or medians), which limits statistical pooling. Where reported, participants were largely adults. Studies focusing on extreme heat most frequently involved older adults, whereas the other hazard types such as flood, cyclones, and earthquakes more often involved general adult population who have been exposed to the hazard.

The gender of participants was reported in 52 (47%) of the included studies. Where reported, there was an overall even spread of male and female beneficiaries of early warning systems. There were 17 female-majority studies and 21 male majority studies, with six studies including a balanced number of male and female beneficiaries. In most studies using administrative datasets or household surveys, gender distribution was markedly male skewed, highlighting how the unit of participant enrolment – mostly household heads who are often male – can bias the gender distribution of studies. Very few studies reported a non-binary gender category.

Ethnicity, race or language was reported in only 18 (16%) of the studies, and the type reported differed substantially by setting. Where reported, high-income countries (for example the United Kingdom, United States, Australia, New Zealand) used ethnicity/race categories such as Black, BAME groupings, Hispanic, or White. In lower- and middle-income countries, the most reported category was often language or caste. This was seen in studies originating from Nepal, Bangladesh, Malawi, and Fiji.

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The occupation or livelihoods of participants were reported in 32 (29%) of the included studies. Where reported, some clear patterns emerged: in studies conducted in low resource settings, participants were mainly farmers, fishers, agricultural works, pastoralists and herders, with their livelihoods directly exposed to hazards such as cyclone, droughts, and floods. Most of these studies focused on evaluating community/local level early warning systems. In studies focusing on national/regional level early warning systems, participants were predominantly practitioners, policy makers and government officials – for example disaster management officers, meteorologists, evacuation centre managers, and warning system volunteers (many of which were described as experienced, often retired practitioners). In studies conducted in high income settings, those that reported occupation mostly used broad categories, including 'white/blue colour', with no further description of this job category.

The educational level of participants was only reported in 22 (20%) studies – ranging from participants with predominantly primary level or no formal education (mainly reported in studies originating from rural communities or lower-income settings) to participants with tertiary education. These were reported inconsistently across studies, making it difficult to aggregate findings.

Disability was reported in only six studies, and where reported, the proportion of participants declaring a disability spanned around 6% to 25%, including physical/mobility issues, mental illness, and blindness/visual impairments. Religion was the least reported characteristic, with only two (less than 2%) studies reporting a Christian/Muslim split.

Appendix S provides details of the demographics of participants for each included study.

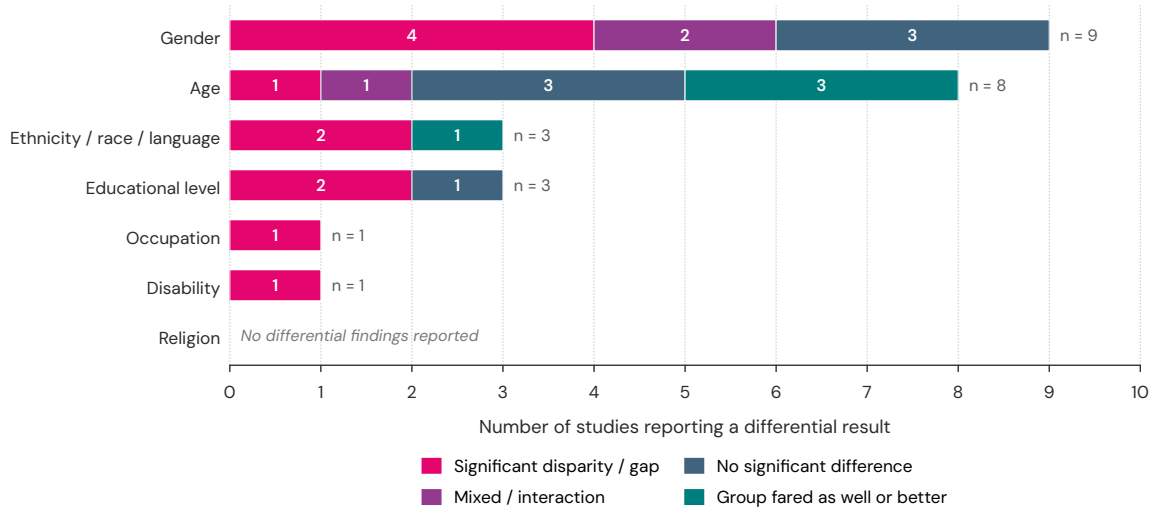
RQ1cii. Which early warning systems are more or less effective for different populations, communities, and regions?

This research question assessed the differential effectiveness of early warning systems for different communities and regions, looking specifically at the impact on the different population characteristics reported above. The included studies provided very limited evidence on the differential effectiveness of interventions for subgroups of participants, such as disabled people, the elderly and young people, and underserved communities. That notwithstanding, this review identified important contextual and demographic factors that impact the effectiveness of early warning systems.

Overall, we found that no single early warning system is universally more effective. Effectiveness is conditional, driven less by the type of warning system, and more by its design and implementation that factors the unique needs of beneficiary communities. Early warning systems were more effective when they used multi-channel communication and dissemination sources, were locally owned, and are delivered in the local language of communities, through trusted intermediaries.

For studies that reported differential effectiveness of early warning systems across different population characteristics, the harvest plot below shows the direction of effect, number of studies per each characteristic, and the study quality.

Figure 5. Differential effect of early warning systems by population characteristics



***Note**: each study contributing a differential effect is counted once per characteristic. a study may appear under more than one characteristic; Disparity/gap = a group that is less well served or more adversely affected; Group fared as well or better = a typically vulnerable/older group accessed/benefited equally or more. Religion was recorded in sample composition, but no differential effect assessed. No differential effect findings were reported for other protected characteristics (e.g., sexual orientation, pregnancy/maternity, gender reassignment)*

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Gender

The evidence shows that access to and awareness of early warning messages were unequal among males and females. In Somalia, Omer et al. (2026) reported that only 38% of females (compared with 100% males) were aware of the early warning system (χ^2=181, p<0.001). In Nepal, Shrestha et al. (2021) found that traditional gender roles and social norms limited women's meaningful participation in disaster risk management.

In studies that evaluated perceived effectiveness or response behaviours, gender differences were mostly absent. In Nepal, Shah et al. (2012) found that socio-economic factors, including gender had no influence on household response to early warning messages, and in Greece, Diakakis et al. (2022) reported that gender showed no correlation with perceived effectiveness of flood early warning systems.

Disproportionate health impacts were observed across genders. In China, Wu et al. (2020) found significantly higher heat-related morbidity among males, particularly in middle-aged and young men, and in Canada, Mehiriz (2024) found a rise in women health service use during extreme heat events despite early warnings. In a study conducted in the UK, Smith et al. (2022) found a significant association between warning fatigue (i.e., feeling overwhelmed by a warning) and gender (p = 0.008), with women feeling more overwhelmed by the warning.

In a multi-country study conducted in the USA and Japan, there was no gender differences in willingness to pay for earthquake early warning systems (Ahn et al., 2021)

Age

Findings on differential effect by age are mixed and mainly depended on whether the outcome was averted harm or access to early warning messages. On averted harm, Weinberger et al. (2018)'s study covering 20 US cities found no association between age – particularly among those aged 65+ years – and effectiveness of heat alerts. However, In Germany, Heudorf and Schade (2014) reported significant excess heat-related mortality among participants aged 80 years and over. In Australia, Nitschke et al. (2016) found reduced ambulance use/call-outs among those aged 75 and over. Smith et al. (2022) showed that in the UK, young people aged 18-21 years old were more likely to verify the authenticity of an early warning message (p = 0.04).

On access to early warning messages, Prathumchai and Bhula-or (2020) found that older household heads (aged 60+ years) in Thailand were more likely to access early warning messages (Odd ratio = 1.17, p<0.05). In Greece, older participants rated early warnings as more effective (Diakakis et al., 2022), and in Japan, Naylor et al. (2018) reported disproportionate differences in access among age groups, with 74% of those aged over 60 years more likely to receive earthquake and tsunami alerts compared to 67% of those aged under 60 years old.

Ethnicity, race, language

In Narainapur (in Nepal), Shrestha et al. (2025) found that text messages were less effective due to messages communicated in Nepali rather than the local language.

In Smith et al. (2022)'s study conducted in the UK, participants from Black, Asian, and Minority Ethnic (BAME)[1] backgrounds were more trusting of emergency services and were less likely to expect early warnings from the Environmental Agency. Smith et al. (2022) also found that participants from BAME backgrounds were more likely to experience warning fatigue compared with those from other backgrounds. In the USA, Bostrom et al. (2022) reported that participants who identified as Hispanic (compared to White non-Hispanic participants) had positive perceived usefulness of the ShakeAlert early warning system (coefficient = 0.123, p<0.0001).

Educational level

In Omer et al. (2026)'s study conducted in Somalia, the authors found that all participants (100%) who were formally educated were aware of the existence of an early warning system compared to 42% of those without formal education (χ^2=163, p<0.001). In a study conducted in Thailand, Prathumchai and Bhula-or (2020) reported that those with higher education had a higher probability of accessing early warnings (high school = OR 1.22; bachelor's degree and above = OR 1.30, both p<0.05). Contrarily, Diakakis et al. (2022) found no association between educational level and perceived effectiveness of a flood early warning system implemented in Greece.

Disability

Evidence on differential effectiveness for disabled people was only reported in Smith et al. (2022)'s study conducted in the UK. The authors found that disabled people were significantly more likely to experience sensory and wholly negative reactions to early warnings (p=0.016), although this did not lead to warning fatigue (i.e., feeling overwhelmed from early warning alerts). Qualitative evidence (from Zimbabwe, Fiji, Vietnam, and Bangladesh) showed that early warning communication methods such as radio and auditory sirens exclude hard-of-hearing and deaf people. Sign language interpretation of warnings was typically absent and disabled people often depended on relatives to receive or act on warnings.

Occupation

There was very limited evidence on the differential effect of occupation and livelihoods. Differential effect was reported by one study and this focused on the professional roles of early warning beneficiaries/users. In the UK, Ochoa-Rodríguez et al. (2018) found that understanding of forecast services varied by professional roles – flood risk managers and drainage engineers showed limited understanding of the technical distinctions of forecast services, while emergency planners had good general understanding. More broadly across the included studies, occupations such as fishers, farmers, and pastoralists were mainly the recipients of flood, drought, and cyclone early warnings in low resource settings.

1 Note that we have used the term BAME as reported in the paper by Smith et al. (2022): https://link.springer.com/article/10.1007/s11069-022-05241-x

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Table 17 below provides a summary of the early warning systems features that are more or less effective for the population groups discussed above.

Table 17. Population characteristics and the features that make early warning systems more or less effective for each group

Population characteristic	Contributing Studies	EWS features that make it MORE effective	EWS features that make it LESS effective
Gender	Ahn 2021; Prathumchai 2020; Shah 2012; Diakakis 2022; Wu 2020; Mehiriz 2018; Omer 2026; Shrestha 2021; Smith 2022 (9)	Multi-channel delivery reaching women's informal/digital networks; women's participation quotas on warning committees; female intermediaries.	Single formal-channel systems and committee structures that exclude women; systems assuming equal household access.
Age	Prathumchai 2020; Shah 2012; Diakakis 2022; Weinberger 2018; Nitschke 2016; Heudorf 2014; Naylor 2018; Smith 2022; Omer 2026 (9)	Warnings paired with active response support for the oldest-old (check-ins, cooling access); age-targeted heat action plans	Alert-only heat systems that assume recipients can self-protect; systems relying on smartphones where older adults have lower uptake.
Ethnicity / race / language	Bostrom 2022; Shrestha 2025; Smith 2022; Thongs 2025 (4)	Local-language, culturally tailored messages; trusted community/ ethnic intermediaries; integrating with indigenous/local knowledge.	Single-national-language text/SMS warnings; systems that assume one trusted institutional source for all groups.
Education / literacy	Prathumchai 2020; Diakakis 2022; Omer 2026 (3)	Pictorial/audio and verbally relayed warnings; community meetings and door-to-door relay; simple, actionable content.	Text-heavy or written warnings; systems requiring reading or interpretation of technical thresholds.
Disability	Smith 2022 (1 quant; + qualitative)	multi-sensory alerts (visual + audible + vibration); sign-language and accessible formats; disability-inclusive evacuation support.	auditory-only sirens/radio; any single-modality channel; systems with no response support for those who cannot self-evacuate.
Occupation / livelihood	Ochoa-Rodríguez 2018; Omer 2026 (2)	Livelihood-relevant, sector-specific advice (e.g. when to move boats, livestock, crops); forecast-based anticipatory action.	Generic warnings not tied to the recipient's exposure or protective options.
Setting / income level	Exemplars: Rai 2020; Pandey 2023; Chinguwo 2022; Global DisasterPreparednessCenter 2025; Escaleras 2008; Thongs 2025; WMO 2018	Community-owned systems where national infrastructure is weak; regional pooling for small/island states (Caribbean, Pacific tsunami).	Infrastructure-dependent national systems in low-capacity settings; coverage gaps in remote/poor areas.
Informal settlements	Adegun 2024; Trahan 2023 (2)	Community-embedded heat warnings routed through structures residents already use; alerts paired with locally accessible cooling/resource guidance and practical response options.	City-wide alerts assuming access to air-conditioning, cooling or media that slum residents lack; warnings issued without actionable local response.
Hard-to-reach/ underserved communities	Cao 2024; Naylor 2018; Pescaroli 2023; Rahman 2013; RedCrossRedCrescentClimate Centre 2022; Shah 2023; Thongs 2025 (7)	Integrating local/traditional knowledge and community relay; multi-channel dissemination (TV, radio, SMS + word of mouth); pre-positioned response and evacuation support; involving underserved communities in EWS design.	Systems that stop at national dissemination and depend on infrastructure that fails to reach underserved communities; single-channel alerts vulnerable to power or network outages.

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RQ2. What elements or components of these early warning systems are associated with reductions in loss of life and assets?

This section presents findings from synthesis of the common elements associated with successful early warning systems. It includes a description of the components of early warning systems identified as effective in this review and categorises them into the United Nation's recommended four pillars of effective early warning systems: disaster risk knowledge; detection, monitoring and foresting; warning dissemination and communication; and preparedness and response capability.

Most of the studies were focused on warning dissemination and communication, with risk knowledge and response capability the least evaluated components.

Table 18 summarises the early warning components and the number of studies that covered them.

Table 18. Early warning system components evaluated in the included studies

EWS pillar	Number of studies that evaluated it	Percentage share
Warning dissemination & communication	97	87%
Detection, monitoring & forecasting	59	53%
Preparedness & response capability	40	36%
Risk knowledge	31	28%

Overall, preparedness and response capability – knowing what to do with an early warning – emerged as the component that is most consistently associated with improved outcomes. However, this was the least evaluated component (after risk knowledge) in the studies included in this review. Across the evidence, warning dissemination and communication alone was rarely effective. Outcomes improved when a timely, credible, multi-channel sourced warning is combined with the knowledge and capability to act on it.

The various components of early warning systems evaluated in the included studies are described below.

Risk knowledge

Risk knowledge was the least evaluated component. Thirty-one of the included studies focused on this but none of them evaluated its association with improved outcomes. It was mainly included as a component of most early warning systems that were assessed in qualitative studies, which do not provide evidence of their association with improved outcomes.

Detection, monitoring and forecasting – and lead time

Hazard monitoring and forecasting was examined in 59 of the included studies, but none of them showed its association with improved outcomes. For example, we found no evidence of forecasting accuracy being associated with improved outcomes. However, forecasting lead time was examined and produced mixed findings regarding its association with reduction in losses. Sahana et al. (2023) found that shorter lead times were associated with increased house damage, but reduced asset and livestock losses. Kreibich et al. (2021) reported that adequate lead time only provided people the opportunity to act, but whether it can improve outcomes depended on people's preparedness and response capabilities.

Warning dissemination and communication – timeliness, credibility, dissemination modality

The findings show that issuing a warning in itself saves lives, especially for rapid onset hazards such as tsunamis. Escaleras and Register (2008) found that issuing a tsunami early warning was associated with about 15% fewer deaths.

The findings also show that timely, accurate and credible warning messages disseminated through official channels outperformed informal, slower ones. In India, Sahana et al. (2023) found that early warnings that were transmitted through informal channels (i.e., neighbours, relatives, and the village assembly) – rather than formal channels such as TV, radio and newspaper – were significantly associated with increased house damages, land losses, and livestock deaths. Informal channels were found to be less accurate and slower, while community intermediaries added value alongside official dissemination sources.

Preparedness and response capability

This component was found to be strongly associated with improved outcomes. Kreibich et al. (2021) found that warning lead time only protects people when combined with adequate preparedness and response capability. In Kreibich et al. (2021)'s study, the authors found that a warning lead time of 1 hour or more produced no significant reduction in flood related losses, but the same lead time when combined with adequate preparedness and response capability led to significant reduction in both house damage and building content loss. Aguirre et al. (2019) reinforced this finding in their evaluation of an anticipatory/early action programme, showing that 72.6% of households involved in the programme did not experience flood-related losses compared to 21% of those who did not participate in the early action programme.

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RQ3. What is the cost-effectiveness of adopting early warning systems for reducing the impact of extreme weather- and climate-related events?

This research question assessed the cost-benefit of investing in an early warning system. Eight of the included studies addressed this question, of which six were economic evaluations (Arias et al., 2015, Bouta et al., 2020, Fakhruddin and Schick, 2019, Islam et al., 2024b, Williams et al., 2022, Rai et al., 2020b), and two studies (Ebi et al., 2004, Huy et al., 2021) reported cost alongside other outcome data.

The studies reporting on cost spanned four hazard types – extreme heat, flood, cyclone, and earthquake, and originated from a range of settings – Australia, United States, Nepal, Bangladesh, Samoa, Vietnam, and the Philippines. Five of the six economic evaluations were assessed as methodologically sound (using the CASP economic evaluation tool), and one (Williams et al., 2022) was found to be relatively poor.

All eight studies reported consistent evidence of a high benefit-cost ratio of adopting early warning systems, ranging from 6:1 to 414:1. In Samoa, Fakhruddin and Schick (2019) found a benefit-cost ratio of 6:1, indicating a US$6 returns on every US$1 invested in cyclone early warning systems. In the Philippines, Arias et al. (2015) reported a benefit-cost ratio of 33:1, and a positive net present value of about US$82.5million, with a setup cost of US$50,000 and an annual operating cost of about US$42,500. Similarly, in the United States, Bouta et al. (2020) reported a positive net present value of about US$289million over a 50 year period, with a 98% modelled probability of a positive return on investment. Ebi et al. (2004) evaluated the cost-effectiveness of a heat warning system in Philadelphia, United States, and reported an estimated gross benefit of about US$468million (117 lives saved, valued at US$4million each), with an operational cost of approximately US$10,000 per warning day – about US$210,000 over a three-year period. In Bangladesh, Islam et al. (2024a) reported a large benefit-cost ratio of 414:1, with a positive net-present value of about US$161million, and a rate of return of 883%.

Two studies (Rai et al., 2020a, Huy et al., 2021) evaluated the effectiveness of a community-based early warning system and assessed its cost-benefit. Rai et al. (2020a) found that a community-based early warning system had a present value of about US$200,000 over a 20 year period (about US$55,000 a year in staffing), and was associated with a 96% reduction in asset losses. Huy et al. (2021) found that a community-based person-centred system costs about US$14,750 per year at the community level, and about US$38 per household, and resulted in reduction in typhoon-related deaths from 14 to 2. While these studies show that community-based systems are highly cost-effective, neither of them performed a cost-benefit analysis, and Huy et al. (2021) was rated very low on methodological quality.

More broadly, although the direction of effect is consistent, most benefits were estimates, with studies using descriptive and modelling approaches – such as the Monte-Carlo simulation, value of statistical life, and averted cost assumptions – instead of observational measures. These findings reflect the inherent difficulties in measuring avoided losses, valuing intangibles, putting monetary value on human life, and limited data availability. Nonetheless, within these limitations, the evidence consistently indicates that adopting an early warning system is cost-effective across different hazards and income settings, with community-based early warning systems appearing especially cost-effective given their low operational cost.

The evidence on cost-effectiveness of early warning systems is summarised below.

Table 19. Cost-effectiveness of early warning systems, by study

Study (hazard)	Country	Early warning system / design	Cost reported	Cost-effectiveness finding	Critical appraisal
Fakhruddin 2019 (cyclone)	Samoa	Cyclone EWS — economic evaluation	US$2.56m over 10 years (cyclone-specific)	**BCR ≈ 6 (US$6 per US$1); benefits US$15.2m/10yr**	Sound (CASP)
Arias 2015 (flood)	Philippines	Technology-Based EWS — economic evaluation	Setup ~US$50,000; ops ~US$42,500/yr	**BCR = 33; NPV ~US$82.5m**	Sound (CASP)
Islam 2024 (flood)	Bangladesh	Regional & community flood EWS — economic evaluation	Not separately reported	**BCR = 414; IRR = 883%; PV benefits ~US$161m (implausibly high)**	Sound (CASP)
Bouta 2020 (earthquake)	USA (Washington)	Earthquake EEWS — economic evaluation	Modelled (50-year horizon)	**NPV ~+US$289m/50yr; 98% prob. positive**	Sound (CASP)
Ebi 2004 (extreme heat)	USA (Philadelphia)	Hot Weather–Health Warning System — quasi-experimental	~US$10,000/warning day; ~US$210,000 over 3 yrs	**Gross benefit ~US$468m (117 lives × US$4m VSL)**	Moderate RoB (ROBINS-I)
Williams 2022 (extreme heat)	Australia	Heat Health Warning System — economic evaluation	AU$593,000 per 7-day activation	**Compared to averted health-service costs; no BCR computed**	Poor (CASP)

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Study (hazard)	Country	Early warning system / design	Cost reported	Cost-effectiveness finding	Critical appraisal
Rai 2020 (flood)	Nepal	Community-based flood EWS — economic evaluation	PV ~US$200,736 over 20 yrs (~US$5,000/yr staff)	**96% of households saved property (descriptive)**	Sound (CASP)
Huy 2009 (flood)	Vietnam	People-centred EWS — mixed methods	~US$14,750/yr (commune); ~US$38/household	**Typhoon deaths fell 14 → 2 between events (descriptive)**	Very low (MMAT 0/5)

Note: *BCR = benefit–cost ratio; NPV = net present value; IRR = internal rate of return; VSL = value of a statistical life. Sound / Poor = CASP economic-evaluation appraisal (methodologically sound / relatively poor).*

3.5 Findings on implementation, usefulness and acceptability of early warning systems (RQs4&5)

This section addresses the following research questions:

1. What are the enablers and barriers to successful implementation of early warning systems?
2. What are the views and experiences of target populations, organisations and governments regarding the acceptability and usefulness of early warning systems?

Findings from these research questions were organised into finding statements, and the GRADE-Cerqual framework was used to assess confidence in each finding. See the full GRADE-Cerqual ratings in Appendix T.

3.6 RQ4: What are the enablers and barriers to successful implementation of early warning systems?

Enablers to successful implementation of early warning systems

Following thematic synthesis of the seventy-eight included qualitative studies, four interrelated factors were identified as enabling the successful implementation of early warning systems (EWS). These findings highlight the importance of community participation, supportive governance arrangements, effective communication systems, and capacity-building activities in strengthening the design and implementation of early warning systems across diverse hazards and geographical contexts. Although the factors identified are interdependent, each finding provides insight into a specific process through which early warning system implementation was strengthened.

Summaries of each review finding are presented below, together with contributing studies and supporting evidence from participants.

Finding 1: Community participation, local knowledge, and trusted local networks strengthened the relevance, legitimacy, and sustainability of early warning systems

Contributing papers: 19

- Abid et al. (2024); Chisty et al. (2021); Graves and Kuleshov (2025); Katsekpor et al. (2025); Lumbroso et al. (2016); Mamba et al 2025; Mishra and Mohapatra (2024); Moises and Kunguma (2022); Obiero et al. (2025); Pandey and Basnet (2023); Pescaroli et al. (2023); Rahman et al. (2013); Rohman (2024); Salgado et al. (2025); Shrestha et al. (2021); Trahan et al. (2023); United Nations Office for Disaster Risk Reduction (2023); VanderMolen et al. (2022); World Food Programme (2025)

Community members were regarded as active contributors rather than passive recipients of early warning information. Across studies, community members played important roles in hazard monitoring, warning dissemination, preparedness planning, emergency response, and recovery activities. Their close familiarity with local environmental conditions, hazard patterns, and community vulnerabilities enabled warning systems to be grounded in local realities and strengthened the practical relevance of warning information.

The integration of indigenous and local knowledge emerged as an important mechanism for improving the credibility and applicability of warnings. Participants reported that community knowledge often complemented scientific forecasting by providing locally meaningful interpretations of risk, particularly in settings where formal monitoring systems were limited. Local knowledge was also viewed as enhancing trust in warning information and improving community willingness to act on warnings.

> *"We actually know and use traditional ways of weather prediction and early warning which we continue to use. It's very, very reliable and accurately predicts how the weather and year will look like for proper decision-making, especially for us as farmers. We learned this from our forefathers who have been relying on this traditional system due to its reliability and accuracy since it uses natural indicators. Nature will never go wrong in telling us what to expect. Through IK (indigenous knowledge), we are able to predict different*

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phenomena such as rainfall onset, drought, hunger/famine (poor harvest), and many other things, including a good year (bumper harvest)" – (Mamba et al. 2022, Pg 41).

Trusted relationships were another important aspect of implementation. Participants highlighted the contribution of community leaders, faith-based organisations, volunteer groups, civil society organisations, and local networks in facilitating warning dissemination and fostering public confidence in EWS. These actors were frequently perceived as trusted intermediaries between formal institutions and at-risk populations.

"You can connect better with the community if someone who looks like them or speaks the language can provide the information. I think that's very vital. Or someone that you actually know and interact with on more of a regular basis, like a church or anywhere else people attend. You're going to trust someone that you know or you see more often." - (VanderMolen et al, 2022, Pg 5)

Collectively, participants described community participation, local knowledge, and trusted local networks as strengthening local ownership of early warning systems and contributing to the long-term sustainability, legitimacy, and effectiveness of warning processes.

Confidence in finding 1: High

Finding 2: Strong governance, institutional coordination, and multi-stakeholder partnerships enabled effective implementation of early warning systems

Contributing papers: Seven

- Chunga and Manda (2025); Katsekpor et al. (2025); Lumbroso et al. (2016); Moises and Kunguma (2022); Oktari et al. (2014); Pandey and Basnet (2023); Salgado et al. (2025)

Participants consistently linked effective implementation of early warning systems to the presence of strong governance arrangements and coordinated institutional systems. Supportive legislation, policies, standard operating procedures, and clearly defined responsibilities were perceived as important for establishing accountability and ensuring warnings were generated, disseminated, and acted upon in a timely manner.

Across studies, participants emphasised the importance of coordination between different institutions involved in forecasting, communication, emergency management, and response. Effective collaboration between governmental agencies, local authorities, communities, non-governmental organisations, academia, media organisations, and international partners was viewed as facilitating timely information exchange, coherent warning messages, and coordinated emergency actions.

"As councillors, we receive warning messages via phone from the District Council. We then share these messages with the villagers. MRCS donated megaphones, which we used to relay information through individuals riding bicycles." - (Chunga and Manda, 2025, Pg 31).

"[Before Cyclone Freddy] warning messages reached us through our committees at DoDMA and Non-governmental organizations, such as Malawi Red Cross Society and others, who warned us that there will be a lot of rain... The warning message was first received by us. We then passed the messages on to VCPCs, who in turn shared them with the community members." - (Chunga and Manda, 2025, Pg 31).

Institutional capacity and sustainable resource allocation were also described as important enablers. Participants highlighted the value of technical expertise, forecasting capability, operational infrastructure, and dedicated financial resources in maintaining effective early warning system operations. Multi-stakeholder partnerships were perceived as particularly important for mobilising expertise, extending warning reach, and strengthening the resilience of systems over time.

"We were able to relay the early warning message to community members before the disaster, thanks to the support of the Malawi Red Cross Society through the ECHO IDREAM project. Through this project, we received resources such as megaphones, which we used to spread the warning message. As the VCPC, we visited every village under GVH Mpama to ensure the message reached everyone." - (Chunga and Manda, 2025, Pg 32)

Overall, participants viewed effective governance and coordination as critical foundations that enabled warning systems to operate efficiently and maintain public confidence.

Confidence in finding 2: High

Finding 3: Multi-channel, inclusive, and locally tailored communication systems enabled warning accessibility, reach, and understanding

Contributing papers: 19

- Adeogun et al. (2024); Al-Zaabi and Al-Zadjali (2022); Chunga and Manda (2025); Cross (2022); Hosen; Lumbroso et al. (2016); Mamba et al. (2025); Mehta et al. (2022); Obiero et al. (2025); Pescaroli et al. (2023); Rohman (2024); Roy et al. (2015); Salgado et al. (2025); Shrestha et al. (2021); Smith et al. (2022); Thongs et al. (2025); Trahan et al. (2023); VanderMolen et al. (2022); World Food Programme (2025)

Participants consistently described communication systems as more effective when information was disseminated through multiple complementary channels rather than relying on a single mode of communication. Multi-channel dissemination channels such as Short Messaging System (SMS), radio, television, social media, community-based dissemination mechanisms, loudspeakers, traditional warning methods, face-to-face communication, and local networks were all

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described as playing important roles in ensuring warnings reached diverse audiences.

Accessibility was enhanced when warning information was tailored to local contexts and communicated in ways that were easy to understand. Participants valued the use of local languages, visual communication methods, simplified terminology, culturally relevant messaging, and communication formats adapted to the needs of different audiences. Multi-channel communication was viewed as important not only for expanding warning reach but also for ensuring redundancy when individual communication systems failed.

> *"I want to implore you to consider sending the SMS in the Hausa language so that they can also benefit from it" - (Adeogun et al 2024, Pg 40)*

Participants also highlighted the importance of trusted communication channels and locally recognised messengers. Warning information was considered more likely to be understood and acted upon when it was delivered through familiar and credible sources.

> *"We have leaders in our community – VCPC members – who warned us about the cyclone" - (Chunga and Manda, 2025, Pg 32)*

Across studies, inclusive and locally appropriate communication approaches were perceived as strengthening warning accessibility, increasing comprehension, and improving the likelihood of timely response.

Confidence in finding 3: High

Finding 4: Training, capacity-building, preparedness measures, and access to timely and actionable information enabled individuals and communities to respond effectively to warnings

Contributing papers: 19

- Alam (2024); Chisty et al. (2021); Huy 2009; Katsekpor et al. (2025); Katsetsiadou et al. (2023); Mehta et al. (2022); Mishra and Mohapatra (2024); Moises & Kunguma (2022); Oktari et al. (2014); Pandey and Basnet (2023); Pescaroli et al. (2023); Rohman (2024); Roy et al. (2015); Salgado et al. (2025); Sharafi et al.; Shrestha et al. (2021); Thongs et al. (2025); United Nations Office for Disaster Risk Reduction (2023); World Food Programme (2025)

Participants consistently described training and capacity-building as essential for enabling effective use of early warning information. Education programmes, awareness campaigns, drills, simulations, and practical preparedness activities were perceived as key to improving understanding of warning information and increasing confidence in emergency decision-making.

Preparedness measures were viewed as particularly important because warning information alone was often considered insufficient to support protective action. Participants reported that evacuation plans, designated safe locations, drills, response protocols, and preparedness resources made it easier for individuals and communities to translate warning information into action during emergencies.

> *"Nowadays the Red Cross and commune CFSC explain the signals and train us in how to respond to the storm warnings. We hear news about the signals, and we know how strong the storms are with the scale of wind speeds, which I heard before but did not really understand." - (Huy, 2009, Pg 43)*

> *"By the month of August, we start to improve our houses, putting sandbags on the roof to avoid our houses being destroyed by strong winds, because we know that the storm and flood season is coming." - (Huy, 2009, Pg 34)*

Access to timely, locally relevant, and actionable information also emerged as a critical enabling factor. Participants described warnings as more useful when they provided clear guidance regarding hazards, potential impacts, recommended protective actions, and the timing of those actions. Timely information enabled households, communities, businesses, and emergency responders to prepare in advance and reduce potential losses.

> *"There is a need for community engagement, sufficient simulation exercises, and drills to prepare people's minds for what will occur during floods and to understand the implications of not evacuating. Regular community engagement is essential to sensitize the people. Also, community drills are necessary to clarify the roles they play when a flood occurs" - (Katsekpor et al. 2025, Pg 9).*

Overall, participants perceived training, preparedness, and actionable information as strengthening both individual and collective capacity to respond effectively to early warnings and reducing barriers between receiving information and taking action.

Confidence in finding 4: High

Barriers to successful implementation of early warning systems

Five interrelated barriers to the successful implementation of early warning systems were identified. These findings highlight how weaknesses within governance structures, communication systems, community engagement processes, technical and data infrastructures, and preparedness and response arrangements constrained the effectiveness of early warning systems across diverse hazard contexts. While these barriers seem to overlap, however, each finding represents a specific factor that impeded the implementation of early warning systems.

Summaries of each review finding are presented below, together with contributing studies and illustrative quotations.

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Finding 1: Weak governance, coordination, institutional capacity, and sustainable resourcing constrained the implementation and long-term sustainability of early warning systems

Contributing papers; 22

- Abid et al (2024); Adams et al. (2024); Chinguwo and Deus (2022); Katsekpor et al. (2025); Lumbroso et al. (2016); Moises and Kunguma (2022); Obiero et al. (2025); Ochoa-Rodríguez et al. (2018); Oktari et al. (2014); Omer et al. (2026); Pandey and Basnet (2023); Pescaroli et al. (2023); Potter et al. (2021); Rahman et al. (2013); Rohman (2024); Salgado et al. (2025); Sari et al. (2023); Shrestha et al. (2021); United Nations Office for Disaster Risk Reduction (2023); VanderMolen et al. (2022); World Meteorological Organization (2018); World Food Programme (2025)

Across diverse settings, participants described governance and institutional weaknesses as fundamental barriers to effective early warning system implementation. Weak institutional arrangements, fragmented responsibilities, inadequate leadership, unstable funding, and limited technical and human resources were perceived to undermine both the operational effectiveness and long-term sustainability of warning systems.

> *"In a country where security is an everyday concern at any governmental scale, focusing funds for disaster risk reduction might not be the priority" - (Pescaroli et al. 2023, Pg 328)*

Participants frequently reported poor coordination between agencies responsible for forecasting, dissemination, emergency management, and response, resulting in delays, information gaps, and unclear accountability.

> *"There is a disconnect here; the village elders are under the national government. However, village administrators who are under the jurisdiction of the county government don't share the information with the elders." - (Obiero et al. 2025, Pg 33)*

Insufficient maintenance of infrastructure and over-reliance on externally funded projects further threatened system sustainability, particularly in resource-constrained settings.

> *"We do budget allocations at the national level, yes. Regional and local authorities need to motivate funding. Currently, the budget for disaster risk management activities is quite limited, but we are working on it. For now, these authorities just need to tap into their operational budgets." - (Moises and Kunguma 2022, Pg 10)*

Confidence in finding 1: High

Finding 2: Warning communication was often inaccessible, poorly tailored, and insufficiently actionable for diverse users

Contributing papers; 30

- Alam (2024); Adeogun et al. (2024); Cao et al. (2016); Cao et al. (2024); Chunga and Manda (2025); Ebhuoma and Leonard (2021); Graves and Kuleshov (2025); Huy 2009; Katsekpor et al. (2025); Mamba et al. (2025); Mehta et al. (2022); Mishra and Mohapatra (2024); Oktari et al. (2014); Omer et al. (2026); Pandey and Basnet (2023); Pereira et al. (2024); Pescaroli et al. (2023); Potter et al. (2021); Rahman et al. (2013); Rohman (2024); Salgado et al. (2025); Sari et al. (2023); Shrestha et al. (2021); Smith et al. (2022); Thongs et al. (2025); UNDRR (2023); VanderMolen et al. (2022); WMO (2018); WFP (2025); Yangquiling (2024)

Across the evidence, participants frequently reported challenges in accessing, understanding, and acting upon warning information. Communication barriers included delayed dissemination, unreliable communication infrastructure, language mismatches, inaccessible technologies, low literacy, and the use of technical terminology that was difficult for many users to interpret.

> *"Warnings themselves, we have noticed over and over again, it's been proven in many catastrophic events that they don't really make people do anything, because they don't understand what they mean. So that's why we need to move further than that now" (Potter et al, 2021, Pg 307).*

Participants also described warning messages as less effective when they lacked localisation, failed to communicate expected impacts, or did not provide clear guidance on protective actions. As a result, warning information often failed to support timely decision-making among intended users.

> *"If we said minor impacts to a member of the public, that might [be perceived to] mean their garden being wet, but actually for us a "minor impact" will be a few houses [flooded] . . .So when we're writing for the public, rather than just say "minor impacts," we should say "there'll be flooding for low lying fields, minor roads, isolated properties, or individual properties" - (Potter et al, 2021, Pg 308)*

Confidence in finding 2: High

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Finding 3: Limited community engagement, weak trust, and inadequate integration of local knowledge reduced the credibility, relevance, and uptake of warning systems

Contributing papers; 16

- Cross (2022); Ebhuoma and Leonard 2021; Haque (1995); Huy 2009; Katsekpor et al. (2025); Mamba et al. (2025); Martin (2024); Obiero et al. (2025); Omer et al. (2026); Pereira et al. (2024); Roy et al. (2015); Salgado et al. (2025); Shah et al. (2023); Shrestha et al. (2025); World Meteorological Organization (2018); World Food Programme (2025)

Participants frequently linked poor uptake of warnings to limited trust in warning systems and weak engagement with at-risk communities. Trust was undermined by inaccurate, inconsistent, overly general, or repeatedly false warnings, as well as by unclear warning sources and weak relationships between authorities and communities.

> *"Sometimes an alert from Civil Défense arrives, right, and I sometimes have doubts if it's really true. Because sometimes people start circulating things on the internet and you stay in a state of alert, right, because whether you like it or not, you get scared when it says 'Civil Défense Alert,' you know? But sometimes it doesn't have a symbol, doesn't have a logo, doesn't have… anyone can pick up a cell phone nowadays and make, like, a card and send it on the internet to scare people, you know? I find this very worrying."- (Pereira et al. 2024, Pg 30/31)*

Participants also described the exclusion of indigenous knowledge, community experiences, and local actors from forecasting, planning, and decision-making processes as reducing the relevance, legitimacy, and cultural appropriateness of warning systems. These factors collectively weakened community ownership and reduced willingness to respond to warnings.

> *"Local communities are cut off from the formal framework of flood early warning systems in the White Volta basin. There is a need for a bottom-up approach, where community members are involved in developing the flood early warning system (respecting the culture of the people). They have the knowledge to identify flood risk areas and provide mitigation procedures (Knowledge is in their hands) - (Katsekpor et al. 2025, Pg 9)*

Confidence in finding 3: High

Finding 4: Limited preparedness, response capacity, evacuation arrangements, and social vulnerabilities constrained the ability of individuals and communities to act on warnings

Contributing papers; 25

- Alam and Islam (2023); Chisty et al. (2021); Haque (1995); Katsekpor et al. (2025); Martin (2024); Melo et al. (2017); Mishra and Mohapatra (2024); Naylor et al. (2018); Obiero et al. (2025); Pereira et al. (2024); Pescaroli et al. (2023); Potter et al. (2021); Rohman (2024); Salgado et al. (2025); Sari et al. (2023); Shah et al. (2023); Sharma et al. (2009); Shrestha et al. (2021); Shrestha et al. (2025); Thongs et al. (2025); Trahan et al. (2023); United Nations Office for Disaster Risk Reduction (2023); VanderMolen et al. (2022); World Food Programme (2025)

Participants emphasised that receiving a warning did not necessarily translate into protective action. Limited preparedness measures, inadequate shelter capacity, poorly maintained evacuation facilities, insufficient transportation and emergency support, lack of contingency planning, and inadequate training frequently constrained response.

> *"There is no evacuation centre in the ward, so people move to identified schools or churches (for example Nyaimbo, Rweya and Rongo primary schools) until the floods recede. However, during school days, the affected villagers are housed by willing villagers not affected by the floods. Currently about 50 households are still living outside their homesteads due to floods. They are being housed by others in the community since there is no evacuation centre in the area" - (Obiero et al. 2025, Pg 30)*

These barriers were further intensified by poverty, livelihood pressures, mobility limitations, and broader social inequalities. Women, people with disabilities, older adults, geographically isolated populations, minority-language speakers, and low-literacy groups often experienced additional obstacles because their communication, mobility, safety, and support needs were not adequately addressed within preparedness and response arrangements.

> *"At normal times, it is tough for me to get out from my house and move around. People cannot imagine how difficult it is for me to find a safe place during a flood. All the roads get submerged, and it becomes impossible to use a wheelchair." - (Chisty et al. 2021, Pg 499)*

> *"As there is no mechanism to disseminate warning to persons with disabilities, my whole family had to live in the flooded house for 2 weeks. We have 3 disabled persons in the house and not getting a warning in due time affected us badly." - (Chisty et al. 2021, Pg 502)*

Confidence in finding 4: High

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Finding 5: Technical, monitoring, forecasting, and data-system limitations reduced the accuracy, timeliness, and reliability of warning systems

Contributing papers; 20

- Abid et al (2024); Adams et al. (2024); Alam (2024); Adeogun et al. (2024); Cao et al. (2024); Chunga and Manda (2025); Ebhuoma and Leonard 2021; Graves and Kuleshov (2025); Moises and Kunguma (2022); Obiero et al. (2025); Ochoa-Rodríguez et al. (2018); Omer et al. (2026); Pereira et al. (2024); Potter et al. (2021); Salgado et al. (2025); Sari et al. (2023); Shrestha et al. (2025); United Nations Office for Disaster Risk Reduction (2023); World Meteorological Organization (2018); Yangquiling (2024)

Participants described substantial technical and information-system constraints that limited the effectiveness of early warning systems. Challenges included inadequate monitoring infrastructure, outdated or insufficient monitoring stations, weak forecasting capacity, lack of real-time data systems, poor-quality or inaccessible data, limited technical expertise, and weak mechanisms for integrating information across agencies and data sources.

> *"Our forecasting capacity is relatively low, as we only rely on rainfall data. We require particular kinds of software to run specific models and to be able to calculate inundation levels, the extent of impact and so forth, and we just do not have money for it. We also do not have qualified personnel to operate these systems, so there are a lot of issues." -Moises and Kunguma 2022, Pg 11)*

Participants also reported difficulties in generating accurate, localised, and timely forecasts because of inadequate modelling approaches, poor

data-sharing arrangements, and insufficient capacity to analyse and interpret risk information.

> *"Getting more accurate predictions depends on the quality of the historical data, which serves as the input data for the model. For example, if we have 30–60 years' historical data, we are likely to make better predictions. The more backlog data we have, the higher the resolution of the weather forecasts generated" - (Ebhuoma and Leonard 2021, Pg 2648)*

> *"We have to wait for the MAWF to send us forecasts; sometimes, this is delayed. But it helps that we know each other, so we can call each other directly and intervene even if the official information is delayed." - (Moises and Kunguma 2022, Pg 10)*

Collectively, these limitations reduced confidence in warning accuracy and weakened the utility of warning information for preparedness and response.

Confidence in finding 5: High

3.7 RQ5. What are the views and experiences of target populations, organisations and governments regarding the acceptability and usefulness of early warning systems?

Perceived usefulness of early warning systems

Four interrelated dimensions of usefulness were identified. These findings demonstrate that perceptions of usefulness were shaped not only by whether warnings were received, but also by whether they arrived early enough to support action, providing information that users considered relevant and actionable, reduced losses, and could be translated into meaningful protective responses.

Summaries of each review finding are presented below, together with contributing studies and participants' quotations.

Finding 1: Early warning systems were perceived as useful when they provided sufficient lead time to support preparedness and protective action

Contributing papers: 23

- Akwango et al. (2017); Alemayehu et al. (2025); Allen et al. (2025); Arif et al. (2019); Bajracharya et al. (2021); Bossu et al. (2022); Chinguwo and Deus (2022); Cross (2022); Doermann et al. (2021); Goltz et al. (2024); Hoshiba (2014); Malawi Red Cross Society & Danish Red Cross (2024); Mehta et al. (2022); Melo et al. (2017); Moises and Kunguma (2022); Nakayachi et al. (2019); Nieland and Mushtaq (2016); Obiero et al. (2025); Ochoa-Rodríguez et al. (2018); Ringo et al. (2024); Sa'adi et al. (2024); Tan et al. (2023); VanderMolen et al. (2022)

Across hazard contexts, participants consistently linked the usefulness of early warning systems to the amount of time available to prepare before hazard impacts occurred. Warnings were perceived as most useful when they enabled households, businesses, communities, and emergency responders to undertake preparedness measures, evacuate safely, protect assets and livelihoods, and mobilise response resources.

Participants described timely warnings as providing opportunities to make informed decisions, reduce uncertainty, and implement protective actions before hazards materialised.

> *"Getting flood information is critical. Now we do not need to go door to door to get flood information before moving to a safer place. The siren warns us and our confidence for avoiding the flood risk has increased" (Bajracharya et al. 2021, Pg 11)*

Conversely, delayed warnings were frequently reported as reducing the utility of warning systems because opportunities for evacuation, preparedness, and coordinated response had already passed. Participants often described timely warnings as helpful, especially when compared with warnings that came after the hazard had already begun.

Confidence in finding 1: High

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Finding 2: The usefulness of warning information depended on its relevance, specificity, and actionability

Contributing papers; 26

- Adams et al. (2024); Akwango et al. (2017); Allen et al. (2025); Budimir et al. (2020); Cao et al. (2016); Chinguwo and Deus (2022); Chisty et al. (2021); Cross (2022); Doermann et al. (2021); Ebhuoma and Leonard (2021); Graves and Kuleshov (2025); Huy 2009; Laure et al. (2022); Lumbroso et al. (2016); Mamba et al. (2025); Martin (2024); Mehta et al. (2022); Moises and Kunguma (2022); Oberai et al. (2025a); Obiero et al. (2025b); Rahman et al. (2013); Roy et al. (2015); Smith et al. (2022); Thongs et al. (2025); United Nations Office for Disaster Risk Reduction (2023); Vinnell et al. (2023)

Participants consistently described warning information as most useful when it was relevant to local conditions, reflected users' priorities and decision-making needs, and provided clear guidance about what actions should be taken. Users valued warnings that specified expected impacts, affected locations, timing, severity, and recommended protective measures. The ability to translate warning information into practical decisions was frequently viewed as central to its usefulness.

> *"While weather forecasts are often broadcasted through the radio, it is not produced for communities in ISLGA. What I often hear are forecasts for cities like Lagos, which does not share the same weather patterns with Uzere." - (Ebhuoma and Leonard 2021, Pg 2648)*

> *"It is difficult for them (public) to decide based on probabilistic information; we need to be more specific." (Budimir et al. 2020, Pg 59)*

Participants also highlighted circumstances in which warning information was perceived as less useful for preparedness and decision-making. These included generic forecasts, broad geographical predictions, unclear probabilities, insufficiently localised information, inaccurate forecasts, and warnings lacking actionable guidance.

> *"We do not know the contribution of rainfall to river water, how much it rains and when river rises, it's all based upon judgement. We need scientific information in easily accessible format to understand this such that we know what is happening upstream and link to downstream." (Budimir et al. 2020, Pg 60).*

Across settings, participants expressed a preference for information that was tailored to their circumstances and directly supported decision-making.

Confidence in finding 2: High

Finding 3: Early warning systems were valued because they reduced losses and strengthened preparedness, resilience, and coordinated response

Contributing papers: Six

- Allen et al. (2025); Bajracharya et al. (2021); Budimir et al. (2020); Chisty et al. (2021); Lumbroso et al. (2016); Ringo et al. (2024)

Participants frequently assessed usefulness in relation to the outcomes associated with warning systems. Early warning systems were perceived to contribute to reductions in injuries, loss of life, property damage, livelihood losses, and wider disaster impacts.

> *"During the 2010 and 2012 floods, the number of deaths was high partly because the issue of warnings was very low. However, in the recent floods, the number of deaths has decreased compared to the time when we had no early warning at all" (Ringo et al. 2024, Pg 6)*

Participants also reported that warning systems enhanced preparedness, supported evacuation, increased community resilience, and improved coordination between households, communities, emergency responders, organisations, and government agencies.

> *"People in the village know which paths to use during an evacuation after receiving warnings through phone calls from neighbouring villagers. However, the challenge is that during evacuation, they carry many family belongings and are slowed down by the floodwaters, which are often mixed with mud, stones and uprooted trees. As a result, injuries are common, and it is especially difficult for the disabled and elderly to escape safely" (Ringo et al. 2024, Pg 8)*

Beyond immediate protective benefits, participants described warning systems as contributing to greater confidence in preparedness and increased capacity to manage future hazard events. These positive outcomes reinforced perceptions that warning systems were valuable and worthwhile investments.

Confidence in finding 3: High

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Finding 4: Perceived usefulness declined when warnings could not be translated into meaningful protective action

Contributing papers: 18

- Budimir et al. (2020); Cross (2022); Doermann et al. (2021); Haque (1995); Hoshiba (2014); Huy (2009); Katsekpor et al. (2025); Mamba et al. (2025); Martin (2024); Melo et al. (2017); Obiero et al. (2025); Omer et al. (2026); Pereira et al. (2024); Roy et al. (2015); Salgado et al. (2025); Shah et al. (2023); Shrestha et al. (2025); World Meteorological Organization, 2018.

Participants reported that warning systems were less useful when the information provided could not be acted upon effectively. Warnings were perceived as having limited value when they arrived too late, contained insufficient information about expected impacts or protective measures, lacked local relevance, or did not correspond with available response options. Participants also described situations in which they lacked the resources, infrastructure, evacuation arrangements, or response capacity required to act on warning information, diminishing the practical utility of warnings.

> *"I think there isn't [risk communication]. Information only arrives after the event has already happened and many people have died. Now, someone is saying: Look, there's heavy rain coming, today there's heavy rain in such and such region, subject to flooding [...]. It's only when it happens, this is cultural. They wait for it to happen to then do something, and most of the time they don't even do that." (Pereira et al. 2024, Pg 29)*

Across several studies, participants emphasised that receiving a warning alone was insufficient; usefulness depended on the ability to convert warning information into concrete protective actions. When this transition from warning to action was disrupted, perceptions of usefulness declined substantially.

> *"Forecast uncertainties message should be communicated through different media along with forecast information, but it should be in easily understandable term/words/languages to everybody. (Representative, UN WFP; Budimir et al. 2020, Pg 61)*

Confidence in finding 4: High

Perceived acceptability of early warning systems

Three interrelated factors were identified as shaping the acceptability of early warning systems among populations, organisations, and government stakeholders. Participants' acceptance of warning systems was influenced by trust in warning providers and warning accuracy, the clarity and usability of warning information, and the extent to which warning systems reflected the needs, preferences, and circumstances of different users.

Summaries of each finding are presented below, together with contributing studies and participants' quotations.

Finding 1: Acceptability was shaped by trust in warning providers and confidence in the accuracy and credibility of warning information

Contributing papers: 14

- Adams et al. (2024); Budimir et al. (2020); Cao et al. (2016); Chinguwo and Deus (2022); Chisty et al. (2021); Cross, (2022); Huy (2009); Malawi Red Cross Society and Danish Red Cross (2024); Mehta et al. (2022); Moises and Kunguma (2022); Obiero et al. (2025); Sharma et al. (2009); Smith et al. (2022); United Nations Office for Disaster Risk Reduction (2023)

Across studies, participants consistently linked acceptance of early warning systems to trust in warning providers and confidence in the reliability of warning information. Warning systems were more likely to be accepted when information was perceived as accurate, timely, and delivered through trusted institutions, authorities, or communication channels. Participants described repeated experiences of accurate warnings as strengthening confidence in warning systems and increasing willingness to engage with future alerts.

> *"The early warning messages have been inaccurate in the past. Weather forecast on application is mostly 95% accurate. In the past, the weather forecasts from the Kenya meteorological department (KMD) are sometimes inaccurate and unreliable. In the last two years the forecast from KMD has been accurate. Early warning messages from KALRO were accurate and reliable" (Obiero et al. 2025b, Pg 27)*

Conversely, trust and acceptance were undermined by perceived inaccuracies, false alarms, conflicting information, unclear warning sources, and warnings that were viewed as exaggerated or inconsistent with local experience. Participants often described trust as something that developed over time through repeated positive experiences with warning systems and could be weakened when warnings failed to match observed conditions.

> *"What we did post event, once we got back in and we had to go through all of that process of dealing with each stakeholder. . .and what we learnt from that process, is we started doing crisis management plans up." (Mehta et al. 2022, Pg 406)*

Confidence in finding 1: High

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Finding 2: Acceptability was enhanced when warning information was clear, understandable, and supported decision-making

Contributing papers: Nine

- Bossu et al. (2022); Budimir et al. (2020); Huy (2009); Melo et al. (2017); Mehta et al. (2022); Oberai et al. (2025a); Obiero et al. (2025b); Roy et al. (2015); Smith et al. (2022)

Participants generally viewed warning systems more favourably when warning information could be easily understood and translated into practical action. Acceptance was strengthened when messages clearly described the nature and severity of the hazard, identified affected locations, communicated expected impacts, and included specific guidance regarding protective actions. Participants also valued warning formats that simplified complex information and supported rapid interpretation.

> *"There has to be what it [disaster and impact] means and a call to action to what you should do — the sorts of things you should be doing, and/or who you should be seeing about something." (Mehta et al. 2022, Pg 407)*

Across studies, participants reported lower acceptance of warning systems when messages were vague, overly technical, difficult to interpret, lacked actionable information, or failed to provide sufficient context for decision-making.

> *"I know I would take it more seriously if emergency services said, hey, look, this is our recommendation. I think it would be good to see emergency services take the lead and the government support them. . . . The initial e-mail might come from emergency services with the core information from government about where you can get your updates and that sort of thing" (Mehta et al. 2022, Pg 408)*

Clear communication was therefore viewed not only as a feature of effective dissemination but also as a fundamental determinant of whether warning systems were perceived as acceptable.

Confidence in finding 2: High

Finding 3: Acceptability was strengthened when warning systems were accessible, user-centred, and responsive to diverse needs and preferences

Contributing papers: Eleven

- Adams et al. (2024); Cao et al. (2016); Mehta et al. (2022); Oberai et al. (2025b); Rohman (2024); Roy et al. (2015); Sa'adi et al. (2024); Sharma et al. (2009); Thongs et al. (2025); United Nations Office for Disaster Risk Reduction (2023); Vinnell et al. (2023)

Participants described early warning systems as more acceptable when they reflected local circumstances, communication preferences, and the needs of different user groups. Acceptance was enhanced when warning information was delivered through trusted and familiar channels, including radio, television, SMS, social media, sirens, maps, and community-based dissemination networks, particularly when multiple channels were used in combination.

> *"In addition to the information I share in sign language, there are TV broadcasts with relevant information before storms. A day or two before a storm, I observe information on TV regarding the upcoming storm and floods. I create small bulletins related to this information using sign language. Afterward, I capture images from this information and integrate them into videos with sign language, which I then share for everyone else to be aware of and prepare accordingly. Besides posting on Facebook, I also share this information in Zalo groups to ensure that people receive timely updates and make early preparations. I will use images or videos related to natural disasters, along with subtitles and sign language suitable for the different proficiency levels of deaf individuals. For example, those who understand Vietnamese can read the subtitles, while those who don't know how to read can rely on sign language or images. On a frame like that, there are multiple options for them to access the information more effectively. That's the approach I have used before." (Rohman 2024, Pg 15)*

Participants also emphasised the importance of inclusive approaches that considered the needs of women, people with disabilities, businesses, geographically exposed populations, and other groups with distinct communication requirements. Warning systems that were adaptable, locally relevant, and responsive to users lived experiences were generally perceived as more acceptable than systems viewed as generic, exclusionary, or poorly targeted.

> *"Instead of things like 'secure loose items'—that's great stuff but what does that actually mean for my business? If I have a car yard, do I pull the cars in or not?" (Mehta et al. 2022, Pg 407)*

> *"I would expect that they [State Emergency Service] would give us pointers as to what we can do to shore up [the premises] further to reduce the amount of damage that could potentially happen. Where we could actually go to get sandbags if we needed to get sandbags." (Mehta et al. 2022, Pg 407)*

Confidence in finding 3: High

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4. Discussion

This systematic review set out to comprehensively collate and synthesise the evidence on the effectiveness of disaster early warning systems in reducing the impact of weather and climate related events, as well assess factors associated with their successful implementation. This included collating evidence to address five research questions, and the key findings are discussed below by research question.

4.1 Key findings for the research questions and objectives

RQ1. What works and for whom

The findings show mixed evidence on the effectiveness of early warning systems across the six assessed outcomes – mortality, morbidity, loss of assets, loss of livelihoods, timeliness of warning alerts and accuracy of alerts. There was a low GRADE rating for the evidence on mortality reduction and very low GRADE ratings for the other five outcomes, with several of the studies using descriptive approaches to assess effectiveness rather than robust impact evaluations.

These findings reflect the difficulties with measuring the performance and success of an early warning system. Effectiveness of early warnings is assessed by an averted harm (a harm that did not happen), and robust randomised designs to measure this are rarely feasible. In this review, the only randomised controlled trial study (Mehiriz et al., 2018) that evaluated the effectiveness of a heat health early warning system was rated 'serious concern' on risk of bias due to bias in the selection of the reported result, as it was not clear whether data was analysed according to an analysis plan or a protocol that was publicly registered before data analysis began.

RQ1a. What are the different types of early warning systems that have been used to reduce the impact of extreme weather- and climate-related events?

The findings show that research on early warning systems is mostly focussed on the upstream, technical end of the warning chain – the national agencies that monitor and issue a warning – while the downstream community end of the chain is under-studied.

In this review, most of the included studies were focussed on national, hydrometeorological systems, with a few studies researching community/locally operated early warning systems. Thus, the evidence base focuses less on systems that integrate local knowledge, enhance community ownerships, and empowers and builds trust among communities. An early warning system functions well when it puts 'people' at the centre, focusing on the safety and unique needs of the community instead of just technical data.

Most of the studies researched flooding/heavy rains and this was recorded as the most experienced disaster across the included studies. This supports recent findings from the World Risk Poll (2025) which reported flooding or heavy rains as the most cited disaster experience globally.

RQ1b. What is the effectiveness of different types of early warning systems in reducing the impact of extreme weather- and climate-related events?

Effectiveness was more clearly evaluated by the type of hazard than the operational level of the early warning system. Flood early warning systems showed the most consistent positive effect on asset protection across several of the included studies. The global study on tsunami early warning system found positive effect in reducing tsunami-related deaths. Evidence on cyclone and drought early warning systems is limited and where available, the findings show mixed effect on outcomes. There was inconsistent evidence on heat early warning systems, with evidence from the same study showing positive effect in one city and not the other.

Taken together, the findings suggest that effectiveness is contingent on context and the achievable protective action – a heat early warning only helps if people can take protective action (e.g., staying hydrated), and a cyclone loudspeaker broadcast warning protects people who can move to a shelter, but not fixed assets such as buildings.

A typhoon community-based early warning system was found to reduce deaths, from 14 to 2; however, this evidence was descriptive and not statistically tested.

RQ1c. What are the demographics and characteristics of communities served by these early warning systems? Which early warning systems are more or less effective for different populations, communities, and regions?

Most of the included studies did not report participants' demographic characteristics, and where reported, the majority were done inconsistently – for example reporting age ranges instead of mean age – making it difficult to pool aggregates of the different characteristics.

Where differential effectiveness was examined, the findings were consistent with the wider literature on disaster risk management (e.g., Villarreal et al., 2025; Budimir et al., 2025) – disproportionate differences exist in access and reach, not in detection and forecasting. In low resource settings, access to, and awareness of early warning systems were stratified by education, literacy, language and gender. In Somalia, for example, awareness was male-skewed, with 100% of men aware of early warning systems compared to only 38% of women. Also, educated people (100% of them) were more aware of existing warning systems compared to 42% of those without education.

In heat early warning systems evaluated in high-income countries, the warnings reached people but did not lead to protective action, especially among older adults, who may need help to take action.

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Disability was among the least reported characteristic, yet, the evidence shows that disabled people are the most systematically excluded group, with significantly poor outcomes during disasters.

Overall, the evidence shows that no single early warning system is universally successful. Effectiveness is dependent on the fit between the early warning system and the population it is designed to reach. However, the population groups that are least served are also the ones that are least researched, so inequities examined in the literature understate existing inequalities in access and reach of early warning systems.

RQ2. What elements or components of these early warning systems are associated with reductions in loss of life and assets?

Four of the included studies reported statistically tested findings showing positive effects of early warning systems and these were split by outcome and component. Warning dissemination – using for example, rural loudspeaker systems – reduced injuries and deaths, while preparedness and response capability reduced asset losses.

A warning received but not actionable does not prevent harm. The findings show that adequate warning lead time alone did not reduce losses – it only led to improved outcomes when paired with the knowledge and capacity to act on received warnings. However, the component most associated with reduced losses (preparedness and response capability) was among the most under-studied component after risk knowledge.

Detection, monitoring and forecasting – the most researched pillar – was not associated with any positive outcome by itself unless when combined with effective warning dissemination and communication, and improved preparedness and response capability.

Taken together, the findings show that early warning systems save lives when all the individual components work effectively, with two key components – getting the warning alert to people who need it and empowering them to act – found to be most associated with improved outcomes.. Thus, to reduce the impact of disasters and improve outcomes, it is important to accompany every warning with an achievable protective action.

RQ3. What is the cost-effectiveness of adopting early warning systems for reducing the impact of extreme weather- and climate-related events?

In this review, every included economic evaluation as well as studies that reported cost alongside outcome data, all reported benefits exceeding the cost of adoption, often by large margins, with reported benefit-cost ratios ranging from 6 to over 400, and a strongly positive net present value. The findings are consistent across hazard types and income settings, and community-based systems appeared particularly favourable at very low absolute cost. These findings support existing literature on the cost-benefit of early warning systems (see for example, the Global Commission on Adaptation, 2019 report).

However, this evidence is from a few (eight) non-comparable studies, with findings largely estimated from modelling or simulation-based studies rather than through observation. Also, the largest estimated benefit was driven by the monetary value assigned to lives saved (i.e., 117 lives saved, valued at US$4million each). That notwithstanding, the evidence consistently shows that early warning systems are cost-effective and provides a strong case for investing in them.

RQ4. What are the enablers and barriers to successful implementation of early warning systems?

Evidence from qualitative and mixed methods studies were synthesised to address the research question on enablers and barriers to successful implementation of early warning systems. Following synthesis, we identified the following finding statements that addressed implementation enablers and barriers to effective early warning systems.

Finding statements on enablers:

1. Community participation, local knowledge, and trusted local networks strengthened the relevance, legitimacy, and sustainability of early warning systems
2. Strong governance, institutional coordination, and multi-stakeholder partnerships enabled effective implementation of early warning systems
3. Multi-channel, inclusive, and locally tailored communication systems enabled warning accessibility, reach, and understanding
4. Training, capacity-building, preparedness measures, and access to timely and actionable information enabled individuals and communities to respond effectively to warnings

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Finding statements on barriers

1. Weak governance, coordination, institutional capacity, and sustainable funding constrained the implementation and long-term sustainability of early warning systems
2. Warning communication was often inaccessible, poorly tailored, and insufficiently actionable for diverse users
3. Limited community engagement, weak trust, and inadequate integration of local knowledge reduced the credibility, relevance, and uptake of warning systems
4. Limited preparedness, response capacity, evacuation arrangements, and social vulnerabilities constrained the ability of individuals and communities to act on warnings
5. Technical, monitoring, forecasting, and data-system limitations reduced the accuracy, timeliness, and reliability of warning systems

These barriers and enablers mirror one another and are predominantly social and institutional factors – trust, coordination, funding, inclusive warnings, multi-channel sources – rather than technical. These findings suggest that the success of an early warning system depends on governance, capacity, and trust. A technically sound early warning system that is embedded in a weak social and institutional environment may still fail.

RQ5. What are the views and experiences of target populations, organisations and governments regarding the acceptability and usefulness of early warning systems?

Users of early warning systems described them as highly useful and acceptable, but conditionally. A strong finding from this review is that generic, complex warning messages impact usefulness. Across the evidence base, early warning systems were perceived as useful if they were accurate, trustworthy and empowered users to translate warnings into protective action.

Acceptability was less evidenced in the literature, and where reported, early warnings were found to be acceptable when they are timely, accurate, clear and delivered through trusted multiple communication sources. New technologies were acceptable if they avoided over-alerting and false alerts.

The findings show that usefulness and acceptability are enhanced by trust, specificity and actionability. These findings corroborate the effectiveness evidence – an early warning is only as good as the protective action it enables. The finding statement on usefulness and acceptability are outlined below:

Finding statements on usefulness

1. Early warning systems were perceived as useful when they provided sufficient lead time to support preparedness and protective action
2. The usefulness of warning information depended on its relevance, specificity, and actionability
3. Early warning systems were valued because they reduced losses and strengthened preparedness, resilience, and coordinated response
4. Usefulness declined when warnings could not be translated into meaningful protective action

Finding statements on acceptability

1. Acceptability was shaped by trust in warning providers and confidence in the accuracy and credibility of warning information
2. Acceptability was enhanced when warning information was clear, understandable, and supported decision-making
3. Acceptability was strengthened when warning systems were accessible, user-centred, and responsive to diverse needs and preferences

In summary, this systematic review has established that effectiveness of early warning systems is governed by reach, access and response, and the components that are most associated with successful early warning systems are dissemination and response capability – not detection or forecasting alone. There is consistent evidence showing the cost-effectiveness of early warning systems (albeit from limited number of studies) and supporting the economic case for investing in them. The findings also show that implementation of early warning systems succeeds through governance, trust, inclusion and community integration.

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5. Limitations

In this review, efforts were made to ensure that the review methods and processes are comprehensive and produced in line with established standards. We conducted extensive search of the evidence – including database searches, search of relevant organisational websites, and a call for evidence – to ensure that we identify all relevant studies for inclusion. However, as with any evidence reviews, it is likely that we have missed an eligible study. Other limitations related to the systematic review processes include:

- At the full text screening stage, we only included studies with full texts in the English language due to language translation issues. This may have excluded potentially eligible studies.
- Due to time constraints, study authors were not contacted to enquire about missing data where applicable, which may have excluded valuable data in this review.

In addition, there are key limitations of the evidence included in this review which may impact generalisability and interpretation of the findings:

- **Low certainty of the included evidence**: across the studies, confidence in the evidence on effectiveness was rated low (for mortality outcomes) and very low for the other outcomes. However, this finding reflects inherent methodological and practical challenges in using the GRADE tool for assessing certainty of evidence from observational studies, rather than methodological limitations of the studies themselves. The GRADE tool automatically starts assessment of evidence from observational studies at low certainty, and this structural bias reduces the final ratings of evidence from fields – such as disaster risk management – where randomised controlled trials may be unfeasible, rare, or unethical. Most of the included quantitative studies on effectiveness were observational, with only one randomised controlled trial. This is characteristic of the literature on disaster early warning systems, which mainly relies on prospective or retrospective observational cohorts to assess their effectiveness.
- **Population characteristics – age, gender, disability, language, occupation – and their association with the effectiveness of early warning systems were rarely reported,** so differential effectiveness conclusions were largely from the qualitative evidence.
- **There were uneven reporting and heterogeneity across the included studies**, and evidence on cost-effectiveness estimates was only few and heterogenous. In addition, most of the evidence were modelled rather than observed benefits, which largely reflects the inherent challenges in measuring avoided losses, valuing intangibles, putting monetary value on human life, and limited data availability.
- **Evidence from low-income countries – the highest disaster risk settings – were primarily descriptive studies** on implementation of early warning systems, with very limited evidence on effectiveness from these settings. Therefore, the findings on effectiveness may not be applicable to these settings.

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6. Recommendations and next steps

Key recommendations from this review have been structured around implications for policy, practice, and future research. Appendix U shows the findings from this review where each recommendation was drawn.

6.1 Policy recommendations

- **Strengthen institutions and governance**: Embed early warning systems in official plans and legal frameworks to enhance stronger institutional and government funding support in low-resourced disaster-prone regions.
- **Invest in dissemination and response capability, not just detection**: direct funding towards improving warning dissemination and communication, and particularly, preparedness and response capability – the features most associated with improved outcomes – rather than focusing investment on only detection, monitoring and forecasting technologies.
- **Ensure multi-channel, local language delivery of early warning systems**: systems must be required to combine official and community communication channels and to disseminate warnings in local languages and accessible formats. In this way, reach will not be dependent on literacy, access to a single technology (e.g., smartphone) or knowledge of a common national language.
- **Make inclusion a design and implementation requirement for all early warning systems:** ensure that early warning systems are gender- and disability-inclusive (e.g.., uses sign language, multi-sensory alerts, and supports women's participation in community warning committees).
- **Prioritise low-resource, high-exposure settings**: support community-based systems in low-income countries, which the evidence shows are effective and affordable, but remain under-funded and under-researched.
- **Fund early warning systems as ongoing services**: provide sustained funding, training and legal/institutional backing for early warning systems rather than through one-off projects. This will help address the funding, capacity and governance barriers that were identified across the evidence.

6.2 Practice recommendations

- **Make early warning messages clear, specific and actionable**: provide location-specific early warning information that users can relate to local conditions, communicate accurately and clearly, and tailor content differently for different population groups.
- **Promote community awareness and invest in education**: provide targeted disaster risk education to specific groups such as youth and the elderly, and work collaboratively with community actors to raise awareness and knowledge on disaster preparedness and protective action.
- **Use multiple, complementary dissemination channels** to communicate warning information, combining official channels (e.g., TV, radio, newspaper) with existing community-based communication approaches (e.g., loudspeaker systems).
- **Pair early warnings with preparedness and response capability**: ensure warnings are disseminated with sufficient lead time with a pre-planned response strategy.
- **Build and use trusted intermediaries, avoid over-alerting and frequent false alerts**: communicate warnings through locally trusted people and institutions, avoid over-alerting and frequent false alerts, which erode trust.
- **Plan for hard-to-reach communities and power/technology failures**: anticipate network failures and power outages, especially in low-resource settings, and build community-level dissemination and response.

6.3 Research recommendations

- **Report participant demographics as standard**: this should include reports on disability, gender, language, ethnicity, and other key population characteristics that can impact the effectiveness of early warning systems.
- **Use rigorous experimental and quasi-experimental impact evaluations** to assess effectiveness of early warning systems, particularly in low- and middle-income settings where the evidence on effectiveness is mainly descriptive.
- **Include observed costs and benefits in economic evaluations of early warning systems wherever feasible**, and ensure modelling studies are methodologically strong and transparent.
- **Focus future research efforts on the under-studied features of successful early warning systems** – risk knowledge, response capability, underserved community reach and low-resource, high exposure settings which are most often susceptible to disasters.

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Appendix A. MEDLINE Search Strategy

Concept	Query	Search term	Hits/Search results
Intervention (Early warning systems)			
	S1	"Early warning system*"	4,156
	S2	"Early warning advi*"	9
	S3	"System of early warning*"	45
	S4	"System for early warning*"	45
	S5	"Rapid response system*"	702
	S6	"Rapid alert system*"	117
	S7	"Early warning mechanism*"	95
	S8	"Rapid information system*"	3
	S9	"provide early warning*"	532
	S10	"Alerting system*"	294
	SS11	"Early warning*" or ews or "Early action*"	19,593
	S12	"Early detection system*"	156
	S13	"Warning system*"	5,577
	S14	"Advisory system*"	157
	S15	"System for warning*"	42
	S16	"System for early detection*"	226
	S17	"Risk knowledge" OR "risk detection" OR "risk monitoring" OR "risk predict*" OR "hazard predict*" OR "hazard forecast*" OR "risk forecast*"OR "disaster forecast*" OR "disaster predict*" OR "warning dissemination" OR "warning communication" OR "preparedness and response capabilit*"	31,882
	S18	S17 OR S16 OR S15 OR S14 OR S13 OR S12 OR S11 OR S10 OR S9 OR S8 OR S7 OR S6 OR S5 OR S4 OR S3 OR S2 OR S1	22,481 53,934
Context (extreme climate and weather hazards)			
	S19	"Climate* related hazard*"	83
	S20	"Weather* related hazard*" or "Climate*related effect*"	18
	S21	"Natural disaster*"	23,991
	S22	Flood*	33,823
	S23	Cyclone* or hurricane* or typhoon*	10,133
	S24	Landslide*	1,902
	S25	Storm*	41,356
	S26	Tsunami*	3,597
	S27	eruption*	47,204
	S28	Wildfire*	5,776
	S29	Drought*	44,613
	S30	heat wave or extreme heat or prolonged heat or heatwave	13,119
	S31	Snow or avalanche* or "snow avalanche*" or "ice storm*" or "winter storm*"	25,717
	S32	heat*wave*	8,141
	S33	"sand storm*"	46
	S34	"dust storm*"	901
	S35	"Sand and dust storm*"	51
	S36	Earthquake*	14,754
	S37	"Volcanic eruption*"	2,177
	S38	"Insect swarm*" or "desert locust*"	751
	S39	"Harmful algal bloom*" or "HAB*"	395,299
	S40	"Extreme weather event*" or "extreme weather" or "weather extreme*"	3,835
	S41	"Extreme climate event*" or "extreme climate*" or "climate extreme*"	2,349
	S42	S19 OR S20 OR S21 OR S22 OR S23 OR S24 OR S25 OR S26 OR S27 OR S28 OR S29 OR S30 OR S31 OR S32 OR S33 OR S34 OR S35 OR S36 OR S37 OR S38 OR S39 OR S40 OR S41	626,998
Study design (Quantitative)			
	S43	RCT OR Trial* OR randomi* OR random* allocat* OR "random* assign*" OR control* OR treatment* OR Impact OR evaluat* OR control group* OR control condition* OR comparison group* OR comparison condition* OR time series OR before after* OR pre intervention OR post intervention OR pre post OR longitudinal study OR repeated measures OR effect size* OR comparative effective* OR experiment* OR pre experiment* OR difference in difference* OR instrumental variable* OR Propensity score OR treat* OR wait list OR quasi ex* OR quasi experiment* OR "matched control" OR "matched comparison" OR clinical trial OR human study OR pilot study OR case report OR case series OR longitudinal studies OR longitudinal research OR longitudinal method OR longitudinal OR "economic evaluation"	7,991,714
Study design (qualitative and mixed methods)			
	S44	Qualitative OR Survey* OR Questionnaire* OR Implement* OR Interview* OR Focus group* OR Process evaluation OR ethnog* OR ethno*methodolog* OR ethnolog* OR phenomenolog* OR grounded theory OR narrative analysis OR lived experience * OR life experience* OR thematic analys* OR discourse analys* OR perspective*OR case stud* OR mixed method* OR "implementation cost*"	3,342,080
	S45	S41 OR S42	10,603,406
	S46	S18 AND S42	2,482
	S47	S18 AND S42 AND S45	994

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Appendix B. Data items for extraction across research questions 1–5

Number	Data item
Study details, participant characteristics, Early Warning System, comparison, and analysis-method fields	
	Study title
	Study aim(s)/objective(s)/research question(s)
	Year of publication
	Publication type
	Research funder
	Country in which study was conducted
	Type of extreme climate/weather event
	Study design
	Total Sample size
	Intervention sample size
	Control sample size, if applicable
	Total sample Male
	Total sample Female
	Total sample Other
	Intervention Male
	Intervention Female
	Intervention Other
	Control, if applicable Male
	Control, if applicable Female
	Control, if applicable Other
	Total sample Race/ethnicity/language
	Total sample Occupation
	Total sample Religion
	Total sample disability
	Total sample Mean age (years) ± SD
	Intervention Race/ethnicity/language
	Intervention Occupation
	Intervention Religion
	Intervention disability
	Intervention Mean age (years) ± SD
	Control, if applicable Race/ethnicity/language
	Control, if applicable Occupation
	Control, if applicable Religion
	Control, if applicable disability
	Control, if applicable Mean age (years) ± SD
	Primary education Number of participants
	Secondary education Number of participants
	Bachelor's or equivalent level Number of participants
	Master's or equivalent level Number of participants
	Doctoral or equivalent level Number of participants
	None: Number of participants
	Other (Please specify) Number of participants
	Inclusion criteria
	Exclusion criteria
	Group differences at baseline, if applicable
	Name of Early Warning System
	Description of the early warning system
	Implementation cost (if reported)
	Developers/Origin
	Deliverer
	Component/type of Early Warning System
	Risk knowledge
	Detection/Monitoring/forecasting
	Warning dissemination and communication
	Preparedness and response capabilities
	Other
	Type of comparison
	Description of comparison activities
	Unit of randomisation
	Unit of analysis
	Time points measured
	Main statistical analysis method
	Outcome reported (Quantitative RQs 1-3)
	Method of data collection
	Data analysis method
	Outcomes reported (Qualitative RQs 4-5)
	Key findings
	Implications for future research
	Implications for policy or practice

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Number	Data item
	Study limitations
Quantitative outcomes	
	Outcome domain (select from: *mortality, morbidity, loss of livelihood, loss of assets, cost of adoption, timely issuance of alerts, accuracy of alerts, other)*
	Name of measure
	Measure description
	Sample size
	Reported results - intervention
	Reported results - control
	Effect size and CI
	Significance (p-value)
Differential impact	
	Equity dimension (*gender, disability, ethnicity/race/language, occupation, age, educational level)*
	Sample size
	Reported results - intervention
	Reported results - control
	Effect size and CI
	Significance (p-value)
Qualitative outcomes	
	Qualitative category (*enablers, barriers, acceptability, usefulness, other)*
	Name of assessment tool
	Quotes
	Themes
	Summary of findings

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Appendix C. Synthesis Without Meta-analysis (SWiM) Reporting Items Checklist completed for this review

SWiM Reporting item	Item description	Page number and Section in report where the item is reported
1.Grouping studies for synthesis	1a) Provide a description of, and rationale for, the groups used in the synthesis (e.g., groupings of populations, interventions, outcomes, study design). 1b) Detail and provide rationale for any changes made subsequent to the protocol in the groups used in the synthesis.	Methods: Synthesis methods, pp. 15-16; Protocol deviations, p. 10. Key findings: Characteristics of included studies, pp. 19-22; RQ1b effectiveness grouping, pp. 25-32; Effectiveness by operational level, p. 32.
2. Describe the standardised metric and transformation methods used	Describe the standardised metric for each outcome. Explain why the metric(s) was chosen, and describe any methods used to transform the intervention effects, as reported in the study, to the standardised metric, citing any methodological guidance consulted.	Methods: Effect measures, p. 15; Synthesis methods, pp. 15-16. Key findings: RQ1b methods text on vote counting and direction of effect, p. 25.
3. Describe the synthesis methods	Describe and justify the methods used to synthesise the effects for each outcome when it was not possible to undertake a meta-analysis of effect estimates.	Methods: Synthesis methods, pp. 15-16. RQ1b: effectiveness synthesis approach, p. 25. Qualitative synthesis methods, p. 16.
4. Criteria used to prioritise results for summary and synthesis	Where applicable, provide the criteria used, with supporting justification, to select the particular studies, or a particular study, for the main synthesis or to draw conclusions from the synthesis (e.g., based on study design, risk of bias assessments, directness in relation to the review question).	Methods: Eligibility criteria, pp. 11–12; Data items, p. 14; Risk of bias assessment, p. 15; Synthesis methods, pp. 15-16. RQ1b: focus on statistically tested and descriptive findings, pp. 25–32.
5. Investigation of heterogeneity in reported effects	State the method(s) used to examine heterogeneity in reported effects, when it was not possible to undertake a meta-analysis of effect estimates and its extensions to investigate heterogeneity.	Methods: Synthesis methods, pp. 15-16; Sensitivity analyses/robustness checks, p. 16. RQ1b findings by hazard type and outcome, pp. 25–32; Effectiveness by operational level, p. 32; RQ1cii differential effectiveness, pp. 33–35.
6. Certainty of evidence	Describe the methods used to assess certainty of the synthesis findings.	Methods: Certainty assessment, p. 16. Quantitative GRADE ratings: Appendix M–Q. Qualitative CERQual ratings: RQ4/RQ5 findings, pp. 38-46 and Appendix T.
7. Data presentation methods	Describe the graphical and tabular methods used to present the effects (e.g., tables, forest plots, harvest plots). Specify key study characteristics (e.g., study design, risk of bias) used to order the studies, in the text and any tables or graphs, clearly referencing the studies included.	Methods: Synthesis methods, pp. 15-16; Equity considerations, p. 17. Key findings tables and figures: PRISMA flow diagram, p. 18; Tables 7–16, pp. 25-32; Figure 5 harvest plot, p. 33; Appendix R.
8. Reporting results	For each comparison and outcome, provide a description of the synthesised findings, and the certainty of the findings. Describe the result in language that is consistent with the question the synthesis addresses, and indicate which studies contribute to the synthesis.	RQ1b results by outcome and hazard type, pp. 25-32; Effectiveness by operational level, p. 32; RQ1ci/RQ1cii, pp. 32-35; RQ2, p. 36; RQ3, pp. 37-38; Discussion, pp. 47-49; Appendix R.
9. Limitations of the synthesis	Report the limitations of the synthesis methods used and/or the groupings used in the synthesis, and how these affect the conclusions that can be drawn in relation to the original review question.	Discussion: Key findings and interpretation, pp. 47-49. Limitations, p. 50. RQ3 interpretation of economic evidence, pp. 37-38 and 50.

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Appendix D. Funder breakdown by category

Funding agency	Number of studies
Government/National Funding agencies	
UK International Development / UK Government	5
National Science Foundation (NSF) - USA	4
China Meteorological Administration / National Programs	3
Earthquake Commission (EQC) - New Zealand	2
Bushfire and Natural Hazards CRC - Australia	2
Department of Foreign Affairs and Trade (DFAT) - Australia	2
Japan Science and Technology Agency (JST) / MEXT	2
Health Canada / Canadian Institutes of Health Research	2
U.S. Environmental Protection Agency (EPA)	1
National Oceanic and Atmospheric Administration (NOAA) - USA	1
National Health and Medical Research Council (NHMRC) - Australia	1
German Ministry for Education and Research (BMBF)	1
Natural Environment Research Council (NERC) - UK	1
UK Research and Innovation GCRF	1
Hong Kong Research Grants Council	1
Ministry for Foreign Affairs - Finland	1
Ministry of Business, Innovation and Employment - NZ	1
National Research Foundation (NRF) - South Africa	1
Japan Meteorological Agency	1
German Academic Exchange Service (DAAD)	1
Malaysian Ministry of Higher Education	1
Quebec Government	1
CONACYT - Mexico	1
International organisations	
European Union / Horizon 2020	6
ICIMOD	3
UNDRR / United Nations	3
World Bank	1
UNESCO	1
CREWS Initiative	1
World Food Programme	1
NORAD - Norway	1
World Meteorological Organization (WMO)	1
University/academic institutions	
Saudi Arabian Universities (King Khalid/Faisal/Saud)	3
University of Washington / Tohoku University	2
Chulalongkorn University - Thailand	1
Brown University - USA	1
Yale University - USA	1
University of Western Australia	1
Brandon University - Canada	1
University of Dodoma - Tanzania	1
Rabdan Academy - UAE	1
University of Cambridge - UK	1
University of Hull - UK	1
University of Malawi	1
Griffith University - Australia	1
Humanitarian organisations	
Red Cross (American/Danish/Malawi)	7
Zurich Flood Resilience Alliance	2
Lutheran World Federation	1
Charities/Trusts	
Gates Foundation	1
Wellcome Trust	1
Leverhulme Trust	1
David and Lucille Packard Foundation	1
Great British Sasakawa Foundation	1
Hong Kong Jockey Club Charities Trust	1
Private/corporate funding	
Google LLC	1
Electrical Power Research Institute	1
Deutsche Rückversicherung AG	1

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Appendix E. Summary of included studies addressing quantitative outcomes of interest

Reference	Study design	Setting	Population	Intervention name (EWS)	Comparison condition	Sample size (n)	Outcomes reported	Follow-up period
Akwango 2017	Cross-sectional study	Uganda	Households in sub-counties covered by a drought early warning system pilot in Nakapiripirit, Uganda.	Karamoja Drought Early Warning System (KDEWS)	No comparison group (descriptive/observational)	173	Timely issuance	Not reported
Tang 2023	Cross-sectional	China	Not reported.	Early warning systems in China	No comparison group (descriptive/observational)	652	Loss of assets	Single timepoint
Allen 2025	Cross-sectional	Global study (98 Countries, not including the USA)	Not reported (global smartphone app users).	Android Earthquake Alerts (AEA) system	No comparison group (descriptive/observational)	1,555,006	Timely issuance	Multiple timepoints (longitudinal)
Bouta 2020	Economic evaluation	United States	Modelled earthquake scenarios in Washington State, USA (no human participants).	Earthquake early warning system	No comparison group (descriptive/observational)	20 (scenarios)	Cost (adoption)	Not applicable (modelled cost-avoidance comparison)
Goltz 2024	Cross-sectional study	United States	Self-selected respondents who felt the Ojai, California earthquake (via USGS 'Did You Feel It?' system).	ShakeAlert	No comparison group (descriptive/observational)	2,490	Timely issuance	Single timepoint
Nakayachi 2019	Cross-sectional study	Japan	Japanese residents in regions that received earthquake early warnings, recruited via an online research panel; gender/age quota-matched to population.	Earthquake Early Warning System	No comparison group (descriptive/observational)	299 (Study 1); 450 (Study 2)	Accuracy	Single timepoint
Chau 2009	Before-and-after study or Pretest-Postest study	Hong Kong	Aggregate summer-season (May–Sept) mortality data, Hong Kong, 1997–2005; no individual participants.	Very Hot Weather Warning (VHWW)	Business as usual (no intervention)	709 (days)	Loss of life	Multiple timepoints
Chen 2023	Interrupted time series	China	Aggregate daily mortality data for 8 urban areas in Jinan, China (2013–18), stratified by age (<65, 65–74, 75+) and gender.	Graded heat health risk early warning model (GHREWM).	No comparison group (descriptive/observational)	104,346 (deaths)	Loss of life	Time-to-event
Clemens 2022	Interrupted time series	Canada	General population of Ontario, Canada, in three heat-warning regions, including children (<18), older adults (65+), adults with certain chronic conditions, and people 14+ experiencing homelessness.	Heat Warning and Information System (HWIS)	Business as usual (no intervention)	Not reported (entire administrative dataset)	Loss of life	Multiple timepoints
Ebi 2004	Quasi-experimental study	United States	Aggregate excess-mortality data for adults 65+ in Philadelphia during 1995–98 heatwaves; no individual participants.	The Philadelphia Hot Weather-Health Watch/Warning System (PWWS)	No comparison group (descriptive/observational)	210 (days)	Loss of life, Cost (adoption)	Multiple timepoints
Feldbusch 2025	Quasi-experimental study	Germany	Aggregate daily mortality, temperature and heat-alert data for the 15 largest German cities, 1993–2020; no individual participants.	German heat health warning system (HHWS)	Before-after: pre-HHWS (1993–2004) vs post-HHWS (2005–2020)	1,731,269 (deaths)	Loss of life	Multiple timepoints
Heo 2019	Quasi-experimental study	Korea	Residents of 7 major South Korean cities during warm seasons (June–Sept), 2009–14.	Heatwave warning system	Business as usual (no intervention)	50,002 (deaths)	Loss of life	Multiple timepoints
Heudorf 2014	Interrupted time series	Germany	All deaths registered in Frankfurt am Main during summer months (June–Aug), 2003–13; no individual participants.	Heat warning system and heat health action plan (HHAP)	Before-after: 2003 heatwave vs. 2006/2010/2013 heatwaves (post-HHAP)	Not reported (~690,000 population)	Loss of life	Multiple timepoints

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Reference	Study design	Setting	Population	Intervention name (EWS)	Comparison condition	Sample size (n)	Outcomes reported	Follow-up period
Mehiriz 2018	Randomised controlled trial	Canada	Adults meeting at least one heat/smog vulnerability criterion: aged 65+, heart/lung condition, diabetes, kidney failure, neurological disorder, or mental health condition.	Heat episode warning (Télephone Santé)	Business as usual (no intervention)	1,328	Injuries/illnesses	Baseline + follow-up
Nitschke 2016	Ecological study design	Australia	Aggregate morbidity/mortality and ambulance call-out data for metropolitan Adelaide, Australia, 1993–2014; no individual participants.	Heat Warning System	Pre-post: 2009 heatwave (pre-HWS) vs 2014 heatwave (post-HWS)	Not reported (~1.30 million population)	Loss of life, Injuries/illnesses	Multiple timepoints
Weinberger 2018	Case-crossover study	United States	20 US cities with the most heat alerts issued by the National Weather Service, 2001–2006.	National Weather Service (NWS) heat alerts/warnings	Business as usual (no intervention)	20 (US cities)	Loss of life	Multiple timepoints (longitudinal)
Williams 2022	Economic evaluation	Australia	Key informants employed by agencies implementing South Australia's Heat Health Warning System.	Heat Health Warning System (HHWS)	Business as usual (no intervention)	15	Injuries/illnesses, Cost (adoption)	Multiple timepoints
Wu 2020	Retrospective ecological study	China (Shanghai)	Aggregate hospital morbidity data, Shanghai, China; no individual participants.	Heat-health warning systems.	Comparison of five heat-health warning systems (2014–2015 data)	Not reported	Loss of life, Injuries/illnesses	Retrospective (administrative data)
Aguirre 2019	Quasi-experimental study	Peru	Local Red Cross-trained volunteers from eight flood/rainfall-vulnerable communities in Picsi district.	Forecast-Based Financing Intervention	Business as usual (no intervention)	113	Loss of assets	Endline
Agyei 2020	Mixed methods	Philippines	Key informants from Marikina City disaster risk management and planning offices, Philippines.	Flood Early Warning System	No comparison group (descriptive/observational)	100	Loss of life, Injuries/illnesses, Loss of assets, Timely issuance, Accuracy	Baseline + follow-up; Time-to-event
Alias 2020	Cross-sectional study	Malaysia	Flood evacuees in Kelantan, Malaysia, who were government employees (various departments, police, university staff).	Flood dissemination warnings	No comparison group (descriptive/observational)	567	Timely issuance	Single timepoint
Arias 2015	Economic evaluation	Philippines	Households in three Philippine municipalities (Sta. Cruz, Pila, Victoria), stratified by rural/urban and flood vulnerability.	Technology-Based Early Warning System	No comparison group (descriptive/observational)	497	Cost (adoption)	Single timepoint
Bajracharya 2021	Mixed methods	Nepal	Not reported.	Community-Based Flood Early Warning System (CB-FEWS)	No comparison group (descriptive/observational)	180 (baseline); 180 (endline)	Timely issuance	Endline
Global Disaster Preparedness Center 2025	Mixed methods	Malawi	Households in Makhuwira, Chikwawa, Malawi — a highly flood-vulnerable area.	Early Warning/Action Systems (community-based)	No comparison group (descriptive/observational)	378 (households); 17 (KIIs)	Loss of life, Injuries/illnesses, Loss of assets	Single timepoint
Hasan 2024	Mixed methods	Bangladesh	Households purposively sampled from two villages in Sirajganj District, Bangladesh, resident there 10+ years.	Flood Early Warning System (FEWS)/Flood Forecasting and Warning Centre (FFWC)	Two villages: Kaijuri (bankline) vs Thutia (charland/island)	116	Loss of life, Loss of assets, Timely issuance	Single timepoint
Huy 2009	Mixed methods	Vietnam	Households and key informants (local officials, village leaders, Red Cross) in Hai An commune, Vietnam.	People-Centered Early Warning System (EWS)	1985 typhoon (before EWS) vs 2006 typhoon (after EWS)	32 (households); 2 FGDs (10–15 each); KIIs not specified	Loss of life, Loss of assets	Single timepoint
Islam 2024	Economic evaluation	Bangladesh	Households randomly sampled across four upazilas in Kurigram, Bangladesh.	Regional and community-based flood early warning system	No comparison group (descriptive/observational)	1,000	Cost (adoption)	Single timepoint
Kreibich 2021	Quasi-experimental study	Germany	Private households in flood-affected streets, identified via flood reports and satellite data, Germany.	Flood early warning system	No comparison group (descriptive/observational)	4,468	Loss of assets, Timely issuance	Single timepoint
Norkhairi 2022	Simulation-based study	Malaysia	Population at risk downstream of Kenyir Dam, Terengganu, Malaysia.	Warning siren (physical siren)	Five scenarios: no siren vs siren at 0/1/2/4 hours before breach	Not reported (~15,000 population at risk)	Loss of life	Simulated time series (0–~10 hrs)

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Reference	Study design	Setting	Population	Intervention name (EWS)	Comparison condition	Sample size (n)	Outcomes reported	Follow-up period
Ochoa-Rodríguez 2018	Mixed methods	United Kingdom	Flood risk managers, emergency officers and engineers in England (survey); flood professionals from the UK and EU (workshops).	Extreme Rainfall Alerts (ERAs); Surface Water Flood Risk Assessment (SWFRA)/Flood Guidance Statement (FGS)	No comparison group (descriptive/observational)	74 (survey, 42 complete); 40+ (workshops)	Timely issuance	Single timepoint
Omer 2026	Mixed methods	Somalia	Households across four regions of Somaliland, stratified by region and covering men, women and youth (survey); government officials, community leaders and NGO staff (KIIs); women, youth and elders (FGDs).	Early Warning Systems (Somaliland); Famine Early Warning Systems Network (FEWS NET)	No comparison group (descriptive/observational)	390 (survey); 8 KIIs; 5 FGDs (6-10 each)	Timely issuance, Accuracy	Single timepoint
Prathumchai 2020	Cross-sectional study	Thailand	Households directly affected by a 2011 flood who did not evacuate and received warnings at home (not in shelters).	Flood early warning system	No comparison group (descriptive/observational)	3,207,260	Timely issuance	Single timepoint
Rai 2020	Mixed methods	Nepal	Households benefiting from a flood EWS in five municipalities of Kailali and Bardia districts, Nepal.	Community-Based Flood Early Warning System (CBEWS)	Business as usual (no intervention)	Not reported	Loss of life, Loss of assets, Timely issuance	Single timepoint
Raphela 2025	Cross-sectional study	South Africa	Adults 18+ in Vosloorus Extension 21, South Africa, an area prone to flash flooding.	Flood early warning system (FEWS)/ Early warning messages (EWMs)	No comparison group (descriptive/observational)	100	Timely issuance	Single timepoint
Ringo 2024	Mixed methods	Tanzania	Key informants (flood/EWS coordination officials) and six elderly and youth residents (men and women) in flood-prone wards, Tanzania.	Flood Early Warning System (FEWS) — described as informal/hybrid (no structured system)	Business as usual (no intervention)	412 (375 surveyed; 20 KIIs; 17 FGD)	Loss of life, Loss of assets	Single timepoint
Shah 2012	Cross-sectional study	Bangladesh	Farmer household heads in Uria Union, stratified equally between high and low flood-prone areas (25 each).	The national flood early warning system	No comparison group (descriptive/observational)	50	Loss of assets	Single timepoint
Shrestha 2025	Mixed methods	Nepal	Randomly sampled residents across 13 flood-prone villages in three rural municipalities, Nepal; seven purposively selected key informants (DHM staff, gauge reader, ward chair, DRR representative).	Flood early warning system	No comparison group (descriptive/observational)	107 (100 survey; 7 KIIs)	Loss of assets	Single timepoint
Thieken 2007	Cross-sectional study	Germany	11,146 randomly selected households in flood-affected areas of Saxony, Saxony-Anhalt and Bavaria, Germany.	Flood Early Warning System	No comparison group (descriptive/observational)	1,697	Loss of assets, Timely issuance	Single timepoint
Fakhruddin 2019	Economic evaluation	Samoa	Stakeholders (national agencies, community representatives) consulted on Cyclone Evan cost-benefit data, Samoa.	Cyclone early warning system	Counterfactual: losses without EWS vs with EWS	8	Loss of assets, Cost (adoption)	Modelled/projected scenario
Malawi Red Cross Society 2024	Cross-sectional study	Malawi	Adults 18+ in five Cyclone Freddy-affected districts of Southern Malawi; household surveys plus focus groups.	Anticipatory Action (AA) / ECHO IDREAM Early Warning and Anticipatory Action system	Business as usual (no intervention)	1,663	Timely issuance, Accuracy	Single timepoint
Sahana 2023	Cross-sectional study	India	Households across 38 purposively sampled villages in the Sundarban Biosphere Reserve, India.	Cyclone Early Warning System	No comparison group (descriptive/observational)	570	Loss of assets, Timely issuance	Single timepoint
Song 2024	Longitudinal study	China	Aggregate county-level administrative, warning-device and typhoon-disaster data, Guangdong, China; no individual participants.	Rural loudspeaker Systems (used for Typhoon Early Warnings)	No comparison group (descriptive/observational)	595	Loss of life, Injuries/illnesses, Loss of assets	Longitudinal (2016–2021)
Chatfield 2013	Mixed methods	Indonesia	Not reported (Twitter users during a tornado warning).	Not named	No comparison group (descriptive/observational)	4,000,000	Timely issuance	Single timepoint

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Reference	Study design	Setting	Population	Intervention name (EWS)	Comparison condition	Sample size (n)	Outcomes reported	Follow-up period
Escaleras 2008	Quasi-experimental study	United States	Tsunami events worldwide (1966–2004) with complete data; no individual participants.	Pacific Tsunami Warning Center (PTWC); West Coast/Alaska Warning Centre; TWSP	Business as usual (no intervention)	146 (tsunamis)	Loss of life, Timely issuance	Single timepoint
Oktari 2014	Mixed methods	Indonesia	Disaster management officials and practitioners involved in Indonesia's tsunami EWS dissemination chain (government, military, police, meteorological agency, media).	Tsunami Early Warning System (EWS) in Aceh	No comparison group (descriptive/observational)	Not reported	Timely issuance, Accuracy	Single timepoint

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Appendix F. Summary of included studies addressing qualitative phenomenon of interest

Reference	Study design	Setting	Population	Intervention name (EWS)	Sample size (n)	Phenomena reported	Qualitative data collection method(s)	Analysis approach
Akwango 2017	Cross-sectional study	Uganda	Households in sub-counties covered by a drought early warning system pilot in Nakapiripirit, Uganda.	Karamoja Drought Early Warning System (KDEWS)	173	Barriers; Usefulness; 'Understandability'	Focus group interviews; 1:1 interviews; For analysis of 'DEWS implementation processes' – documentary analysis was also conducted	Not reported
Alemayehu 2025	Qualitative research	Ethiopia	Experts with knowledge of livestock water/pasture monitoring and early warning systems.	Early warning systems	60	Enablers; Barriers	Focus group interviews; 1:1 interviews; 'consultative workshops'	Not reported
Graves 2025	Qualitative research	Australia	Farming individuals owning, consulting on, or managing a farm in the Murray-Darling Basin (Victoria/NSW/Queensland) with prior drought experience.	Early warning system for drought	100	Enablers; Barriers; Usefulness	1:1 interviews	Thematic analysis
Mamba 2025	Mixed methods	Kingdom of Eswatini	Households in two drought-prone regions of Eswatini (survey); focus groups included people with disabilities, elderly and young people.	Eswatini National Multi-Hazard Early Warning System	796	Enablers; Barriers; Usefulness	Not reported	Not reported
Sharafi 2021	Cross-sectional study	Iran	Wheat farmers in Kermanshah Township, Iran, selected via multi-stage cluster random sampling.	Drought Early Warning System	370	Enablers; Barriers	Survey	Not reported
Adams 2024	Cross-sectional study	United States	Public school superintendents in Alaska, California or Oregon.	ShakeAlert	225	Barriers; Acceptability	Survey	Not reported
Allen 2025	Cross-sectional	Global study (98 Countries, not including the USA)	Not reported (global smartphone app users).	Android Earthquake Alerts (AEA) system	1,555,006	Usefulness; Trust	Survey	Not reported
Bossu 2022	Cross-sectional study	Multi-country (user survey data from Peru)	App users aged 18+ within 1,500 km of an earthquake epicentre.	Smartphone-based earthquake early warning system	~2,625	Barriers; Acceptability; Usefulness	Survey	Not reported
Goltz 2024	Cross-sectional study	United States	Self-selected respondents who felt the Ojai, California earthquake (via USGS 'Did You Feel It?' system).	ShakeAlert	2,490	Usefulness	Survey	Quantitative descriptive analysis
Hoshiba 2014	Cross-sectional study	Japan	Recipients of earthquake early warnings in Japan: 5,500 households surveyed by mail across three prefectures, plus a nationwide web survey.	Japan Meterological Agency Earthquake Early Warning System	2,817	Usefulness	Survey	Not reported
Laure 2022	Case study using questionnaire surveys	Peru (77% of participants in Peru); others in Ecuador (19%); Columbia (3%); Venezuela or Brazil (1%)	Users of the Earthquake Network app who were within the felt-shaking area.	Earthquake Network (EQN)	2,625	Acceptability; Usefulness; Perceived legitimacy and propensity to pay for the service	Survey	Descriptive quantitative analysis
Nakayachi 2019	Cross-sectional study	Japan	Japanese residents in regions that received earthquake early warnings, recruited via an online research panel; gender/age quota-matched to population.	Earthquake Early Warning System	299 (Study 1); 450 (Study 2)	Usefulness	Survey	Descriptive analysis of survey responses.
Naylor 2018	Mixed methods	Japan	Survivors of the 2011 Great East Japan Earthquake and Tsunami living in temporary housing, Tohoku region — primarily elderly residents.	Earthquake Early Warning System; Tsunami Early Warning System	78	Barriers	Not reported	Not reported
Pescaroli 2023	Mixed methods	Mexico	Representatives of public/private organisations (government, business, civil protection, education, NGOs, academia) in Mexico City.	SASMEX (Seismic Alert System of Mexico)	93 (15 interviews; 78 questionnaire)	Enablers; Barriers; Acceptability; Usefulness	Not reported	Not reported
Sari 2023	Qualitative research	Indonesia	Village head, disaster risk reduction forum chair and regional facilitator involved in a local early warning system, Indonesia.	People-Centered Early Warning System (EWS)	3	Barriers	1:1 interviews	Thematic analysis
Tan 2023	Cross-sectional study	New Zealand	Adults 18+ in Aotearoa New Zealand who received a mobile phone alert.	Android Earthquake Alert (AEA) System	1,195	Usefulness; Perceived trust	Survey	Statistical and descriptive analysis
Vinnell 2023	Cross-sectional study	New Zealand	Not reported.	Android Earthquake Alert System (AEA)	1,087 (Survey 1); 2,063 (Survey 2)	Acceptability; Usefulness	Survey	Descriptive analysis
Adegun 2024	Qualitative research	Nigeria	Residents of slum communities in Lagos and Akure, Nigeria.	Community Heat Early Warning System (CHEWS)	637	Enablers; Barriers; Usefulness; Behavioural and health changes reported by residents following heat warning information	Focus group interviews; Survey	Thematic analysis

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Reference	Study design	Setting	Population	Intervention name (EWS)	Sample size (n)	Phenomena reported	Qualitative data collection method(s)	Analysis approach
Oberai 2025	Mixed methods	Australia	Adults aged 65+ living in Southeast Queensland, Australia (Brisbane, Gold Coast, Sunshine Coast); not in residential aged care, no psychological disorders.	Ethos (Extreme heat and older persons) system	78	Acceptability; improved heat preparedness	Survey; Closed-ended survey questionnaire for quantitative data collection and open-ended questionnaire for qualitative data collection.	Descriptive analysis (quantitative); thematic analysis (qualitative)
Trahan 2023	Qualitative research	India	Female outdoor labourers in Ahmedabad, India, all members of the Self Employed Women's Association (SEWA).	Ahmedabad's Heat Action Plan (HAP)	85	Enablers; Barriers	1:1 interviews	Thematic analysis
VanderMolen 2022	Qualitative research	United States	Community leaders, non-profit/CBO representatives, government agency staff, healthcare professionals and educators serving heat-vulnerable communities in San Diego County, USA.	Heat Health Warning System (HHWS)	43	Enablers; Barriers; Usefulness	Focus group interviews	Grounded theory
Abid 2024	Qualitative research	Saudi Arabia	Government officials, NGO staff and community members/leaders in three Malaysian regions (Sarawak, Johor, Kuala Lumpur), purposively sampled.	Community-based flood mitigation (CBFM)	20	Enablers; Barriers	1:1 interviews	Thematic analysis
Bajracharya 2021	Mixed methods	Nepal	Not reported.	Community-Based Flood Early Warning System (CBFEWS)	180 (baseline); 180 (endline)	Usefulness	1:1 interviews; Survey	Thematic analysis
Budimir 2020	Qualitative research	Nepal	National/district stakeholders (hydrology and meteorology officials, NGOs, emergency centres) and community members across three regions of Nepal.	Flood Early Warning System (FEWS)	43 (11+25 national; 7 district; rest not specified)	Acceptability; Usefulness	1:1 interviews; Survey; Workshops	Thematic analysis
Cao 2024	Cross-sectional	Japan	Municipalities across Japan's 47 prefectures.	Flood Early Warning System (FEWS)	350	Barriers	Survey	Not reported
Chinguwo 2022	Mixed methods	Malawi	Key informants from district/village/area Civil Protection Committees (government, NGO staff) and disaster management staff, Malawi.	Community-based early warning system (CBEWS).	40 (16 + 21 members; 3 staff)	Enablers; Barriers; Usefulness	Focus group interviews; Survey	Thematic analysis
Chisty 2021	Qualitative research	Bangladesh	People with disabilities (focus group participants).	Bangladesh's flood EWS	80	Enablers; Barriers; Usefulness	Focus group interviews	Thematic analysis
Ebhuoma 2021	Qualitative research	Nigeria	Farmers of both genders with 10+ years' experience, flood-affected household assets/livelihoods, cultivating low-lying farmland.	Nigerian Emergency Management Agency (NEMA) Early Warning	116	Barriers	Focus group interviews; 1:1 interviews; Survey	Thematic analysis
GlobalDisasterPreparednessCenter 2025	Mixed methods	Malawi	Households in Makhuwira, Chikwawa, Malawi — a highly flood-vulnerable area.	Early Warning/Action Systems (community-based)	378 (households); 17 (KIIs)	Enablers; Barriers	Focus group interviews; 1:1 interviews; Survey	Thematic analysis
Hasan 2024	Mixed methods	Bangladesh	Households purposively sampled from two villages in Sirajganj District, Bangladesh, resident there 10+ years.	Flood Early Warning System (FEWS)/ Flood Forecasting and Warning Centre (FFWC)	116	Usefulness	1:1 interviews	Not reported
Hosen 2019	Descriptive cross-sectional study using survey and interviews for data collection	Bangladesh	Flood-vulnerable community members aged 18–65 in Daudkandi, Bangladesh; FGD participants selected regardless of gender or occupation.	Flood Early Warning Dissemination System (FEWDS)	142 (survey); 2 FGDs (10–12 each); KIIs not specified	Enablers; Acceptability; Usefulness	Focus group interviews; 1:1 interviews; Survey	Descriptive statistics (SPSS/Excel); content analysis (KII/FGD)
Huy 2009	Mixed methods	Vietnam	Households and key informants (local officials, village leaders, Red Cross) in Hai An commune, Vietnam.	People-Centered Early Warning System (EWS)	32 (households); 2 FGDs (10–15 each); KIIs not specified	Enablers; Barriers; Usefulness; Acceptability	Focus group interviews; 1:1 interviews; Survey	Unclear
Islam 2024	Economic evaluation	Bangladesh	Households randomly sampled across four upazilas in Kurigram, Bangladesh.	Regional and community-based flood early warning system	1,000	Usefulness	Focus group interviews; 1:1 interviews; Survey	Not reported
Katsekpor 2025	Qualitative research	Ghana	Institutional, technical and community-level actors selected by professional role and flood/EWS experience.	White Volta Flood Early Warning System (FEWS)	18	Enablers; Barriers	1:1 interviews	Thematic analysis
Lumbroso 2016	Mixed methods	Multiple (Africa, Caribbean and South Asia)	Stakeholders who use or work with early warning systems and weather-hazard risk assessments globally.	Range of EWS in Africa, Carribbean and South Asia	247 (survey; 30 interviewed); ~150 (workshops)	Enablers; Barriers; Usefulness	Focus group interviews; 1:1 interviews; Survey	Not reported
Martin 2024	Qualitative research	India	Traditional/artisanal fishers (10 per village) across five villages in Thiruvananthapuram district, Kerala, India.	Early warning system	60 (50 fishers; 10 KIIs)	Barriers; Usefulness	Focus group interviews; 1:1 interviews; Survey	Thematic analysis

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Reference	Study design	Setting	Population	Intervention name (EWS)	Sample size (n)	Phenomena reported	Qualitative data collection method(s)	Analysis approach
Mehta 2022	Mixed methods	Australia	Individuals from hazard-affected regions (Phase 1 interviews, convenience/snowball sample) and Australian small businesses (Phase 2 survey).	Not named (multiple EWS)	16 (interviews); 161 (survey)	Enablers; Barriers; Acceptability	1:1 interviews; Survey	Thematic analysis
Melo 2017	Cross-sectional study	Brazil	Community leaders (neighbourhood association presidents) in Brazil.	Alerta Rio	71	Barriers; Acceptability; Usefulness	Survey	Not reported
Moises 2022	Qualitative research	Namibia	9 key informants (government/NGO officials operating the flood EWS) and 8 focus groups of 7–9 residents (village heads, volunteers, farmers, women's committee members), Namibia.	Nambia National Flood Early Warning System	9 (interviews); 8 FGDs (7–9 each)	Enablers; Barriers; Usefulness	Focus group interviews; 1:1 interviews	Thematic analysis
Nieland 2016	Cross-sectional study	Australia	75 households across four flood-affected areas, randomly selected by street.	Flash Flood Warning System	75	Usefulness; Perceived Lead time needed after a flash flood warning for safe evacuation	Survey	Descriptive analysis
Obiero 2025	Qualitative research	Kenya	Stakeholders (county/national government, local administration, community, NGOs, private sector) in a flood-vulnerable underserved community, Kenya.	Early Warning Messages	94 (16 KIIs; 78 FGDs)	Enablers; Barriers; Acceptability; Usefulness	Focus group interviews; 1:1 interview	Thematic analysis
Ochoa-Rodríguez 2018	Mixed methods	United Kingdom	Flood risk managers, emergency officers and engineers in England (survey); flood professionals from the UK and EU (workshops).	Extreme Rainfall Alerts (ERAs); Surface Water Flood Risk Assessment (SWFRA)/Flood Guidance Statement (FGS)	74 (survey, 42 complete); 40+ (workshops)	Barriers; Usefulness	Survey; Workshops	Descriptive analysis (survey); thematic synthesis (workshops)
Omer 2026	Mixed methods	Somalia	Households across four regions of Somaliland, stratified by region and covering men, women and youth (survey); government officials, community leaders and NGO staff (KIIs); women, youth and elders (FGDs).	Early Warning Systems (Somaliland); Famine Early Warning Systems Network (FEWS NET)	390 (survey); 8 KIIs; 5 FGDs (6-10 each)	Barriers	Focus group interviews; 1:1 interviews; Survey	Thematic analysis
Pandey 2023	Qualitative research	Nepal	Communities in flood-prone wards of Chitwan and Parasi districts, Nepal.	Community-Based Flood Early Warning System (CBFEWS)	26 KIIs; 8 FGDs (total not reported)	Barriers; Enablers	Focus group interviews; 1:1 interviews; Field observations, secondary data review (journal articles, books, government/NGO reports, websites)	Thematic analysis
Pereira 2024	Mixed methods	Brazil	Household heads (18+) in two traditional/Indigenous communities in Costa Verde, Brazil; separate storytelling sessions with 4 traditional leaders per territory; workshops with community members. People with disabilities and under-18s excluded.	Sistema Nacional de Proteção e Defesa Civil (Civil Defence); People-Centred EWS (PCEWS) prototype	51 (28 + 23); 4 leaders/territory	Barriers; Accessibility to EWS	Survey; Workshops and storytelling	Descriptive statistics; thematic analysis; spatial analysis; triangulation
Rahman 2013	Mixed methods	Bangladesh	Flood-vulnerable communities in two Bangladesh subdistricts (flash-flood-prone Dhobaura and river-flood-prone Shibalaya).	Early Flood Warning Dissemination System (EFWDS); Flood Forecasting and Warning Centre (FFWC)	217 (117 + 100)	Enablers; Usefulness; Barriers	Survey; Interaction/consultation with officials of organisations involved in flood forecasting and dissemination (BWDB, FFWC, Hydrology Directorate, Bangladesh Meteorological Department, Disaster Management Bureau, research organisations)	Descriptive statistics
Ramsden 2025	Qualitative research	United Kingdom	Community flood groups actively using flood forecasting/monitoring information in England, identified via regional/national flood stakeholders and networks.	Flood early warning systems (FEWS)	10 flood groups; 14 representatives	Use of FEWS by community flood groups in England, including types of information used, actions taken, and challenges faced.; Enablers; Barriers	1:1 interviews	Thematic analysis
Ringo 2024	Mixed methods	Tanzania	Key informants (flood/EWS coordination officials) and six elderly and youth residents (men and women) in flood-prone wards, Tanzania.	Flood Early Warning System (FEWS) — described as informal/hybrid (no structured system)	412 (375 surveyed; 20 KIIs; 17 FGD)	Usefulness	Key informant interviews	Thematic analysis
Rohman 2024	Qualitative research	Vietnam	Deaf and hard-of-hearing individuals.	Early warning messages	108 (20 interviews; 88 FGD)	Enablers; Barriers	Focus group interviews; 1:1 interviews	Thematic analysis
Sa'adi 2024	Mixed methods	Malaysia	Residents of two flood-prone districts, Johor, Malaysia (survey); Department of Irrigation and Drainage officers (interviews).	National Flood Forecasting and Warning System (PRAB)	106	Acceptability	1:1 interviews	Not reported

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Reference	Study design	Setting	Population	Intervention name (EWS)	Sample size (n)	Phenomena reported	Qualitative data collection method(s)	Analysis approach
Salgado 2025	Qualitative research	Colombia	Community leaders, company representatives, fire brigade commander, schools and disaster-response experts in Manizales, Colombia.	Flood Early Warning Systems (FEWs)	98 (33 interviews; 32+23 workshops; 10 survey)	Enablers; Barriers	1:1 interviews; Survey; Workshop	SWOT framework analysis
Shah 2023	Mixed methods	Pakistan	Households in four flood-prone districts of Khyber Pakhtunkhwa, Pakistan (survey); participants with flood/EWS experience (focus groups).	Flood Early Warning System (FEWS)	600 (survey); 7 FGDs (10–15 each)	Barriers	Focus group interviews; Survey	Thematic analysis
Shrestha 2014	Qualitative research	Nepal	26 disaster risk reduction organisations (government, INGOs, UN agencies, national NGOs) consulted; focus groups and observations in two districts with EWS in place, Nepal.	GLOF EWS (Tsho Rolpa); Bhote Koshi flood EWS; DHM web-based telemetry flood EWS (Koshi Basin); Community-based flood EWS (Practical Action/DHM/NRCS/ Mercy Corps)	26 orgs; 61 stakeholders	Enablers; Barriers	1:1 interviews	Project Cycle Analysis (PCA) framework; gender analysis; descriptive/ comparative analysis
Shrestha 2021	Qualitative research	Nepal	Officials implementing a flood EWS at national/district/local level (KIIs); community disaster management committee members, including a women-only group (FGDs), Nepal.	Flood Early Warning Systems	28 (2 FGDs) + KIIs (n not specified)	Enablers; Gaps in flood risk communication; Barriers	1:1 interviews	Alexander (2015) risk communication framework
Shrestha 2025	Mixed methods	Nepal	Randomly sampled residents across 13 flood-prone villages in three rural municipalities, Nepal; seven purposively selected key informants (DHM staff, gauge reader, ward chair, DRR representative).	Flood early warning system	107 (100 survey; 7 KIIs)	Barriers	1:1 interviews; Survey	Thematic analysis
Smith 2022	Qualitative research	United Kingdom	368 university-affiliated participants purposively selected from a stratified cohort of 80, with flooding experience; diverse representation including Black, Asian and minority ethnic and disabled participants sought.	Cell Broadcast (CB)	80	Enablers; Barriers; Acceptability; Usefulness	Focus group interviews; Workshops using post-it exercises (i.e., suggestions written on post-its and stuck on wall), participant activity sheets (written answers)	NVivo thematic coding; matrix queries; descriptive statistics (Excel)
Thieken 2007	Cross-sectional study	Germany	11,146 randomly selected households in flood-affected areas of Saxony, Saxony-Anhalt and Bavaria, Germany.	Flood Early Warning System	1,697	Perceived knowledge about flood hazards	Survey	Correlations (Spearman's rho)
Thongs 2025	Cross-sectional study	Jamaica, Saint Vincent and the Grenadines, Saint Lucia, and Trinidad and Tobago	Adults 18+ resident in the study location for 5+ years, across Jamaica, St Vincent and the Grenadines, St Lucia and Trinidad and Tobago.	Caribbean-based Multi-hazard early warning system (MHEWS)	416	Enablers; Barriers; Acceptability; Usefulness	Survey	Not reported
WorldFoodProgramme(WFP) 2025	Mixed methods	Southern African countries (Madagascar, Zimbabwe, Malawi, and Tanzania)	Randomly selected households (men, women, people with disabilities, vulnerable groups) across Zimbabwe, Tanzania, Malawi and Madagascar; separate focus groups by gender and age.	Not named (anticipatory action inclusion)	2,477 (households)	Enablers; Barriers; Acceptability	Focus group interviews; 1:1 interviews; Survey	Descriptive statistics with cross-tabulation (quantitative); Thematic analysis (qualitative)
Yangquiling 2024	Mixed methods	Philippines	Randomly sampled adults (18+) who experienced Typhoon Mangkhut in two villages, Pangasinan, Philippines.	Not named (TV, radio, SMS channels)	229 (survey); ~25–35 (KIIs, inconsistent in source)	Barriers	1:1 interviews; Survey	OLS regression; descriptive analysis; thematic analysis
Al-Zaabi 2022	Qualitative research	Oman	Officials responding to cyclone/ depression emergencies in Oman.	Early warning system	Not reported	Usefulness	Twitter data	Not reported
Alam 2024	Mixed methods	Bangladesh	Household heads aged 60+ in cyclone-affected communities, selected to describe socio-economic change and vulnerability.	Cyclone Preparedness Programme (CPP)	362	Barriers	Focus group interviews; Survey	Content analysis
HAQUE 1995	Cross-sectional	Bangladesh	Households in cyclone-affected urban (Bandar) and rural/offshore (Kutubdia Island) areas of Bangladesh, 1991.	Cyclone warning system	268 (162 urban; 106 rural)	Barriers	Survey	Not stated
MalawiRedCrossSociety 2024	Cross-sectional study	Malawi	Adults 18+ in five Cyclone Freddy-affected districts of Southern Malawi; household surveys plus focus groups.	Anticipatory Action (AA) / ECHO IDREAM Early Warning and Anticipatory Action system	1,663	Usefulness	Focus group interviews; Survey	Not reported
Mishra 2024	Mixed methods	India	Women (one per household) and stakeholders/disaster response personnel involved in EWS and evacuation in Puri district, India, after Cyclone Fani.	Early warning system	384 (211 survey; 173 IDI/ KIIs)	Barriers; Enablers	Focus group interviews; 1:1 interviews; Survey	Thematic analysis
RedCrossRedCrescentClimateCentre 2022	Qualitative research	Palau Island	Youth aged 18 and over.	Community-based Early Warning Early Action	52 (survey); 6 (consultations)	Enablers; Barriers; Usefulness	Focus group interviews; Survey	Thematic analysis
Roy 2015	Mixed methods	Bangladesh	Individual households in four unions across two districts (Bagerhat and Patuakhali), Bangladesh.	Cyclone early warning system	200 (survey); 3 (interviews)	Enablers; Barriers; Acceptability	1:1 interviews; Survey	Thematic analysis

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Reference	Study design	Setting	Population	Intervention name (EWS)	Sample size (n)	Phenomena reported	Qualitative data collection method(s)	Analysis approach
Sharma 2009	Before-and-after study or Pre-test-Post-test study	India	Household decision-makers who received a cyclone warning in Krishna district, Andhra Pradesh, India.	Cyclone early warning system	44	Barriers; Acceptability	Focus group interviews; 1:1 interviews; Survey	Thematic analysis
World Meteorological Organization (WMO) 2018	Mixed methods	Anguilla, Antigua and Barbuda, Dominica, the Virgin Islands (United Kingdom), and the Turks and Caicos Islands.	Senior meteorological/government officials and NGO representatives across several hurricane-affected Caribbean countries and territories.	Caribbean Multi-Hazard Early Warning Systems (MHEWS)	28 stakeholders; 4 orgs; 4 offices (total not reported)	Barriers; Acceptability; Usefulness	Focus group interviews; Survey	Descriptive analysis (survey); thematic analysis (qualitative)
Alam 2023	Qualitative research	Bangladesh	Community members, community leaders, experts and administrators in three districts of Southeast Bangladesh.	Various	59	Enablers	Focus group interviews; 1:1 interviews	Not reported
Yik 2023	Mixed methods	Hong Kong	Residents of landslide-prone rural Hong Kong (Study 1); pedestrians aged 18+ at high-traffic public locations (Study 2).	Hong Kong Landslip Early Warning System	39 (5 FGDs, Study 1); 1,834 (Study 2)	Acceptability	Focus group interviews; Survey	Not reported
Potter 2021	Qualitative research	New Zealand	Forecast meteorologists, flood forecasters, governance officials and communicators across the UK, France, Switzerland and New Zealand.	Impact-based forecast and warning (IBFW) systems	67 (9 interviews; 40+9+9 workshops)	Barriers	Focus group interviews; Workshops	Thematic analysis
United Nations Office for Disaster Risk Reduction 2023	Qualitative research	Fiji	Community members (urban/rural, coastal/inland, Fijian and Indo-Fijian) in seven villages, Fiji; consultations prioritised women, girls, people with disabilities and older persons.	Not named (Fiji Meteorological Service/NDMO early warning process)	36 (consultations)	Enablers; Barriers; Acceptability; Usefulness	Focus group interviews; 1:1 interviews; Survey	Descriptive analysis with intersectionality analysis
Arif 2019	Qualitative research	Indonesia	Community members affected by tsunamis and key informants operating the tsunami early warning system.	Indonesian Tsunami Early Warning System	125 (55 community; 70 KIIs)	Usefulness	Focus group interviews; 1:1 interviews	Thematic analysis
Katsetsiadou 2023	Cross-sectional study	Greece	Residents of the tsunami-affected area, open to all respondents.	Tsunami early warning system	344	Enablers; Usefulness	Survey	Not reported
Oktari 2014	Mixed methods	Indonesia	Disaster management officials and practitioners involved in Indonesia's tsunami EWS dissemination chain (government, military, police, meteorological agency, media).	Tsunami Early Warning System (EWS) in Aceh	Not reported	Enablers; Barriers	Focus group interviews; 1:1 interviews; Document review for verification of scoring	Scoring framework (modified UNISDR 2008)
Cao 2016	Cross-sectional	Australia	Residents of three wildfire-prone suburbs in Western Australia with varying urban/rural character.	Wildfire warning system	261	Barriers; Acceptability	Survey	Not reported
Doermann 2021	Qualitative research	United States	Not reported (message/alert content analysis, no human participants).	Wireless emergency alert (WEA)	Not reported	Usefulness	Comparative case study (content analysis)	Message design analysis/content analysis

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Appendix G. Detailed risk of bias assessment for included studies – RoB 2

Study	D1	D2	D3	D4	D5	Overall
Mehiriz 2018	Low	Low	Low	Low	Some concerns	Some concerns

D1: Risk of bias due to the randomisation process

D2: Risk of bias due to deviations from intended interventions

D3: Risk of bias due to missing outcome data

D4: Risk of bias in measurement of the outcome

D5: Risk of bias in selection of the reported result

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Appendix H. Detailed risk of bias assessment for included studies – ROBINS-I

Study	D1	D2	D3	D4	D5	D6	Overall
Kreibich 2021	Low (except for concerns about uncontrolled confounding)	Low	Moderate	Low	Low	Low	Moderate risk of bias
Agyei 2020	Low (except for concerns about uncontrolled confounding)	Low	Moderate	Low	Low	Low	Moderate risk of bias
Aguirre 2019	Low (except for concerns about uncontrolled confounding)	Low	Low	Low	Low	Moderate	Moderate risk of bias
Song 2024	Moderate	Low	Serious	Serious	Low	Low	Serious risk of bias
Escaleras 2008	Low (except for concerns about uncontrolled confounding)	Moderate	Low	Critical	Low	Serious	Critical risk of bias
Norkhairi 2022	Low (except for concerns about uncontrolled confounding)	Low	Low	Low	Low	Low	Low risk of bias except for concerns about uncontrolled confounding
Clemens 2022	Low (except for concerns about uncontrolled confounding)	Low	Low	Moderate	Low	Moderate	Moderate risk of bias
Altindag 2017	Low (except for concerns about uncontrolled confounding)	Low	Low	Low	Low	Moderate	Moderate risk of bias
Ebi 2004	Low (except for concerns about uncontrolled confounding)	Low	Low	Moderate	Low	Low	Moderate risk of bias
Chau 2009	Serious	Low	Low	Moderate	Low	Low	Serious risk of bias
Weinberger 2018	Low (except for concerns about uncontrolled confounding)	Low	Low	Low	Low	Low	Low risk of bias except for concerns about uncontrolled confounding
Heudorf 2014	Moderate	Low	Low	Moderate	Low	Moderate	Moderate risk of bias
Chen 2023	Low (except for concerns about uncontrolled confounding)	Low	Low	Low	Low	Low	Low risk of bias except for concerns about uncontrolled confounding
Heo 2019	Low (except for concerns about uncontrolled confounding)	Low	Low	Low	Low	Moderate	Moderate risk of bias
Feldbusch 2025	Low (except for concerns about uncontrolled confounding)	Low	Low	Low	Low	Low	Low risk of bias except for concerns about uncontrolled confounding

D1: Bias due to confounding

D2: Bias in the selection of participants into the study

D3: Bias in the classification of the interventions

D4: Bias due to missing data

D5: Bias in measurement of the outcome

D6: Bias in selection of the reported results

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Appendix I. Detailed CASP assessment for qualitative studies

Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Overall
Abid 2024	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Positive/Methodologically sound
Adams 2024	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Adegun 2024	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Al-Zaabi 2022	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes	Positive/Methodologically sound
Alam 2023	Yes	Yes	Yes	No	Yes	No	Yes	No	No	Yes	Negative/Relatively poor methodology
Alemayehu 2025	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Positive/Methodologically sound
Arif 2019	Yes	Yes	Yes	Yes	Yes	Can't Tell	No	No	Yes	Yes	Positive/Methodologically sound
Budimir 2020	Yes	Yes	Yes	Can't Tell	Yes	No	Yes	No	Yes	Yes	Positive/Methodologically sound
Chisty 2021	Yes	Yes	Can't Tell	Yes	Yes	Can't Tell	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Doermann 2021	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Positive/Methodologically sound
Ebhuoma 2021	Yes	Yes	Yes	Yes	Yes	Can't Tell	Can't Tell	Yes	Yes	Yes	Positive/Methodologically sound
Graves 2025	Yes	Yes	Yes	Can't Tell	Yes	No	No	Yes	Yes	Yes	Positive/Methodologically sound
Katsekpor 2025	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Positive/Methodologically sound
Martin 2024	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Positive/Methodologically sound
Mehta 2022	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Moises 2022	Yes	Yes	Yes	Yes	Yes	Can't Tell	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Obiero 2025	Yes	Yes	Yes	Yes	Yes	Can't Tell	Can't Tell	Yes	Yes	Yes	Positive/Methodologically sound
Pandey 2023	Yes	Yes	Yes	Yes	Yes	Can't Tell	No	No	Yes	Yes	Positive/Methodologically sound
Potter 2021	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Ramsden 2025	Yes	Yes	Yes	Yes	Yes	Can't Tell	Yes	Yes	Yes	Yes	Positive/Methodologically sound
RedCrossRedCrescentClimateCentre 2022	Yes	Yes	Yes	Can't Tell	Yes	No	No	Can't Tell	Yes	Yes	Negative/Relatively poor methodology
Rohman 2024	Yes	Yes	Yes	Can't Tell	Yes	No	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Salgado 2025	Yes	Yes	Yes	Can't Tell	Yes	Can't Tell	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Sari 2023	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Negative/Relatively poor methodology
Sharma 2009	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Positive/Methodologically sound
Shrestha 2014	Yes	Yes	Yes	Yes	Yes	No	Can't Tell	No	Yes	Yes	Positive/Methodologically sound
Shrestha 2021	Yes	Yes	Yes	Can't Tell	Yes	No	No	Yes	Yes	Yes	Positive/Methodologically sound
Smith 2022	Yes	Yes	Yes	Yes	Yes	Can't Tell	Can't Tell	Yes	Yes	Yes	Positive/Methodologically sound
Trahan 2023	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Positive/Methodologically sound
United Nations Office for Disaster Risk Reduction (UNDRR, 2023)	Yes	Yes	Yes	Can't Tell	No	Can't Tell	No	Can't Tell	Yes	Yes	Negative/Relatively poor methodology
VanderMolen 2022	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Positive/Methodologically sound

Q1: Was there a clear statement of the aims of the research?

Q2: Is a qualitative methodology appropriate?

Q3: Was the research design appropriate to address the aims of the research?

Q4: Was the recruitment strategy appropriate to the aims of the research?

Q5: Was the data collected in a way that addressed the research issue?

Q6: Has the relationship between researcher and participants been adequately considered?

Q7: Have ethical issues been taken into consideration?

Q8: Was the data analysis sufficiently rigorous?

Q9: Is there a clear statement of findings?

Q10: Is the result valuable?

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Appendix J. Detailed CASP assessment for included economic evaluations

Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Overall
Arias 2015	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Bouta 2020	Yes	Yes	Yes	Yes	Can't tell	Can't tell	Yes	Can't tell	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Fakhruddin 2019	Yes	Can't tell	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Islam 2024	Yes	Can't tell	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	Yes	Yes	Yes	Positive/Methodologically sound
Rai 2020	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Can't tell	Yes	Can't tell	Can't tell	Negative/Relatively poor methodology
Williams 2022	Yes	No	No	Yes	Yes	No	Yes	No	No	Can't tell	Can't tell	Can't tell	Negative/Relatively poor methodology

Q1: Was a well-defined question posed?

Q2: Was a comprehensive description of the competing alternatives given?

Q3: Does the paper provide evidence that the programme would be effective? (i.e., would the programme do more good than harm?

Q4: Were the effects of the intervention identified, measured and valued appropriately?

Q5: Were all important and relevant resources required, and health outcomes costs for each alternative identified, measured in appropriate units and valued credibly?

Q6: Were costs and consequences adjusted for different times at which they occurred (discounting)?

Q7: What were the results of the evaluation

Q8: Was an incremental analysis of the consequences and cost of alternatives performed?

Q9: Was an adequate sensitivity analysis performed?

Q10: Is the programme likely to be equally effective in your context or setting?

Q11: Are the costs translatable to your setting?

Q12: Is it worth doing in your setting?

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Appendix K. Detailed MMAT assessment for non-randomised, quantitative descriptive, and mixed methods studies

Study	S1	S2	Q1	Q2	Q3	Q4	Q5	Overall
MMAT (non-randomised) (n=3)								
Prathumchai 2020	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Sahana 2023	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	4/5
Tang 2023	Yes	Yes	Can't tell	Yes	Yes	Yes	Yes	4/5
MMAT (Quantitative descriptive) (n=31)								
Ahn 2021	Yes	Yes	Yes	No	Yes	No	Yes	3/5
Akwango 2017	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Alias 2020	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	4/5
Allen 2025	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	4/5
Bossu 2022	Yes	Yes	No	Can't tell	Yes	Can't tell	Yes	2/5
Bostrom 2022	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Cao 2016	Yes	Yes	Yes	No	Yes	Can't tell	Yes	3/5
Cao 2024	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	3/5
Diakakis 2022	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	3/5
Goltz 2024	Can't tell	Yes	Yes	No	Yes	Yes	Yes	4/5
HAQUE 1995	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Hosen 2019	Yes	Yes	No	Can't tell	Yes	Can't tell	Yes	2/5
Hoshiba 2014	No	Yes	Yes	Yes	Yes	No	Yes	4/5
Katsetsiadou 2023	No	Yes	Yes	Yes	No	No	Yes	3/5
Laure 2022	Yes	Yes	Yes	No	Yes	Can't tell	Yes	3/5
Lumbroso 2016	Yes	Yes	Yes	Yes	Yes	No	No	3/5
MalawiRedCrossSociety 2024	No	Yes	Yes	Yes	Yes	Can't tell	Yes	4/5
Melo 2017	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Nakayachi 2019	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	3/5
Nieland 2016	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	4/5
Nitschke 2016	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Raphela 2025	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Sa'adi 2024	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	4/5
Shah 2012	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	4/5
Sharafi 2021	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Tan 2023	Yes	Yes	Yes	No	Yes	Can't tell	Yes	3/5
Thieken 2007	Yes	Yes	Yes	Yes	Yes	No	Yes	4/5
Thongs 2025	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	3/5
Vinnell 2023	Yes	Yes	Yes	No	Yes	Can't tell	Yes	3/5
Wu 2020	Yes	Yes	Yes	Can't tell	Yes	Yes	Yes	4/5
Yik 2023	Yes	Yes	Yes	Can't tell	Yes	Can't tell	Yes	3/5
MMAT (Mixed methods) (n=24)								
Alam 2024	Yes	Yes	Yes	No	No	Can't tell	No	1/5
Bajracharya 2021	Yes	Yes	Yes	Can't tell	Yes	No	No	2/5
Chatfield 2013	Yes	Yes	Yes	Yes	No	No	No	2/5
Chinguwo 2022	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
GlobalDisasterPreparednessCenter 2025	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Hasan 2024	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	4/5
Huy 2009	Yes	Yes	No	No	No	No	No	0/5
Mamba 2025	No	Yes	Yes	Yes	Yes	No	Yes	4/5
Mishra 2024	Yes	Yes	Yes	Yes	Yes	No	Yes	4/5
Naylor 2018	Yes	Yes	No	Yes	Yes	No	No	2/5
Oberai 2025a	No	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Ochoa-Rodríguez 2018	Yes	Yes	Yes	Yes	Yes	Yes	No	4/5
Oktari 2014	Yes	Yes	No	No	Yes	No	No	1/5
Omer 2026	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	4/5
Pereira 2024	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Pescaroli 2023	Yes	Yes	Yes	Yes	Yes	No	Yes	4/5
Rahman 2013	Yes	Yes	Yes	No	No	No	No	1/5
Ringo 2024	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
Roy 2015	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	4/5
Shah 2023	Yes	Yes	Yes	Yes	Yes	No	Yes	4/5
Shrestha 2025	Yes	Yes	Yes	Yes	Can't tell	No	No	2/5
WorldFoodProgramme(WFP) 2025	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5/5
WorldMeteorologicalOrganization(WMO) 2018	Yes	Yes	Yes	Yes	Yes	Can't tell	Can't tell	3/5
Yangquiling 2024	Yes	Yes	Yes	Yes	Yes	No	Yes	4/5

Screening questions applicable to all MMAT checklists:

S1: Are there clear research questions?

S2: Do the collected data allow to address the research questions?

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MMAT Non-randomised studies:

Q1: Are the participants representative of the target population

Q2: Are measurements appropriate regarding both the outcome and intervention (or exposure)?

Q3: Are there complete outcome data?

Q4: Are the confounders accounted for in the design and analysis?

Q5: During the study period, is the intervention administered (or exposure occurred) as intended?

MMAT Quantitative descriptive studies

Q1: Is the sampling strategy relevant to address the research question?

Q2: Is the sample representative of the target population?

Q3: Are the measurements appropriate?

Q4: Is the risk of non-response bias low?

Q5: Is the statistical analysis appropriate to answer the research question?

MMAT Mixed methods studies

Q1: Is there an adequate rationale for using a mixed methods design to address the research question?

Q2: Are the different components of the study effectively integrated to answer the research question?

Q3: Are the outputs of the integration of qualitative and quantitative components adequately integrated?

Q4: Are divergencies and inconsistencies between quantitative and qualitative results adequately addressed?

Q5: Do the different components of the study adhere to the quality criteria of each tradition of the methods involved?

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Appendix L. Early warning systems by operational level

Study	Name of Early Warning System	Hazard type(s)	Operational level	Setting
Allen 2025	Android Earthquake Alerts (AEA) system	Geological	Global	Global study (98 Countries, not including the USA)
Bossu 2022	Smartphone-based earthquake early warning system	Geological	Global	Multi-country (user survey data from Peru)
Laure 2022	The Earthquake Network (EQN) Public earthquake early warning (PEEW)	Geological	Global	Peru (77% of participants in Peru); others in Ecuador (19%); Columbia (3%); Venezuela or Brazil (1%)
Tan 2023	Android Earthquake Alert (AEA) System	Geological	Global	New Zealand
Vinnell 2023	Android Earthquake Alert System (AEA)	Geological	Global	New Zealand
Escaleras 2008	Multiple EWS (Pacific Tsunami Warning Center (PTWC), West Coast/Alaska Warning Centre), Tsunami Warning System in Pacific (TWSP))	Geological	Regional	United States
Lumbroso 2016	Range of EWS in Africa, Carribbean and South Asia	Geological; Hydrometeorological	Regional	Multiple (Africa, Caribbean and South Asia)
Omer 2026	Multiple: Early Warning Systems (EWS) in Somaliland (general system); Famine Early Warning Systems Network (FEWS NET) specifically identified as a notable strength.	Biological; Hydrometeorological	Regional	Somalia
Thongs 2025	Caribbean-based Multi-hazard early warning system (MHEWS)	Geological; Hydrometeorological	Regional	Jamaica, Saint Vincent and the Grenadines, Saint Lucia, and Trinidad and Tobago
WorldFoodProgramme(WFP) 2025	No named early warning system was assessed - study explores inclusion in anticipatory action.	Hydrometeorological; Multi-hazard (not attributable to a single category)	Regional	Southern African countries (Madagascar, Zimbabwe, Malawi, and Tanzania)
WorldMeteorologicalOrganization(WMO) 2018	Caribbean Multi-Hazard Early Warning Systems (EWSs) or National and Regional Early Warning Systems for Hurricanes (Irma and Maria)	Hydrometeorological	Regional	Anguilla, Antigua and Barbuda, Dominica, the Virgin Islands (United Kingdom), and the Turks and Caicos Islands.
Adams 2024	ShakeAlert	Geological	National	United States
Aguirre 2019	Forecast-Based Financing Intervention	Hydrometeorological	National	Peru
Agyei 2020	Flood Early Warning System	Hydrometeorological	National	Philippines
Ahn 2021	Several (ShakeAlert & Earthquake Early Warning System)	Geological	National	Multiple (Japan & USA)
Akwango 2017	Karamoja Drought Early Warning System (KDEWS)	Hydrometeorological	National	Uganda
Al-Zaabi 2022	Early warning system	Hydrometeorological	National	Oman
Alam 2023	Various	Geological	National	Bangladesh
Alam 2024	Cyclone Preparedness Programme (CPP)	Hydrometeorological	National	Bangladesh
Alemayehu 2025	Early warning systems	Hydrometeorological	National	Ethiopia
Alias 2020	Flood dissemination warnings	Hydrometeorological	National	Malaysia
Altindag 2017	Yellow dust warning system (a warning system with behavioural guidelines)	Health	National	Korea
Arias 2015	Technology-Based Early Warning System	Hydrometeorological	National	Philippines
Arif 2019	Indonesian Tsunami Early Warning System	Geological	National	Indonesia
Bostrom 2022	ShakeAlert	Geological	National	United States
Bouta 2020	Earthquake early warning system	Geological	National	United States
Budimir 2020	Flood Early Warning System (FEWS)	Hydrometeorological	National	Nepal
Cao 2016	Wildfire warning system	Forest fires	National	Australia
Cao 2024	Flood Early Warning System (FEWS)	Hydrometeorological	National	Japan
Chatfield 2013	Not named	Geological	National	Indonesia
Chau 2009	Very Hot Weather Warning (VHWW)	Hydrometeorological	National	Hong Kong
Chen 2023	Graded heat health risk early warning model (GHREWM).	Hydrometeorological	National	China
Chisty 2021	Bangladesh's flood EWS	Hydrometeorological	National	Bangladesh
Clemens 2022	Heat Warning and Information System (HWIS)	Hydrometeorological	National	Canada
Diakakis 2022	Flood and Extreme Weather Early Warnings	Hydrometeorological	National	Greece
Doermann 2021	Wireless emergency alert (WEA)	Forest fires	National	United States
Ebhuoma 2021	Nigerian Emergency Management Agency (NEMA) Early Warning	Hydrometeorological	National	Nigeria
Ebi 2004	The Philadelphia Hot Weather-Health Watch/ Warning System (PWWS)	Hydrometeorological	National	United States
Fakhruddin 2019	Cyclone early warning system	Hydrometeorological	National	Samoa
Feldbusch 2025	German heat health warning system (HHWS)	Hydrometeorological	National	Germany
Goltz 2024	ShakeAlert	Geological	National	United States
Graves 2025	Early warning system for drought	Hydrometeorological	National	Australia
HAQUE 1995	Cyclone warning system	Hydrometeorological	National	Bangladesh
Hasan 2024	Flood Early Warning System (FEWS) operated by the Flood Forecasting and Warning Centre (FFWC).	Hydrometeorological	National	Bangladesh

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Study	Name of Early Warning System	Hazard type(s)	Operational level	Setting
Heo 2019	Heatwave warning system	Hydrometeorological	National	Korea
Heudorf 2014	Heat warning system and heat health action plan (HHAP)	Hydrometeorological	National	Germany
Hosen 2019	Flood Early Warning Dissemination System (FEWDS)	Hydrometeorological	National	Bangladesh
Hoshiba 2014	Japan Meterological Agency Earthquake Early Warning System	Geological	National	Japan
Katsekpor 2025	White Volta Flood Early Warning System (FEWS)	Hydrometeorological	National	Ghana
Katsetsiadou 2023	Tsunami early warning system	Geological	National	Greece
Kreibich 2021	Flood early warning system	Hydrometeorological	National	Germany
Mamba 2025	Eswatini National Multi-Hazard Early Warning System	Hydrometeorological	National	Kingdom of Eswatini
Martin 2024	Early warning system	Hydrometeorological	National	India
Mehiriz 2018	Heat episode warning (Télephone Santé)	Hydrometeorological	National	Canada
Mehta 2022	Multiple EWS in response to natural hazard-related disasters affecting the region	Forest fires; Hydrometeorological	National	Australia
Melo 2017	Alerta Rio	Geological; Hydrometeorological	National	Brazil
Mishra 2024	Early warning system	Hydrometeorological	National	India
Moises 2022	Nambia National Flood Early Warning System	Hydrometeorological	National	Namibia
Nakayachi 2019	Earthquake Early Warning System	Geological	National	Japan
Naylor 2018	Earthquake Early Warning System; Tsunami Early Warning System	Geological	National	Japan
Nieland 2016	Flash Flood Warning System	Hydrometeorological	National	Australia
Nitschke 2016	Heat Warning System	Hydrometeorological	National	Australia
Norkhairi 2022	Warning siren (physical siren)	Hydrometeorological	National	Malaysia
Oberai 2025a	Ethos (Extreme heat and older persons) system, a heat early warning system	Hydrometeorological	National	Australia
Obiero 2025b	Early Warning Messages	Hydrometeorological	National	Kenya
Ochoa-Rodríguez 2018	1) First-generation Extreme Rainfall Alerts (ERAs) – piloted July 2008–April 2009, issued operationally from 2009 until October 2011 2) Second-generation Surface Water Flood Risk Assessment (SWFRA) – launched October 201	Hydrometeorological	National	United Kingdom
Oktari 2014	Tsunami Early Warning System (EWS) in Aceh	Geological	National	Indonesia
Pescaroli 2023	SASMEX — Seismic Alert System of Mexico (Sistema de Alerta Sísmica Mexicana)	Geological	National	Mexico
Potter 2021	Impact-based forecast and warning (IBFW) systems	Hydrometeorological	National	New Zealand
Prathumchai 2020	Flood early warning system	Hydrometeorological	National	Thailand
Rahman 2013	Early Flood Warning Dissemination System (EFWDS) in Bangladesh. Key national system: Flood Forecasting and Warning Centre (FFWC) under Bangladesh Water Development Board (BWDB).	Hydrometeorological	National	Bangladesh
Ramsden 2025	Flood early warning systems (FEWS)	Hydrometeorological	National	United Kingdom
Raphela 2025	Flood early warning system (FEWS)/ Early warning messages (EWMs)	Hydrometeorological	National	South Africa
Ringo 2024	Study mentions 'Flood early warning System (FEWS)' but also states that "there are no structured early warning systems in the study areas. Instead, the community uses a hybrid approach that integrates traditional practi	Hydrometeorological	National	Tanzania
Rohman 2024	Early warning messages	Geological; Hydrometeorological	National	Vietnam
Roy 2015	Cyclone early warning system	Hydrometeorological	National	Bangladesh
Sa'adi 2024	National Flood Forecasting and Warning System (PRAB)	Hydrometeorological	National	Malaysia
Sahana 2023	Cyclone Early Warning System	Hydrometeorological	National	India
Salgado 2025	Flood Early Warning Systems (FEWs)	Hydrometeorological	National	Colombia
Shah 2012	The national flood early warning system	Hydrometeorological	National	Bangladesh
Shah 2023	Flood Early Warning System (FEWS)	Hydrometeorological	National	Pakistan
Sharafi 2021	Drought Early Warning System	Hydrometeorological	National	Iran
Sharma 2009	Cyclone early warning system	Hydrometeorological	National	India
Shrestha 2025	Flood early warning system	Hydrometeorological	National	Nepal
Smith 2022	Cell Broadcast (CB) – simulated/pre-recorded cell broadcast severe flood warning messages (trialled ahead of UK adoption)	Hydrometeorological	National	United Kingdom
Song 2024	Rural loudspeaker Systems (used for Typhoon Early Warnings)	Hydrometeorological	National	China
Tang 2023	Early warning systems in China	Hydrometeorological	National	China
Thieken 2007	Flood Early Warning System	Hydrometeorological	National	Germany
Trahan 2023	Ahmedabad's Heat Action Plan (HAP)	Hydrometeorological	National	India
VanderMolen 2022	Heat Health Warning System (HHWS)	Hydrometeorological	National	United States
Weinberger 2018	National Weather Service (NWS) heat alerts/ warnings	Hydrometeorological	National	United States
Williams 2022	Heat Health Warning System (HHWS)	Hydrometeorological	National	Australia
Wu 2020	Heat-health warning systems.	Hydrometeorological	National	China (Shanghai)
Yik 2023	Hong Kong Landslip Early Warning System	Geological	National	Hong Kong
Abid 2024	Community-based flood mitigation (CBFM)	Hydrometeorological	Community/local	Saudi Arabia

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Study	Name of Early Warning System	Hazard type(s)	Operational level	Setting
Adegun 2024	Community Heat Early Warning System (CHEWS)	Hydrometeorological	Community/local	Nigeria
Bajracharya 2021	Community-Based Flood Early Warning System (CBFEWS)	Hydrometeorological	Community/local	Nepal
Chinguwo 2022	Community-based early warning system (CBEWS).	Hydrometeorological	Community/local	Malawi
Global Disaster Preparedness Center 2025	Early Warning/Action Systems, e.g., Community-based early warning systems, evacuation planning, and prepositioning of emergency supplies.	Hydrometeorological	Community/local	Malawi
Huy 2009	People-Centered Early Warning System (EWS) for storm and flood control	Hydrometeorological	Community/local	Vietnam
Islam 2024	Regional and community-based flood early warning system	Hydrometeorological	Community/local	Bangladesh
Malawi Red Cross Society 2024	Anticipatory Action (AA) programming / ECHO IDREAM project Early Warning and Anticipatory Action system	Hydrometeorological	Community/local	Malawi
Pandey 2023	Community-Based Flood Early Warning System (CBFEWS)	Hydrometeorological	Community/local	Nepal
Pereira 2024	Brazilian national EWS (Sistema Nacional de Proteção e Defesa Civil / Civil Defence); People-Centred Early Warning System (PCEWS) prototype developed by this study	Geological; Hydrometeorological	Community/local	Brazil
Rai 2020	Community-Based Flood Early Warning System (CBEWS)	Hydrometeorological	Community/local	Nepal
Red Cross Red Crescent Climate Centre 2022	Community-based Early Warning Early Action	Hydrometeorological	Community/local	Palau Island
Sari 2023	People-Centered Early Warning System (EWS)	Geological	Community/local	Indonesia
Shrestha 2014	Multiple systems described: (1) GLOF early warning system for Tsho Rolpa (1990s) (2) Bhote Koshi flood early warning system (Bhote Koshi Power Company) (3) DHM web-based telemetry flood early warning system (Koshi Basin)	Hydrometeorological	Community/local	Nepal
Shrestha 2021	Flood Early Warning Systems	Hydrometeorological	Community/local	Nepal
United Nations Office for Disaster Risk Reduction 2023	No named early warning system. Paper assesses the overall national/community-based early warning process in Fiji — involving the Fiji Meteorological Service (NMHS), NDMO, and traditional/local dissemination structures.	Hydrometeorological	Community/local	Fiji
Yangquiling 2024	No single named EWS. The study examined the various channels/sources through which underserved communities received early warning information ahead of Super Typhoon Mangkhut, including: TVS, Radio. SMS alert.	Forest fires; Geological; Hydrometeorological	Community/local	Philippines

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Appendix M. Mortality GRADE ratings

GRADE domain	Description/rationale	Downgrade
Risk of bias	72% of the 18 contributing studies have a low- or moderate-concern rating (50% low, 22% moderate), with 28% serious/ critical concerns.	-0
Inconsistency	Among the studies that assessed causal effect, the most common direction of effect ('No effect') accounted for only 38% of them — very serious concern.	-2
Indirectness	1 of 18 studies (6%) used an indirect/proxy measure — no/minor concern	-0
Imprecision	18 studies — no/minor concern	-0

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Appendix N. Morbidity GRADE ratings

GRADE domain	Description/rationale	Downgrade
Risk of bias	77% of contributing studies (9 in total) have a low- or moderate-concern rating (44% low, 33% moderate; 22% serious/ critical). No/minor concern.	-0
Inconsistency	Among the 5 tested findings for this outcome, no single direction of effect predominates: 'Mixed effect' and 'No effect' are tied for most common, each accounting for 40% of them — very serious concern.	-2
Indirectness	1 of 9 studies (11%) use an indirect/proxy measure — no/minor concern	-0
Imprecision	9 studies — serious concern (small evidence base)	-1

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Appendix O. Loss of livelihood GRADE ratings

GRADE domain	Description/rationale	Downgrade
Risk of bias	Contributing study has a low concern rating on risk of bias (100% low, 0% moderate; 0% serious/critical). No/minor concern.	-0
Inconsistency	Outcome not statistically tested - serious concern.	-1
Indirectness	The study used an indirect/proxy measure of the outcome — very serious concern	-2
Imprecision	1 study — very serious concern (very small evidence base)	-2

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Appendix P. Loss of assets GRADE ratings

GRADE domain	Description/rationale	Downgrade
Risk of bias	71% of contributing studies (14 total, tested and not tested combined) have a low- or moderate-concern reconciled critical appraisal rating (50% low, 21% moderate; 29% serious/critical). No/minor concern.	-0
Inconsistency	Among the 5 tested findings for this outcome, the most common direction of effect ('Positive effect') accounts for only 40% of them — very serious concern.	-2
Indirectness	3 of 14 studies (21%) use an indirect/proxy measure — serious concern	-1
Imprecision	14 studies — no/minor concern	-0

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Appendix Q. Timely issuance of alert GRADE ratings

GRADE domain	Description/rationale	Downgrade
Risk of bias	100% of contributing studies (5 total, tested and not tested combined) have a low- or moderate-concern reconciled critical appraisal rating (80% low, 20% moderate; 0% serious/critical). No/minor concern.	-0
Inconsistency	Among the 2 tested findings for this outcome, no single direction of effect predominates: 'No effect' and 'Mixed effect' are tied for most common, each accounting for 50% of them — serious concern.	-1
Indirectness	2 of 5 studies (40%) use an indirect/proxy measure (Rai 2020's counterfactual expectation of savings from additional lead time, and Ochoa-Rodríguez 2018's explicitly hypothetical warning scenarios) — serious concern	-1
Imprecision	5 studies — serious concern (small evidence base)	-1

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Appendix R. Direction of effect of studies that evaluated early warning systems

Study	Setting	Study design	Outcome	Hazard type	Operational level	Direction of effect
Song 2024	China	Longitudinal study	Mortality	Cyclone/hurricane/typhoon	National	No effect
Chen 2023	China	Interrupted time series	Mortality	Extreme heat	National	Negative effect
Ebi 2004	United States	Quasi-experimental study	Mortality	Extreme heat	National	No effect
Heudorf 2014	Germany	Interrupted time series	Mortality	Extreme heat	National	Mixed effect
Nitschke 2016	Australia	Ecological study design	Mortality	Extreme heat	National	Negative effect
Weinberger 2018	United States	Case-crossover study	Mortality	Extreme heat	National	Mixed effect
Global Disaster Preparedness Centre (GDPC) 2025	Malawi	Mixed methods	Mortality	Flooding	Community/local	No effect
Escaleras 2008	Global study (146 tsunamis, 1966–2004, across Asia, Americas, Europe and Africa; not country-specific)	Quasi-experimental study	Mortality	Tsunami	Regional	Positive effect
Song 2024	China	Longitudinal study	Morbidity	Cyclone/hurricane/typhoon	National	Positive effect
Clemens 2022	Canada	Interrupted time series	Morbidity	Extreme heat	National	No effect
Mehiriz 2018	Canada	Randomised controlled trial	Morbidity	Extreme heat	National	Mixed effect
Nitschke 2016	Australia	Ecological study design	Morbidity	Extreme heat	National	Mixed effect
Global Disaster Preparedness Centre 2025	Malawi	Mixed methods	Morbidity	Flooding	Community/local	No effect
Sahana 2023	India	Cross-sectional study	Loss of assets	Cyclone/hurricane/typhoon	National	Negative effect
Song 2024	China	Longitudinal study	Loss of assets	Cyclone/hurricane/typhoon	National	No effect
Tang 2023	China	Cross-sectional study	Loss of assets	Drought	National	Mixed effect
Aguirre 2019	Peru	Quasi-experimental study	Loss of assets	Flooding	National	Positive effect
Kreibich 2021	Germany	Quasi-experimental study	Loss of assets	Flooding	National	Positive effect
Sahana 2023	India	Cross-sectional study	Timely issuance of alerts	Cyclone/hurricane/typhoon	National	Mixed effect
Kreibich 2021	Germany	Quasi-experimental study	Timely issuance of alerts	Flooding	National	No effect

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Appendix S. Participant demographics reported in included studies

Study	Name of early warning system	Country / setting	Age	Gender	Ethnicity / race / language	Occupation	Educational level	Religion
Ahn 2021	Several (ShakeAlert & Earthquake Early Warning System)	Multiple (Japan & USA)	Sendai = 40–44 (median age group) Seattle = 53 (median age)	NR	NR	NR	NR	NR
Prathumchai 2020	Flood early warning system	Thailand	[Mean age not reported] 20–39: 12.90% (413,737) 40–59: 51.20% 1,642, 117) 60 and over: 35.90% (1,151,406)	M: 69.20% (2,219, 424); F: 30.80% (987,836)	NR	NR	Primary: 0.757; Secondary: 0.197; Bachelor's: 0.044	NR
Thieken 2007	Flood Early Warning System	Germany	Mean age =52 years (no SD)	NR	NR	NR	Secondary: People with high school graduation (Abitur) (22.1%)	NR
Alias 2020	Flood dissemination warnings	Malaysia	Median = 26-35 years old	M: (227) 40.4%; F: 340 (59.6%)	NR	NR	NR	NR
Kreibich 2021	Flood early warning system	Germany	NR	NR	NR	NR	NR	NR
Ramsden 2025	Flood early warning systems (FEWS)	United Kingdom	Not reported quantitatively. Noted that flood groups were mainly comprised of older participants.	NR	NR	Volunteers; many described as experienced, often retired professionals with skills such as engineers, hydrologists, academics, teachers, and IT experts. All flood groups consisted of local volunteers.	NR	NR
Arias 2015	Technology-Based Early Warning System	Philippines	48 years	M: 0.36; F: 0.64	NR	Farming (n=36; 7%) Livestock/poultry (n=26; 5%) Small business (n=135; 27%) Services sector (n=301; 60%)	NR	NR
Agyei 2020	Flood Early Warning System	Philippines	NR	NR	NR	NR	NR	NR
Aguirre 2019	Forecast-Based Financing Intervention	Peru	NR	NR	NR	NR	NR	NR
Shrestha 2014	Multiple systems described: (1) GLOF early warning system for Tsho Rolpa (1990s) (2) Bhote Koshi flood early warning system (Bhote Koshi Power Company) (3) DHM web-based telemetry flood early warning system (Koshi Basin, HKH-HYCOS) (4) Community-based flood early warning systems (Practical Action/DHM/NRCS/Mercy Corps) including case study systems in Bacheuli village (Chitwan District) and Holiya village (Banke District)	Nepal	NR	M: 47; F: 14	NR	Reported by stakeholder type (Table 1): Central government organizations (13) ; Local authorities (DDCs, VDCs, municipalities) (2); International NGOs (5); UN and humanitarian organizations (3); NGOs (6); Community representatives (26); Others e.g. academics/individual experts (6).	NR	NR
Bostrom 2022	ShakeAlert	United States	Age 18-29 California = 14.8% Oregon = 20.5% Washington = 20.2% 30-44 California = 29.9% Oregon = 25.6% Washington = 26.6% 45-59 California = 25.2% Oregon = 22.2% Washington = 25.4% 60+ California = 30.2% Oregon = 31.5% Washington = 27.8%	M: Male: California = 45.1% Oregon = 50.4% Washington = 49.7%; F: California = 52.2% Oregon = 45.8% Washington = 47.9%; Other: Transgender man: California = 0.1% Oregon = 0.9% Washington = 0.7% Transgender woman: California = 0.9% Oregon = 0.2% Washington = 0.3% Gender variant/non-conforming California = 0.2% Oregon = 1.8% Washington = 0.6% Prefer not to say: California = 1.5% Oregon = 1% Washington = 0.9%	White, non-Hispanic California = 44.9% Oregon = 78.8% Washington = 71.8% Black, non-Hispanic California = 5.9% Oregon = 1% Washington = 2.1% Other, non-Hispanic California = 1.5% Oregon = 1.5% Washington = 2.1% Hispanic California = 31.7% Oregon = 11.3% Washington = 9.5% 2+, non-Hispanic California = 2.5% Oregon = 5% Washington = 6% Asian, non-Hispanic California = 13.5% Oregon = 2.4% Washington = 8.6%	NR	Primary: California = 6.9% Oregon = 7.8% Washington = 6.8%; Secondary: California = 22.7% Oregon = 25% Washington = 25.9%; Bachelor's: California = 22.8% Oregon = 24% Washington = 22.6%	NR
Song 2024	Rural loudspeaker Systems (used for Typhoon Early Warnings)	China	NR	NR	NR	NR	NR	NR
Sahana 2023	Cyclone Early Warning System	India	44.72 years [NO SD provided]	M: 80.4% (n=479) ; F: [not reported] ; Other: [not reported]	NR	NR	NR	NR

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Study	Name of early warning system	Country / setting	Age	Gender	Ethnicity / race / language	Occupation	Educational level	Religion
Rai 2020	Community-Based Flood Early Warning System (CBEWS)	Nepal	38.08 (10.96)	M: [Survey respondents] 174 (38%); F: [Survey respondents] 279 (62%)	NR	NR	NR	NR
Escaleras 2008	Multiple EWS (Pacific Tsunami Warning Center (PTWC), West Coast/Alaska Warning Centre), Tsunami Warning System in Pacific (TWSP))	Global study (146 tsunamis, 1966–2004, across Asia, Americas, Europe and Africa; not country-specific)	NR	NR	NR	NR	NR	NR
Shah 2012	The national flood early warning system	Bangladesh	NR	NR	NR	Occupation of households (no specific statistics reported): 1. farmer households most had secondary income sources - livestock rearing, fish culture, agricultural/ non-agricultural labour and/or small businesses 2. about 20% had ponds for fish culture 3. members of some households seasonally migrated to big cities to work as day labourers	NR	NR
Chatfield 2013	NR	Indonesia	NR	NR	NR	NR	NR	NR
Bouta 2020	Earthquake early warning system	United States	NR	NR	NR	NR	NR	NR
Tang 2023	Early warning systems in China	China	Average age was 49.4 years	M: Male-headed households accounted for 91.7% of the total sample	36.9% of respondents are from Inner Mongolia. 31.9% of respondents are from Xinjiang. 31.8% of respondents are from Tibet.	Herders (farmers)	NR	NR
Diakakis 2022	Flood and Extreme Weather Early Warnings	Greece	1. 37.1 years ± 11.31 years 2. Youngest participant = 19 years old 3. Oldest participants = 83 years old	M: 0.451; F: 0.549	NR	NR	Primary: 0.014; Secondary: 0.054; Bachelor's: 0.533	NR
Fakhruddin 2019	Cyclone early warning system	Samoa	NR	NR	NR	NR	NR	NR
Norkhairi 2022	Warning siren (physical siren)	Malaysia	Three age groups reported: a. <15 years (23.8%) b. 15-64 years (69.7%) c. >65 years (6.5%)	NR	NR	NR	NR	NR
Raphela 2025	Flood early warning system (FEWS)/ Early warning messages (EWMs)	South Africa	42 (42%); majority of the respondents were youth between the ages of 18–35. 18-25 years=9 26-35 years=33 36-45 years=28 46-55 years=17 56-65 years=10 No response = 3	M: 28 (28%); F: 71 (71%); Other: No response = 1	NR	3: employed full-time 21 : employed part-time 6: self employed 1: Student 66: Unemployed 3: no response	NR	NR
Clemens 2022	Heat Warning and Information System (HWIS)	Canada	NR	NR	NR	NR	NR	NR
Altindag 2017	Yellow dust warning system (a warning system with behavioural guidelines)	Korea	NR	NR	NR	NR	NR	NR
Ebi 2004	The Philadelphia Hot Weather-Health Watch/Warning System (PWWS)	United States	NR	NR	NR	NR	NR	NR
Chau 2009	Very Hot Weather Warning (VHWW)	Hong Kong	NR	NR	NR	NR	NR	NR
Weinberger 2018	National Weather Service (NWS) heat alerts/warnings	United States	NR	NR	NR	NR	NR	NR
Wu 2020	Heat-health warning systems.	China (Shanghai)	NR	NR	NR	NR	NR	NR
Williams 2022	Heat Health Warning System (HHWS)	Australia	NR	NR	NR	NR	NR	NR
Nitschke 2016	Heat Warning System	Australia	NR	NR	NR	NR	NR	NR
Heudorf 2014	Heat warning system and heat health action plan (HHAP)	Germany	Age groups: <60 years, 60–79 years, ≥80 years	NR	NR	NR	NR	NR

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Study	Name of early warning system	Country / setting	Age	Gender	Ethnicity / race / language	Occupation	Educational level	Religion
Mehiriz 2018	Heat episode warning (Télephone Santé)	Canada	87% of the participants were 65 years of age or older	F: 76% (1328 total; 76% were women)	NR	NR	Secondary: Treatment: 32.9%; Control: 34.1%; Bachelor's: University degree: Treatment 30.6%; Control 34.1%; College diploma: Treatment 20.9%; Control 19.7%	NR
Chen 2023	Graded heat health risk early warning model (GHREWM).	China	1. Age <65 years = 26,877 2. Age 65–74 years = 22,377 3. Age >74 years = 55,082	M: 58,212 (55.8%); F: 46,130 (44.2%)	NR	NR	NR	NR
Heo 2019	Heatwave warning system	Korea	[0-19 years] 715 (1.4%) [20-64 years] 15,675 (31.4%) [65+] 33,600 (67.2%) [75+ years - referenced in main body but n/% not reported.]	M: 28,088 (56.2%); F: 21,914 (43.8%)	NR	[For adults 19+]: [White collar] 3600 (7.2%) [Blue collar] 5676 (11.4%) [Unemployed including 'housewives' and 'students'] 38,970 (77.9%)	Primary: 0.269; Secondary: 0.249; Bachelor's: 0.267; None: 0.169	NR
Feldbusch 2025	German heat health warning system (HHWS)	Germany	Not reported (mortality data for all ages; risk groups noted: young children, adults older than 65 years, people with pre-existing cardiopulmonary and other chronic diseases, outdoor workers)	NR	NR	NR	NR	NR
WorldMeteorologicalOrganization (WMO) 2018	Caribbean Multi-Hazard Early Warning Systems (EWSs) or National and Regional Early Warning Systems for Hurricanes (Irma and Maria)	Anguilla, Antigua and Barbuda, Dominica, the Virgin Islands (United Kingdom), and the Turks and Caicos Islands.	NR	NR	NR	Meteorological officers, Disaster management officials, Shelter managers, Community members, Regional stakeholders	NR	NR
WorldFoodProgramme (WFP) 2025	No named early warning system was assessed - study explores inclusion in anticipatory action.	Southern African countries (Madagascar, Zimbabwe, Malawi, and Tanzania)	Zimbabwe age category of respondents: 18–24 (youth) 25–44 45 and above	M: Malawi: 51%; F: Malawi: 48% were women; Other: 1% not accounted for in the text	Zimbabwe: Survey conducted in Binga, Chiredzi, and Rushinga districts	NR	NR	Tanzania: 54.7% Muslim, 37.9% Christian
United Nations Office forDisaster RiskReduction 2023	No named early warning system. Paper assesses the overall national/community-based early warning process in Fiji — involving the Fiji Meteorological Service (NMHS) , NDMO, and traditional/local dissemination structures.	Fiji	NR	NR	Each of the 7 consulted villages labelled as either "(Fijian)" [iTaukei] or "(Indo-Fijian) ": Narewa (Fijian) Suva (Indo-Fijian) Nadogoloa (Fijian) Nawajikuma (Fijian) Korotale (Indo-Fijian) Qoma (Fijian) Kulukulu (Indo-Fijian)	NR	NR	NR
Arif 2019	Indonesian Tsunami Early Warning System	Indonesia	NR	NR	NR	NR	NR	NR
Obiero 2025	Early Warning Messages	Kenya	NR	NR	NR	NR	NR	NR
Yangquiling 2024	No single named EWS. The study examined the various channels/sources through which last-mile communities received early warning information ahead of Super Typhoon Mangkhut, including: TVS, Radio. SMS alert.	Philippines	1. Mapita: N=108 18-25 years old: 17.59% 26-40 years old: 29.63% 41-59 years old: 31.48% >60: 21.30% 2. Cabalitian: N=121 18-25 years old: 14.88% 26-40 years old: 34.71% 41-59 years old: 30.58% >60: 19.83%	M: There's inconsistency in reporting of the gender distribution. Within the text on page 19: Cabalitian: 57 (47.11%) Mapita: 50 (46.30%) In Table 2: Mapita: 53.70% (58) Cabalitian: 52.89% (57); F: There's inconsistency in reporting of the gender distribution. Within the text on page 19: Cabalitian: 64 (52.89%) Mapita: 58 (53.70%) In Table 2: Mapita: 46.30% (50) Cabalitian: 47.11% (57)	NR	1. Cabalitian (island/coastal village): Primary livelihoods: fishing and ecotourism. 2. Mapita (mountain village): Primary livelihoods: farming, hunting, and vegetable gardening Residents cultivate ~150 hectares of land producing corn, rice, vegetables, and root crops. 3. Occupations mentioned among interview informants (qualitative, not quantified) : a. Cabalitian: fisherfolk, local leaders, professionals, entrepreneurs b. Mapita: vegetable farmers, local leaders, indigenous community members, household members.	Secondary: Mapita: 17.59% Cabalitian: 28.10%; Bachelor's: Mapita: 27.78% Cabalitian: 20.66%	NR

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Study	Name of early warning system	Country / setting	Age	Gender	Ethnicity / race / language	Occupation	Educational level	Religion
MalawiRedCross Society 2024	Anticipatory Action (AA) programming / ECHO IDREAM project Early Warning and Anticipatory Action system	Malawi	[Mean age not reported] [18–30] = 597 (36%) [31–40] = 402 (24%) [41–50] = 247 (15%) [51–60] = 193 (12%) [61–70] = 89 (5%) [Above 70] = 72 (4%) [Not stated] = 63(4%)	M: 612(37%); F: 1, 051 (63%)	[no numbers reported] "Malawi has around 16 local languages. Chichewa is the main administrative language"	NR	NR	NR
Mishra 2024	Early warning system	India	[Mean age not provided] [Age breakdown for household survey n=211) 11–19: 4 (1.89%) 19–35: 39 (18.48%) 35–50: 94 (44.54%) 50–65: 54 (25.59%) 65–80: 17 (8.05%) Above 80: 3 (1.42%). [IDI/KIIS FGD, N=173] Up to 25: 13 (7.5%) 26–35: 70 (40.5%) 36–45: 46 (26.6%) 46–55: 30 (17.3%) Above 56: 14 (8.1%)	M: Stakeholder sample = 37 male (21.38%). Household survey sample = 0 (no male participant included) ; F: [Stakeholder sample] 136 female (78.62%) Household survey sample = 211 (100%)	[Household survey, n=211] General caste = 51 (24.17%) Socially and Economically Backward Classes (SEBC) = 68 (32.22%) Scheduled Caste (SC) = 81 (38.38%) [IDI/KIIS and FGDs, n=173) General caste = 52 (30.1%) Socially and Economically Backward Classes (SEBC) = 70 (40.5%) Scheduled Caste (SC) = 50 (28.9%) ST = 1 (0.5%)	NR	Primary: [Household survey] 24.64% [(IDI/KIIS FGD] 14.5%; Secondary: [Household survey] 23.22% [(IDI/KIIS FGD] Secondary: 19.6%; Higher secondary: 17.9%; Bachelor's: [Household survey] 1.89% [(IDI/KIIS FGD] 20.8%	NR
Mamba 2025	Eswatini National Multi-Hazard Early Warning System	Kingdom of Eswatini	[Mean age not reported] ≤18 = (0) 19-49 = (329; 41.3%) 50-59 = (159; 20%) 60≤ = (308; 38.7%)	M: 388(48.7%); F: 408(51.3%)	NR	[Agriculture is dominant livelihood] - Fig 1 reports specific livelihoods (no numbers/only %s) a. food crop production =(56.9%) b. livestock rearing = (12.3%) c. poultry production = (4.3%) d. cash crop production =(2.3%) e. households relying on remittances = (25.7%), and social protection/elderly grants = (29.1%) f. casual labour = (20.7%).	Primary: 0.185; Secondary: 0.457; None: 0.295	NR
Martin 2024	Early warning system	India	[reported descriptively for some respondents - no formal breakdown provided]	M: [Assumed to be 100% (fishermen) but gender breakdown not reported]	NR	a. All participants are traditional/artisanal fishers: b. Shore seine fishers (St Andrew's and nearby villages). Note: Shore seine involves pulling ropes on either end of a long, baggy net immersed in an arc close to the shore. c. Raft fishers (Puthenthope) d. Fiberglass boat fishers — 10-metre boats with outboard motors (Anjengo and Fatimapuram) e. Ring seine fishers — 12–14 metre mechanised vessels (Perumathura/Muthalappozhi harbor)	NR	NR
Goltz 2024	ShakeAlert	United States	Age approximated a normal distribution with the age range 35–44 (the modal category - reported most frequently).	NR	NR	NR	Bachelor's: 0.364; Master's: 31.7% ["graduate or professional degrees"]	NR
Hoshiba 2014	Japan Meterological Agency Earthquake Early Warning System	Japan	NR	NR	Japanese	NR	NR	NR
Ebhuoma 2021	Nigerian Emergency Management Agency (NEMA) Early Warning	Nigeria	median age = 64	NR	NR	NR	NR	NR
Cao 2016	Wildfire warning system	Australia	n=144(55%) aged 50-69	NR	NR	NR	NR	NR
Potter 2021	Impact-based forecast and warning (IBFW) systems	New Zealand	NR	NR	NR	NR	NR	NR
Doermann 2021	Wireless emergency alert (WEA)	United States	NR	NR	NR	NR	NR	NR
Vinnell 2023	Android Earthquake Alert System (AEA)	New Zealand	[Study 1] 62% were 21–39 years old. no numbers reported [Study 2] 49% between 30 and 49 years old] no numbers reported	M: [Surveys 1 & 2] numbers/% not reported; F: [Survey 1] 66% [n. not reported] [Survey 2] 73% [n. not reported]	[Survey 1] Maori 7.5% [Survey 2] Maori 12.2%	NR	NR	NR

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Ochoa-Rodríguez 2018	1) First-generation Extreme Rainfall Alerts (ERAs) – piloted July 2008–April 2009, issued operationally from 2009 until October 2011 2) Second-generation Surface Water Flood Risk Assessment (SWFRA) – launched October 2011, incorporated into the Flood Guidance Statement (FGS)	United Kingdom	NR	NR	NR	Survey respondents described by professional role: a. 40% flood risk and/or water managers b. 34% emergency planning, resilience and/or business continuity officers c. 26% drainage and/or highways engineers	NR	NR
Katsetsiadou 2023	Tsunami early warning system	Greece	Total sample n=337; [n=] [No data] = 4 [<18] = 2 [18-24] = 18 [24-34] = 82 [35-44] = 114 [45-54] = 68 [55-64] = 36 [65-74] = 12 [>75] = 1	M: 143/344 (42%); F: 201/344 (58%)	NR	NR	Primary: 0.0118; Secondary: 0.3234; Bachelor's: 0.4629; Master's: 0.1869; Doctoral: 0.0148	NR
HAQUE 1995	Cyclone warning system	Bangladesh	NR	NR	NR	NR	NR	NR
Thongs 2025	Caribbean-based multi-hazard early warning system (MHEWS)	Jamaica, Saint Vincent and the Grenadines, Saint Lucia, and Trinidad and Tobago	Approximate data from Figure 3: a. 18–24 years old = ~30% male; ~44% female; ~40% (largest group overall) b. 25–34 years old = ~19% male; ~19%female; ~19% (largest group overall) c. 35–44 years old = ~19% male; ~18% female; ~18% (largest group overall) d. 45–54 years old = ~9% male; ~10% female; ~9% (largest group overall) e. 55–64 years old = ~5% male; ~4% female; ~4%(largest group overall) f. Older than 65 = ~1% male; ~1% female; ~1% (largest group overall)	M: 37% (154); F: 62% (258); Other: 1% (4)	62% (258) Black; 23% (96) mixed race	54% (225) worked more than 40 h a week.	Primary: 0.01; Secondary: 0.09; Bachelor's: 0.41; Master's: 0.23; None: Other = 2% Some high school = 2% Some college/ trade school = 23%	NR
Sari 2023	People-Centered Early Warning System (EWS)	Indonesia	NR	NR	NR	NR	NR	NR
Roy 2015	Cyclone early warning system	Bangladesh	3 meteorologists and 200 participants from the 4 unions	M: 200 participants from the 4 unions; F: 200 participants from the 4 unions	NR	3 meteorologists and 200 participants from the 4 unions	NR	NR
Rahman 2013	Early Flood Warning Dissemination System (EFWDS) in Bangladesh. Key national system: Flood Forecasting and Warning Centre (FFWC) under Bangladesh Water Development Board (BWDB).	Bangladesh	Dhobaura: Mean = 50.65, SD 16.91 (age range 17–90 years) . Shibalaya: Mean = 46.13, SD = 13.72 (age range 17–78 years).	NR	Not reported. Note: respondents are rural communities who know only local Bengali language.	Dhobaura: Agriculture = 68% Business = 10% Service = 14% Student = 6% Others = 3%. Shibalaya: Agriculture = 35% Business = 20% Service = 28% Student = 7% Others = 10%.	NR	NR
Omer 2026	Multiple: Early Warning Systems (EWS) in Somaliland (general system); Famine Early Warning Systems Network (FEWS NET) specifically identified as a notable strength.	Somalia	Age groups: a. 18-24: 35 (8.97%) b. 25-34: 89 (22.82%) c. 35-44: 128 (32.82%) d. 45-54: 95 (24.36%) e. 55+: 43 (11.03%) . Mean/SD not reported.	M: 210 (involved in survey); F: 180 (involved in survey)	NR	a. Farmer: 99 (25.38%) b. Livestock herding: 173 (44.36%) c. Formal employment: 30 (7.28%) d. Other/ non-agricultural: 88 (22.56%)	Primary: 0.253; Secondary: 0.152; Bachelor's: 0.108; None: 0.487	NR
Moises 2022	Nambia National Flood Early Warning System	Namibia	NR	NR	NR	NR	NR	NR
Katsekpor 2025	White Volta Flood Early Warning System (FEWS)	Ghana	NR	NR	NR	NR	NR	NR
Huy 2009	People-Centered Early Warning System (EWS) for storm and flood control	Vietnam	43.25 years [SE 1.297]; [n=32] Male: 44.41 years [SE 1.347]; [n=27] Female: 37.00 years [SE 2.864] [n=5]	M: 27 (84.4%); F: 5 (15.6%)	NR	Main job [Fishery=1; cultivating=2; raising=3; Other=4] [Mean score for whole sample, n=32] = 1.563 [SE = 0.190]	NR	NR
Hosen 2019	Flood Early Warning Dissemination System (FEWDS)	Bangladesh	Age range of questionnaire respondents: 18-65 years.	NR	Bengali-speaking rural community	Only reports occupation of participants involved in qualitative data collection as Farmers, day labourers, fishers (no numerical breakdown by occupation reported)	NR	NR

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Study	Name of early warning system	Country / setting	Age	Gender	Ethnicity / race / language	Occupation	Educational level	Religion
RedCrossRed CrescentClimate Centre 2022	Community-based Early Warning Early Action	Palau Island	18-19 years old = 30.8% 20-21 = 19.2% 21-22 = 17.3% 22-23 = 7.7% 23-24 = 21.2%	M: Survey: 32.7% Stakeholder consultations: 50%; F: Survey: 63.5% Stakeholder consultations: 50%; Other: Prefer not to say: 3.9%	NR	Employed = 53.9% Government sector employed = 57.1% Private sector/NGO employed or volunteering = 14.3%	Bachelor's: 0.222	NR
Global Disaster Preparedness Center 2025	Early Warning/Action Systems, e.g., Community-based early warning systems, evacuation planning, and prepositioning of emergency supplies.	Malawi	Age of household heads 18–24 = 34 (9%) 25–34 = 78 (20.6%) 35–44 = 76 (20.1%) 45–54 = 53 (14.0%) 55–64 = 39 (10.3%) 65+ = 98 (25.9%)	M: 214 (56.6%); F: 164 (43.4%)	NR	Farmer = 165 (43.7) Business owner = 60 (15.9%) Employed = 6 (1.6%) Unemployed = 20 (5.3%) Casual work = 124 (32.9%) Other = 3 (0.8%)	Primary: 0.545; Secondary: 0.146; None: 0.302	NR
Budimir 2020	Flood Early Warning System (FEWS)	Nepal	NR	M: National level stakeholders: Interview = 6 District level stakeholders: Interview = 7 Community level stakeholders: Questionnaires = 35; F: National level stakeholders: Interview = 5 District level stakeholders: Interview = 0 Community level stakeholders: Questionnaires = 92	NR	NR	NR	NR
Rohman 2024	Early warning messages	Vietnam	20 (interviews) 88 (FGD)	M: 20(interviews) 88 (FGD); F: 20 (interviews) 88 (FGD)	NR	NR	NR	NR
Pereira 2024	Brazilian national EWS (Sistema Nacional de Proteção e Defesa Civil / Civil Defence) ; People-Centred Early Warning System (PCEWS) prototype developed by this study	Brazil	Both territories combined: a. 35–39 and 40–44 most represented (17.6% each) b. 18–19 = 15.7% c. 25–29 and 60–64 underrepresented (2.0% each) d. 70–74 = 5.9% (all from Campinho) . Mean/SD not reported.	M: 49% (n = 25 of 51) - combines participants in Campinho and Ubatumirim; F: 49% (n = 25 of 51) - combines participants in Campinho and Ubatumirim; Other: 2% non-binary (n = 1 of 51; only in Ubatumirim: 4.4%)	1. Total (n=51): Black 45.1% White 33.3% Brown (pardo) 19.6% Indigenous 2.0%. 2. Campinho (n=28) : Black 71.4% Brown 25.0% White 3.6% Indigenous 0%. 3. Ubatumirim (n=23) : White 69.6% Black 13.0% Brown 13.0% Indigenous 4.3%	Livelihoods primarily based on family labour and subsistence: a. community-based tourism b. handicrafts c. cocoa and cassava products d. artisanal fishing Note: Specific occupational breakdown not reported by frequency.	NR	NR
Adegun 2024	Community Heat Early Warning System (CHEWS)	Nigeria	18–30 years = 260 31–40 years = 211 41–50 years = 124 51–60 years = 33 over 60 years = 23	M: 341 (53%); F: 296 (47%)	NR	Unemployed = 129 Self-employed = 400 Private = 75 Civil servants = 32 Retired = 15	NR	NR
Laure 2022	The Earthquake Network (EQN) Public earthquake early warning (PEEW)	Peru (77% of participants in Peru) ; others in Ecuador (19%); Columbia (3%); Venezuela or Brazil (1%)	18 years or older, with most participants aged between 25 and 44 years old.	NR	NR	NR	Bachelor's: 0.65	NR
Ringo 2024	Study mentions 'Flood early warning System (FEWS)' but also states that "there are no structured early warning systems in the study areas. Instead, the community uses a hybrid approach that integrates traditional practices with modern scientific warnings"	Tanzania	NR	NR	NR	NR	Primary: 0.696; Secondary: 0.128; Bachelor's: 0.008	NR
Alam 2024	Cyclone Preparedness Programme (CPP)	Bangladesh	66.87 years (mean)	M: 293 (81%); F: 69 (19%)	NR	Agriculture 121 (33.43%) Fishing 50 (13.81%) Day labour 48 (13.26%) Unemployed 45 (12.43%) Small trades 38 (10.50%) Housewives 37 (10.22%) Fish trading 9 (2.49%) Service sector 7 (1.93%) Bangladeshi expats 5 (1.38%) Business 2 (0.55%)	Primary: 0.4061; None: 0.5111	NR

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Study	Name of early warning system	Country / setting	Age	Gender	Ethnicity / race / language	Occupation	Educational level	Religion
Tan 2023	Android Earthquake Alert (AEA) System	New Zealand	October 12 survey median age was 33.4 years October 22 survey median age was 39.1 years	M: October 12 survey = 524(183; 35%) October 22 survey = 671. (164; 24.4%); F: October 12 survey = 524 (309; 59%) October 22 survey = 671. (492; 73.3%) ; Other: October 12 survey = 524 (14; 2.6% as non-binary) (14; 2.7% no response) October 22 survey = 671. (3; 0.5% as non-binary) (10; 1.5% no response)	October 12 survey= 524 (58.4% selected New Zealand European, 34.9% New Zealander, 7.4% as Māori, 6.5% Asian, 1.7% Pacific Islander, and 11% other.) October 22 survey=671 (52.9% selected New Zealand European, 46.7% New Zealander, 12% as Māori, 2.5% Asian, 1% Pacific Islander, and 7% other)	NR	NR	NR
Naylor 2018	Earthquake Early Warning System; Tsunami Early Warning System	Japan	Mean age=68 years (SD not reported) ; Median Age=70 years; Age range=48 years	M: 30 (38.5%); F: 43 (55.1%); Other: [Other/not disclosed] 5 (6.4%)	NR	NR	NR	NR
Islam 2024	Regional and community-based flood early warning system	Bangladesh	41.31 (12.35)	NR	NR	Occupational status (only % provided) Agriculture =(51.5%) Service (doesn't specify which service) =(5.7%) Agricultural labour = (25.4%) Small business = (9.4%) Fisherman =(1.5%) Others =(6.5%)	NR	NR
Nieland 2016	Flash Flood Warning System	Australia	Mentions the following age ranges but no statistics added: Largest proportion of all respondents between 18-30 years; 51-65 years, and 65+ years.	M: 0.49; F: 0.61	NR	NR	Secondary: 0.4	NR
Cao 2024	Flood Early Warning System (FEWS)	Japan	NR	NR	NR	NR	NR	NR
Sa'adi 2024	National Flood Forecasting and Warning System (PRAB)	Malaysia	Aged between 18 and 60 or more years.	M: 0.66; F: 0.34	NR	NR	Bachelor's: 0.443	NR
Lumbroso 2016	Range of EWS in Africa, Caribbean and South Asia	Multiple (Africa, Caribbean and South Asia)	NR	NR	NR	NR	NR	NR
Akwango 2017	Karamoja Drought Early Warning System (KDEWS)	Uganda	Average age of household head (Years) 47.13 (12.62)	M: 78% (135) - Check ERROR in data; F: 59.5% (104) - Check ERROR in data	NR	Occupation of the household head (%) Farming 85.0 Salaried income 4.6 Self-employment off-farm 1.2 Farmer worker 2.3 Off-farm employment 1.2 Causal Labor 2.3 Housekeeping 0.6	NR	NR
Sharma 2009	Cyclone early warning system	India	NR	M: 26 (59.0); F: 18 (41.0%)	NR	Main occupation stated as Fishing and cultivation for all 44 participants	NR	NR
Yik 2023	Hong Kong Landslip Early Warning System	Hong Kong	[Study 1] Age 21–30: 3 (7.7%) Age 31– 40: 8(20.5%) Age 41–50: 4 (10.3%) Age 51–60: 8 (20.5%) Age 61–70: 10(25.6%) Age 71+: 6 (15.4%) [Study 2] Age 18-19: 71 (3.9%) Age 20-24: 70 (3.8%) Age 25-29: 183 (10.0%) Age 30-34: 114 (6.2%) Age 35-39 213 (11.6%) Age 40-44: 120 (6.5%) Age 45-49: 211 (11.5%) Age 50-54: 112 (6.1%) Age 55-59: 221 (12.1%) Age 60-64: 132 (7.2%) Age 65+ 387 (21.1%)	M: [Study 1] 11 (28.2%) [Study 2] 822 (44.8%); F: [Study 1] 28 (71.8%) [Study 2] 1012 (55.2%)	NR	NR	NR	NR

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Study	Name of early warning system	Country / setting	Age	Gender	Ethnicity / race / language	Occupation	Educational level	Religion
Shrestha 2021	Flood Early Warning Systems	Nepal	NR	M: Not specified for FGD 1 (mixed group of CDMC members and community men/women, exact numbers not given) ; F: 18 (FGD 2: 18 women members of various task forces of the CDMC from Wards 6 and 7 of Sarpallo village")	"People from ethnic groups and Dalits (considered the lowest in the caste hierarchy), who primarily speak Maithali language" (contextual description of Ratu watershed population, not sample-specific breakdown)	FGD 1: a mixed group involving CDMC members and relevant women and men stakeholders at the community level. FGD 2: 18 women members of various task forces of the CDMC. KIIs: representatives from government agencies (DHM, NEOC, MOHA) and I/NGOs (Practical Action, Mercy Corps, LWR) and UNDP	NR	NR
Al-Zaabi 2022	Early warning system	Oman	NR	NR	NR	NR	NR	NR
Oktari 2014	Tsunami Early Warning System (EWS) in Aceh	Indonesia	NR	NR	NR	NR	NR	NR
Shrestha 2025	Flood early warning system	Nepal	Community survey: mean age 40 years (range 18-72)	M: 72 (of 100 community survey respondents; derived from the reported 28% female); F: 28 (of 100 community survey respondents, as reported: '100 structured interviews (28 % female)')	NR	Most of the population in the study area are indigenous and depend mainly on agriculture due to the flat, nutrient-rich terrain. Note: no statistics reported.	NR	NR
Graves 2025	Early warning system for drought	Australia	Ages ranged from 28-74. [25-35 years] = 20.0% [35-45 years] = 13.3% [45-55 years] = 13.3% [55-65 years] = 13.3% [65+ years] = 40.0%	M: 0.733; F: 0.267	NR	NR	NR	NR
Shah 2023	Flood Early Warning System (FEWS)	Pakistan	[Survey] = 43 [no SD provided]	NR	NR	NR	NR	NR
Melo 2017	Alerta Rio	Brazil	[only data provided on age]: a. 26-50 years old =(50.7%) b. Over 50 = (47.9%)	M: 50(70.4%); F: 21 (29.6%)	NR	NR	NR	NR
Alemayehu 2025	Early warning systems	Ethiopia	NR	NR	NR	NR	NR	NR
Hasan 2024	Flood Early Warning System (FEWS) operated by the Flood Forecasting and Warning Centre (FFWC).	Bangladesh	NR	NR	NR	NR	NR	NR
Chisty 2021	Bangladesh's flood EWS	Bangladesh	NR	M: 40 (50%); F: 40 (50%)	language: 100% Bengali	Female (%): Unemployed 70.0 30.0 Formal sector 0.0 10.0 Business 0.0 15.0 Student 15.0 32.5 Others 15.0 12.5 Male (%): Unemployed 30.0 Formal sector 10.0 Business 15.0 Student 32.5 Others 12.5	Primary: female: 27.5% male: 30.0%; Secondary: female: 12.5% male: 32.5%; Bachelor's: female: 5.0% male: 10.0%; None: female: 45.0% male: 7.5%	NR
Adams 2024	ShakeAlert	United States	54.91 ± 7.728 [153 respondents, 68%]	M: 57.33% [129]; F: 17.33% [39]; Other: Did not answer = 20.89% (47) Prefer not to say = 4.44% (10)	African American/Black 0.89% [2] Asian American/East Asian/South Asian/Southeast Asian 1.33% [3] Hispanic/Latinx 6.67% [15] Indigenous/Native American/Alaska Native 1.78% [4] White 61.33% [138] Prefer not to answer = 7.56% (17) Did not answer = 20.44% (46)	NR	Master's: 0.56; Doctoral: 0.17	NR
Bajracharya 2021	Community-Based Flood Early Warning System (CBFEWS)	Nepal	NR	NR	NR	NR	NR	NR
Pandey 2023	Community-Based Flood Early Warning System (CBFEWS)	Nepal	NR	NR	NR	Numbers not reported. Stakeholders included: officials from local government, community members, academicians, and representatives from civil society organisations	NR	NR
Bossu 2022	Smartphone-based earthquake early warning system	Multi-country (user survey data from Peru)	NR	NR	NR	NR	NR	NR

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Study	Name of early warning system	Country / setting	Age	Gender	Ethnicity / race / language	Occupation	Educational level	Religion
Salgado 2025	Flood Early Warning Systems (FEWs)	Colombia	NR	M: 0.35; F: 65 % were women	NR	NR	NR	NR
VanderMolen 2022	Heat Health Warning System (HHWS)	United States	NR	NR	NR	NR	NR	NR
Trahan 2023	Ahmedabad's Heat Action Plan (HAP)	India	NR	F: 85	NR	Street vendors, construction workers and waste recyclers (numbers not given).	NR	NR
Smith 2022	Cell Broadcast (CB) – simulated/pre-recorded cell broadcast severe flood warning messages (trialled ahead of UK adoption)	United Kingdom	The mean age = 26.	M: Not directly reported as a count; complement of reported 60% female (calculated â‰ˆ 32 of 80, i.e. 40%); F: Just under two-thirds (60%) of the sample was female (nâ‰ˆ48 of 80, calculated)	Participants from black, Asian or minority ethnic (BAME) backgrounds made up 21% of the total sample cohort.	NR	Bachelor's: 0.725; Master's: 0.15; Doctoral: 5% – reported as post-doctoral researchers or junior academics	NR
Sharafi 2021	Drought Early Warning System	Iran	NR	NR	NR	NR	NR	NR
Chinguwo 2022	Community-based early warning system (CBEWS).	Malawi	25-30 years = 27% 31-35 years = 16% 36-45 years = 33% Over 45 years = 24%	M: 0.81; F: 0.19	NR	NR	NR	NR
Nakayachi 2019	Earthquake Early Warning System	Japan	Study 1: 15-19 years = 5% 20s = 11% 30s = 16% 40s = 20% 50s = 16% 60s = 20% 70s and above = 12% Study 2: 15-19 years = 5% 20s = 13% 30s = 15% 40s = 19% 50s = 15% 60s = 18% 70s and above = 15%	M: Study 1: 51% Study 2: 225 (50%) ; F: Study 1: 49% Study 2: 225 (50%)	NR	NR	NR	NR
Alam 2023	Various	Bangladesh	NR	NR	NR	NR	NR	NR
Mehta 2022	Multiple EWS in response to natural hazard-related disasters affecting the region	Australia	NR	M: Phase 1: 9 (56.25%) Phase 2: 72 ((44.7%); F: Phase 1: 7 (43.75%) Phase 2: 89 (55.3%)	NR	NR	NR	NR
Abid 2024	Community-based flood mitigation (CBFM)	Saudi Arabia	NR	NR	NR	NR	NR	NR
Pescaroli 2023	SASMEX — Seismic Alert System of Mexico (Sistema de Alerta Sísmica Mexicana)	Mexico	NR	M: [Questionnaire respondents, n=78] Male: 48% (n=37) ; F: [Questionnaire respondents, n=78] Female: 48% (n=38); Other: [Questionnaire respondents, n=78] Other/prefer not to answer: 4% (n=3)	NR	NR	NR	NR
Oberai 2025a	Ethos (Extreme heat and older persons) system, a heat early warning system	Australia	Mean age = 75 years (Range: 65-100; SD = 7)	M: 37 (47%); F: 41 (53%)	NR	NR	NR	NR
Allen 2025	Android Earthquake Alerts (AEA) system	Global study (98 Countries, not including the USA)	NR	NR	NR	NR	NR	NR

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Appendix T. GRADE-CERQual assessment of confidence in the evidence from RQs 4&5

Research Question Theme	Summary of review finding	Studies contributing to the review finding	Methodological limitations	Coherence	Adequacy	Relevance	*CERQual assessment of confidence in the evidence*	Explanation of CERQual assessment
Enablers to successful implementation of early warning systems	***Finding 1: Community participation, local knowledge, and trusted local networks strengthened the relevance, legitimacy, and sustainability of early warning systems***	Abid et al.2024; Chisty et al.2021; Graves & Kuleshov (2025); Katsekpor et al. (2025); Lumbroso et al. (2016); Mamba et al 2025; Mishra & Mohapatra (2024); Moises & Kunguma (2022); Obiero et al. (2025); Pandey & Basnet (2023); Pescaroli et al. (2023); Rahman et al. (2013); Rohman (2024); Salgado et al. (2025); Shrestha et al. (2021); Trahan et al. (2023); United Nations Office for Disaster Risk Reduction (2023); VanderMolen et al. (2022); World Food Programme (2025)	Minor methodological limitations Six studies with moderate methodological limitations (four with unclear recruitment and sampling strategy and two with no ethical consideration reported) One study had serious concern with relatively poor methodology	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (Nineteen studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 2: Strong governance, institutional coordination, and multi-stakeholder partnerships enabled effective implementation of early warning systems	Chunga & Manda; Katsekpor et al. (2025); Lumbroso et al. (2016); Moises & Kunguma (2022); Oktari et al. (2014); Pandey & Basnet (2023); Salgado et al. (2025)	Minor methodological limitations One study with negative methodology	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Moderate concerns about adequacy (Seven studies that together offered not so rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 3: Multi-channel, inclusive, and locally tailored communication systems enabled warning accessibility, reach, and understanding	Adeogun O. B. et al. (2024); Al-Zaabi & Al-Zadjali (2022); Chunga & Manda; Cross P.R; Hosen; Lumbroso et al. (2016); Mamba et al. (2025); Mehta et al. (2022); Obiero et al. (2025); Pescaroli et al. (2023); Rohman (2024); Roy et al. (2015); Salgado et al. (2025); Shrestha et al. (2021); Smith et al. (2022); Thongs et al. (2025); Trahan et al. (2023); VanderMolen et al. (2022); World Food Programme (2025)	Minor methodological limitations. 2 studies with moderate limitation (with unclear recruitment and sampling strategy)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (Nineteen studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 4: Training, capacity-building, preparedness measures, and access to timely and actionable information enabled individuals and communities to respond effectively to warnings	Alam (2024); Chisty et al. (2021); Huy 2009; Katsekpor et al. (2025); Katsetsiadou et al. (2023); Mehta et al. (2022); Mishra & Mohapatra (2024); Moises & Kunguma (2022); Oktari et al. (2014); Pandey & Basnet (2023); Pescaroli et al. (2023); Rohman (2024); Roy et al. (2015); Salgado et al. (2025); Sharafi et al.; Shrestha et al. (2021); Thongs et al. (2025); United Nations Office for Disaster Risk Reduction (2023); World Food Programme (2025)	Minor methodological limitations. 2 studies with moderate limitation (with no adequate rationale for using a mixed methods design to address the research question.)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (Nineteen studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence

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Research Question Theme	Summary of review finding	Studies contributing to the review finding	Methodological limitations	Coherence	Adequacy	Relevance	*CERQual assessment of confidence in the evidence*	Explanation of CERQual assessment
Barriers to successful implementation of early warning systems?	***Finding 1: Weak governance, coordination, institutional capacity, and sustainable resourcing constrained the implementation and long-term sustainability of early warning systems***	Abid et al (2024); Adams et al. (2024); Chinguwo & Deus; Katsekpor et al. (2025); Lumbroso et al. (2016); Moises & Kunguma (2022); Obiero et al. (2025); Ochoa-Rodríguez et al. (2018); Oktari et al. (2014); Omer et al. (2026); Pandey & Basnet (2023); Pescaroli et al. (2023); Potter et al. (2021); Rahman et al. (2013); Rohman (2024); Salgado et al. (2025); Sari et al. (2023); Shrestha et al. (2021); United Nations Office for Disaster Risk Reduction (2023); VanderMolen et al. (2022); World Meteorological Organization (2018); World Food Programme (2025).	Minor methodological limitations. 3 studies with moderate limitation (not clear how the qualitative components were integrated into the findings. Qualitative component (i.e., stakeholder interactions) not well described.)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (twenty-two studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 2: Warning communication was often inaccessible, poorly tailored, and insufficiently actionable for diverse users	Alam (2024); Adeogun O.B. et al. (2024); Cao et al. (2016); Cao et al. (2024); Chunga & Manda; Ebhuoma & Leonard (2021); Graves & Kuleshov (2025); Huy 2009; Katsekpor et al. (2025); Mamba et al. (2025); Mehta et al. (2022); Mishra & Mohapatra (2024); Oktari et al. (2014); Omer et al. (2026); Pandey & Basnet (2023); Pereira et al. (2024); Pescaroli et al. (2023); Potter et al. (2021); Rahman et al. (2013); Rohman (2024); Salgado et al. (2025); Sari et al. (2023); Shrestha et al. (2021); Smith et al. (2022); Thongs et al. (2025); United Nations Office for Disaster Risk Reduction (2023); VanderMolen et al. (2022); World Meteorological Organization (2018); World Food Programme (2025); Yangquiling (2024).	Minor methodological limitations. 4 studies with moderate limitation (No adequate rationale for using a mixed methods design to address the research question and not clear how the qualitative components were integrated into the findings.)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (thirty studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 3: Limited community engagement, weak trust, and inadequate integration of local knowledge reduced the credibility, relevance, and uptake of warning systems	Cross P.R; Ebhuoma & Leonard 2021; HAQUE (1995); Huy 2009; Katsekpor et al. (2025); Mamba et al. (2025); Martin (2024); Obiero et al. (2025); Omer et al. (2026); Pereira et al. (2024); Roy et al. (2015); Salgado et al. (2025); Shah et al. (2023); Shrestha et al. (2025); World Meteorological Organization (2018); World Food Programme (2025).	Moderate methodological limitations. 3 studies out of 16 with moderate/negative limitation (poor methodology with some strengths, NO adequate rationale for using a mixed methods design to address the research question and a mixed method study with Qualitative findings not clearly presented, mainly presents findings from the quantitative data collection.)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (sixteen studies that together offered rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 4: Limited preparedness, response capacity, evacuation arrangements, and social vulnerabilities constrained the ability of individuals and communities to act on warnings	Alam & Islam ; Chisty et al. (2021); Cross (2022); HAQUE (1995); Katsekpor et al. (2025); Martin (2024); Melo et al. (2017); Mishra & Mohapatra (2024); Naylor et al. (2018); Obiero et al. 2025; Pereira et al. (2024); Pescaroli et al. (2023); Potter et al. (2021); Rohman (2024); Salgado et al. (2025); Sari et al. (2023); Shah et al. (2023); Sharma et al. (2009); Shrestha et al. (2021); Shrestha et al. (2025); Thongs et al. (2025); Trahan et al. (2023); United Nations Office for Disaster Risk Reduction (2023); VanderMolen et al. (2022); World Food Programme (2025).	Moderate methodological limitations. 8 studies out of 25 studies with negative/moderate limitation (poor methodology with some strengths, NO adequate rationale for using a mixed methods design to address the research question and a mixed method study with Qualitative findings not clearly presented, mainly presents findings from the quantitative data collection and not clear how the qualitative components were integrated into the findings.)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (twenty-five studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence

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Research Question Theme	Summary of review finding	Studies contributing to the review finding	Methodological limitations	Coherence	Adequacy	Relevance	*CERQual assessment of confidence in the evidence*	Explanation of CERQual assessment
	Finding 5: Technical, monitoring, forecasting, and data-system limitations reduced the accuracy, timeliness, and reliability of warning systems	Abid et al (2024); Adams et al. (2024); Alam (2024); Adeogun O.B. et al. (2024); Cao et al. (2024); Chunga & Manda; Ebhuoma & Leonard 2021; Graves & Kuleshov (2025); Moises & Kunguma (2022); Obiero et al. (2025); Ochoa-Rodríguez et al. (2018); Omer et al. (2026); Pereira et al. (2024); Potter et al. (2021); Salgado et al. (2025); Sari et al. (2023); Shrestha et al. (2025); United Nations Office for Disaster Risk Reduction (2023); World Meteorological Organization (2018); Yangquiling (2024).	Moderate methodological limitations. 4 studies out of 20 studies with negative/moderate limitation (poor methodology with some strengths, NO adequate rationale for using a mixed methods design to address the research question and a mixed method study with Qualitative findings not clearly presented, mainly presents findings from the quantitative data collection and not clear how the qualitative components were integrated into the findings.)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (twenty studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
Perceived usefulness of early warning systems?	***Finding 1: Early warning systems were perceived as useful when they provided sufficient lead time to support preparedness and protective action***	Akwango et al. (2017); Alemayehu et al. (2025); Allen et al. (2025); Arif et al. 2019; Bajracharya et al. (2021); Bossu et al. (2022); Chinguwo & Deus; Cross (2022); Doermann et al. (2021); Goltz et al. (2024); Hoshiba (2014); Malawi Red Cross Society & Danish Red Cross (2024); Mehta et al. (2022); Melo et al. (2017); Moises & Kunguma (2022); Nakayachi et al. (2019); Nieland & Mushtaq (2016); Obiero et al. (2025); Ochoa-Rodríguez et al. (2018); Ringo et al. (2024); Sa'adi et al. (2024); Tan et al. (2023); VanderMolen et al. (2022).	Moderate methodological limitations. 7 studies out of 23 studies with moderate limitation (two studies have poor methodology with some strengths, Findings are reported in percentages, and no quotes were reported, as questions) appear to be closed ended.	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (twenty-three studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ whether events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 2: The usefulness of warning information depended on its relevance, specificity, and actionability	Adams et al. (2024); Akwango et al. (2017); Allen et al. (2025); Budimir et al. (2020); Cao et al. (2016); Chinguwo & Deus; Chisty et al. (2021); Cross (2022); Doermann et al. (2021); (Ebhuoma & Leonard 2021,; Graves & Kuleshov (2025); Huy 2009; Laure et al. (2022); Lumbroso et al. (2016); Mamba et al. (2025); Martin (2024); Mehta et al. (2022); Moises & Kunguma (2022); Oberai et al. 2025b; Obiero et al. (2025b); Rahman et al. (2013); Roy et al. (2015); Smith et al. (2022); Thongs et al. (2025); United Nations Office for Disaster Risk Reduction (2023); Vinnell et al. (2023).	Moderate methodological limitations. 7 studies out of 26 with moderate limitation (two studies have poor methodology with some strengths, and Data analysis methods not sufficiently explained and ethical approval processes not described)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (twenty-six studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ whether events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 3: Early warning systems were valued because they reduced losses and strengthened preparedness, resilience, and coordinated response	Allen et al. (2025); Bajracharya et al. (2021); Budimir et al. (2020); Chisty et al. (2021); Lumbroso et al. (2016); Ringo et al. 2024;	Moderate methodological limitations. 1 study out of 6 with moderate limitation (Ethical approval processes not described)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Moderate concerns about adequacy (six studies that together offered not so rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because there were only minor concerns regarding methodological limitations, relevance and coherence although data was not very rich.

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Research Question Theme	Summary of review finding	Studies contributing to the review finding	Methodological limitations	Coherence	Adequacy	Relevance	*CERQual assessment of confidence in the evidence*	Explanation of CERQual assessment
	Finding 4: Perceived usefulness declined when warnings could not be translated into meaningful protective action	Budimir et al. (2020); Cross (2022); Doermann et al. (2021); Haque (1995); Hoshiba (2014); Huy 2009; Katsekpor et al. (2025); Mamba et al. (2025); Martin (2024); Melo et al. (2017); Obiero et al. (2025); Omer et al. (2026); Pereira et al. (2024); Roy et al. (2015); Salgado et al. (2025); Shah et al. (2023); Shrestha et al. (2025); World Meteorological Organization (2018).	Moderate methodological limitations. 4studies out of 18 with moderate limitation (one study has poor methodology with some strengths, and Data analysis methods not sufficiently explained and Ethical approval processes not described)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (eighteen studies that together offered very rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
Perceived acceptability of early warning systems	***Finding 1: Acceptability was shaped by trust in warning providers and confidence in the accuracy and credibility of warning information***	Adams et al. (2024); Budimir et al. (2020); Cao et al. (2016); Chinguwo & Deus; Chisty et al. (2021); Cross P.R; Huy 2009; Malawi Red Cross Society & Danish Red Cross (2024); Mehta et al. 2022; Moises & Kunguma (2022); Obiero et al. (2025); Sharma et al. (2009); Smith et al. (2022); United Nations Office for Disaster Risk Reduction (2023)	Moderate concerns with methodological limitations. 6 studies out of 14 with moderate/negative limitation (poor methodology with some strengths, NO adequate rationale for using a mixed methods design to address the research question and a mixed method study with Qualitative findings not clearly presented, mainly presents findings from the quantitative data collection, data analysis methods not sufficiently explained and ethical approval processes not described.	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (fourteen studies that together offered rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence
	Finding 2: Acceptability was enhanced when warning information was clear, understandable, and supported decision-making	Bossu et al. (2022); Budimir et al. (2020); Huy 2009; Melo et al. (2017); Mehta et al. 2022; Oberai et al. (2025a); Obiero et al. (2025b); Roy et al. (2015); Smith et al. (2022)	Moderate methodological limitations. 2 studies out of 9 with moderate limitation (Used survey questionnaire to collect data on user's perceived usefulness and acceptability of the Earthquake alert app. Findings are reported in percentages, and no quotes were reported, as questions appear to be closed ended.)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Moderate concerns about adequacy (nine studies that together offered not so rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because there were only minor concerns regarding methodological limitations, relevance and coherence although data was not very rich.
	Finding 3: Acceptability was strengthened when warning systems were accessible, user-centred, and responsive to diverse needs and preferences	Adams et al. (2024); Cao et al. (2016); Mehta et al. (2022); Oberai et al. (2025a); Rohman (2024); Roy et al. (2015); Sa'adi et al. (2024); Sharma et al. (2009); Thongs et al. (2025); United Nations Office for Disaster Risk Reduction (2023); Vinnell et al. (2023)	Moderate methodological limitations. 3 studies out of 11 with moderate limitation (Study used a closed-ended Likert scale-type questionnaire to assess participant's subjective preference and opinions, as well as ease of understanding. Not an appropriate approach for an in-depth qualitative data collection)	Minor concerns about coherence. (some concerns about fit, as several contributing studies report participants' recommendations for improving early warning systems rather than accounts of systems as experienced, although it is not always possible to distinguish the two in the reported data)	Minor concerns about adequacy (eleven studies that together offered rich data)	Minor concerns about relevance (studies of early warning systems from different countries covering different types of extreme climate/ weather events)	High	The findings were graded as high because of the richness of the data and there were only minor concerns regarding methodological limitations, relevance and coherence

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Appendix U. Review findings where recommendations were drawn

Recommendation	RQ / evidence	Review findings
For Policy		
1. Strengthen institutions and governance	**RQ4—Implementation:** Enabler finding 2, on governance, institutional coordination and partnerships; Barrier finding 1, on weak governance, capacity and sustainable resourcing.	Supportive legislation, policies, operating procedures and clear responsibilities enabled coordinated warning delivery and response. Conversely, fragmented responsibilities, unstable funding and limited technical and human resources undermined implementation and sustainability.
2. Invest in dissemination and response capability, not just detection	**RQ2—Components associated with improved outcomes**, including **Table 18**; supported by RQ4 communication and preparedness findings.	Preparedness and response capability—knowing what to do when a warning arrives—was identified as the component **most consistently associated with improved outcomes**. Communication barriers also prevented warnings from supporting decisions.
3. Ensure multi-channel, local-language delivery	**RQ1cii—Differential effectiveness**; **RQ4—Enabler finding 3**, on inclusive, locally tailored communication, and **Barrier finding 2**, on inaccessible communication; **RQ5—Acceptability finding 3**.	Systems were more effective when locally owned and delivered through multiple channels, local languages and trusted intermediaries. Language mismatches, low literacy, inaccessible technologies and technical terminology limited understanding and action. Users found systems more acceptable when familiar channels and accessible formats were combined.
4. Make inclusion a design and implementation requirement for all early warning systems	**RQ1cii—Differential effectiveness**; **RQ4—Communication and preparedness barriers**; **RQ5—Acceptability finding 3; Table 17** on population characteristics and features that make warning systems more or less effective.	The review identifies communication, mobility and support needs that were inadequately addressed in warning and response arrangements. Findings on acceptability include use of sign-language videos, images and subtitles as accessible ways of sharing warnings.
5. Prioritise low-resource, high-exposure settings	**Characteristics of included studies – study location; RQ1a—Types and operational levels of systems**; **RQ1cii—Contextual/differential effectiveness**; **RQ3—Cost-effectiveness**, including **Table 19**; **RQ4—Resourcing barriers**.	When categorised by World Bank income level (World Bank, 2026), included studies were evenly distributed between middle-income and high-income economies, with a much smaller number from low-income countries. In particular, methodologically robust quantitative studies were more focused in high-income countries compared to qualitative studies, which mostly originated from lower-middle and low-income countries. Thus, evidence on the effectiveness of early warning systems from low-resource settings was more limited compared with evidence on implementation of early warning systems, which mostly originated from those settings. National early warning systems dominated the evidence base, with fewer studies of community/local systems. Community-based systems appeared particularly favourable economically because of low operating costs, and resource constraints threatened sustainability.
6. Fund early warning systems as ongoing services	**RQ4—Barrier finding 1**, on governance, institutional capacity and sustainable resourcing; **Enabler findings 2 and 4**, on institutional support and capacity-building.	Unstable funding, insufficient maintenance, staff and technical-resource limitations, and over-reliance on externally funded projects threatened long-term sustainability. Training and preparedness activities strengthened the ability to act on warnings.
For Practice		
1. Make early warning messages clear, specific and actionable	**RQ4—Barrier finding 2**, on inaccessible, poorly tailored and insufficiently actionable communication; **Enabler finding 4**, on timely and actionable information; **RQ5—Perceived usefulness**.	Technical terminology, generic information, poor localisation and an absence of clear protective guidance reduced usefulness. Warnings supported action when they explained the hazard, likely impacts, what to do and when.
2. Promote community awareness and invest in education	**Table 17** on population characteristics and features that make warning systems more or less effective**; RQ4—Enabler finding 4**, on training, capacity-building and preparedness; **RQ1cii**, on differing needs and limited subgroup evidence.	Training, community engagement, simulation exercises and drills helped people understand warning signals, clarify responsibilities and prepare to respond.
3. Use multiple, complementary dissemination channels	**RQ1cii—Differential effectiveness**; **RQ4—Enabler finding 3**; **RQ5—Acceptability finding 3**.	Combining familiar channels—including broadcast, mobile and community networks—supported reach and acceptance. Multi-channel delivery, local ownership and trusted intermediaries were associated with effectiveness.
4. Pair early warnings with preparedness and response capability	**RQ2—Components associated with improved outcomes**; **RQ4—Enabler finding 4 and preparedness/response barriers**; **RQ5—Usefulness**.	Preparedness and response capability was the component most consistently associated with improved outcomes. Timely information enabled preparation, but warnings were useful only when recipients could translate them into protective action.
5. Build and use trusted intermediaries; avoid over-alerting and frequent false alerts	**RQ1cii—Differential effectiveness**; **RQ4—Enabler finding 1**, on trusted local networks, and **Barrier finding 3**, on weak trust; **RQ5—Acceptability**.	Trusted intermediaries supported effectiveness and credibility. Inaccurate, inconsistent, overly general or repeatedly false warnings undermined trust and uptake; the discussion also linked acceptability of new technologies to avoiding over-alerting and false alerts.
6. Plan for hard-to-reach communities and power/technology failures	**RQ1cii—Underserved communities and contextual effectiveness**; **RQ4—Barrier finding 2**, on communication access, and **Barrier finding 5**, on technical and data-system limitations; **Table 17** on population characteristics and features that make warning systems more or less effective	Unreliable communication infrastructure, inaccessible technology and weak operational capacity limited reach, timeliness and reliability. Systems that stop at national dissemination and depend on infrastructure that fails to reach underserved communities, as well as systems that use single-channel alerts vulnerable to power or network outages impede their effectiveness.
For Research		
1. Report participant demographics as standard	**RQ1ci—Demographics and characteristics of communities served**; **RQ1cii—Differential effectiveness**; **Appendix S**.	Demographic information was incompletely and inconsistently reported, limiting aggregation and assessment of who benefits. Age was reported in 59 of 111 studies, gender in 52, ethnicity/race/language in 18, and disability in six studies. Evidence on differential effectiveness was very limited.
2. Use rigorous experimental and quasi-experimental impact evaluations, especially in LMICs	**Characteristics of included studies – study location; RQ1b—Effectiveness findings**; **Risk of bias in studies**	Much of the evidence was better suited to describing experiences and associations than establishing causality, and effectiveness varied across outcomes and hazards. When categorised by World Bank income level (World Bank, 2026), included studies were evenly distributed between middle-income and high-income economies, with a much smaller number from low-income countries. In particular, methodologically robust quantitative studies were more focused in high-income countries compared to qualitative studies, which mostly originated from lower-middle and low-income countries. Thus, evidence on the effectiveness of early warning systems from low-resource settings was more limited compared with evidence on implementation of early warning systems, which mostly originated from those settings.

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Recommendation	RQ / evidence	Review findings
3. Include observed costs and benefits in economic evaluations of early warning systems wherever feasible, and ensure modelling studies are methodologically strong and transparent	**RQ3—Cost-effectiveness**, **Table 19**, and the **Discussion of RQ3**.	Only eight studies reported economic evidence, including six economic evaluations. More broadly, although the direction of effect is consistent, most benefits were estimates, with studies using descriptive and modelling approaches – such as the Monte-Carlo simulation, value of statistical life, and averted cost assumptions – instead of observational measures. These findings reflect the inherent difficulties in measuring avoided losses, valuing intangibles, putting monetary value on human life, and limited data availability. Nonetheless, within these limitations, the evidence consistently indicates that adopting an early warning system is cost-effective across different hazards and income settings, with community-based early warning systems appearing especially cost-effective given their low operational cost. Findings relied substantially on modelling, simulations or descriptive estimates, with limited comparability and some implausibly high estimates.
4. Focus future research efforts on the under-studied features of successful early warning systems – risk knowledge, response capability, underserved community reach and low-resource, high exposure settings which are most often susceptible to disasters	**RQ2—Component coverage, Table 18**; **RQ1a—System types**; **RQ1ci–ii—Demographic reporting and differential effectiveness**.	Risk knowledge and preparedness/response capability were the least evaluated pillars: 31 studies (28%) and 40 (36%), respectively, compared with dissemination/communication in 97 (87%) and detection/monitoring/forecasting in 59 (53%). Community/local systems and differential effectiveness for underserved populations also received less attention.

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