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A framework for addressing the interconnectedness of early warning to action and finance to strengthen multiscale institutional responses to climate shocks and disasters

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ABSTRACT

Early warning systems (EWS) inform decision making and planning in response to climate shocks and catastrophic disasters. However, the current disaster response mechanism falls short due to the fragmented warning, action, and finance systems, coupled with inadequate institutional collaboration, coordination and inclusive engagement for effective anticipatory action. This study addresses this challenge by introducing an Early Warning, Action and Finance (AWARE) platform to promote anticipatory action through multistakeholder engagement. Data from literature reviews, expert surveys, and stakeholder workshops in Senegal, Zambia and Sri Lanka helped identify the platform's needs and priorities. The study draws upon theories of technological frames, interpretative flexibility, boundary objects, social learning, collaborative governance and adaptive co-management to conceptualize a framework for AWARE. Results demonstrate the potential of AWARE as a boundary object that fosters social engagement, active involvement, open communication, collaboration, and shared commitment to safeguarding lives and livelihoods. Analysis of technological frames and interpretative flexibility underscores the role of social learning in shaping the design and user features that promote multiscale institutional responses to disasters. AWARE aligns with the priorities of the Sendai Framework and emphasizes system thinking, co-production of knowledge, and the need for context-specific solutions to enhance anticipatory action. Recognizing the limitations of one-size-fits-all EWS, the AWARE framework acknowledges contextual factors as barriers to implementation. The study underscores the importance of integrated EWS and collaborative efforts to overcome implementation barriers and improve anticipatory action outcomes.

1. Introduction

The 21st century has recorded a surge in weather-related disasters such as droughts, floods, and cyclones, yielding repercussions that extend beyond immediate losses, such as social and economic instability, disruption of infrastructure and services, and undermined well-being (Clarke et al., 2022; Banholzer et al., 2014). In extreme cases, these events can lead to the collapse of societies (Schipper and Pelling, 2006). These disasters transcend national boundaries, causing widespread impact (Challinor et al., 2018; O'Neill et al., 2022).To mitigate these effects various initiatives are being implemented globally, with early warning systems (EWS)

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playing a central role. EWS is crucial for resilience building, providing timely, accurate information that helps communities and decision-makers to reduce vulnerability and take action to lessen disaster impacts (Azadi et al., 2022; Shammin et al., 2022; Willison et al., 2022; Wang et al., 2022).

Resilience building against climate change and disasters requires a systemic approach involving diverse stakeholders to address the root causes of vulnerability (Rehman et al., 2019). Government and non-governmental organizations focus on enhancing EWS for better decision-making (Luther et al., 2017). Proactive EWS models are essential for reducing human suffering and economic losses (Weingärtner and Otto, 2013). For example, FAO's analysis in the Philippines showed a return of USD 0.8 to USD 7 gains per USD 1 invested (FAO, 2020). Therefore, effective anticipatory action mechanisms should link early warning to early action and predefine early financing agreements (Rüth et al., (2017). However, while EWS especially in developing countries can issue alerts for water-related hazards, the gap between the technological capabilities and the public's ability to respond promptly limits its efficay (de León et al., 2006; Glantz and Ramírez, 2018). Despite the existence of policies and strategies supporting proactive action, knowledge gaps persist in integrating EWS components effectively for anticipatory action.

Anticipatory action in the context of climate and disasters refers to proactive measures taken to mitigate the impacts of anticipated events, such as extreme weather, natural disasters, and climate change. It aims to reduce vulnerability, increase resilience, and protect communities and ecosystems. Anticipatory action focuses on preparing ahead of time to prevent or lessen the negative effects of impending hazards on vulnerable ecosystems, populations and their livelihoods (Anticipation hub,2022; Tozier De La Poterie et al., 2022; UNDRR, 2023). However, fragmented components and a lack of a unifying platform, impede implementation (Glantz and Ramírez, 2018). The connection between early warning, action, and finance remains inadequately addressed in the literature and international discussions. The focus on the technicalities of EWS has overshadowed the need to understand the social processes essential for multiscale institutional collaboration (Williams and Edge, 1996).

The current EWS framework comprises four components: Risk Knowledge, Monitoring and Warning Service, Dissemination and Communication, and Response Capabilities (see Supplementary Fig. S1 for details). Failure in any component compromises the entire disaster management cycle (UNISDR, 2006; Dutta et al., 2018; Garcia and Fearnley, 2012; Kafle, 2017). Also, scholarly discourse highlights two principal EWS implementation approaches: the "last mile" (hazard-centered and top-down) and the "first mile" (people-centered and bottom-up), with the latter gaining more recognition for its effectiveness and community ownership (Kelman and Glantz, 2014; Aitsi-Selmi et al., 2016; Marchezini et al., 2018).

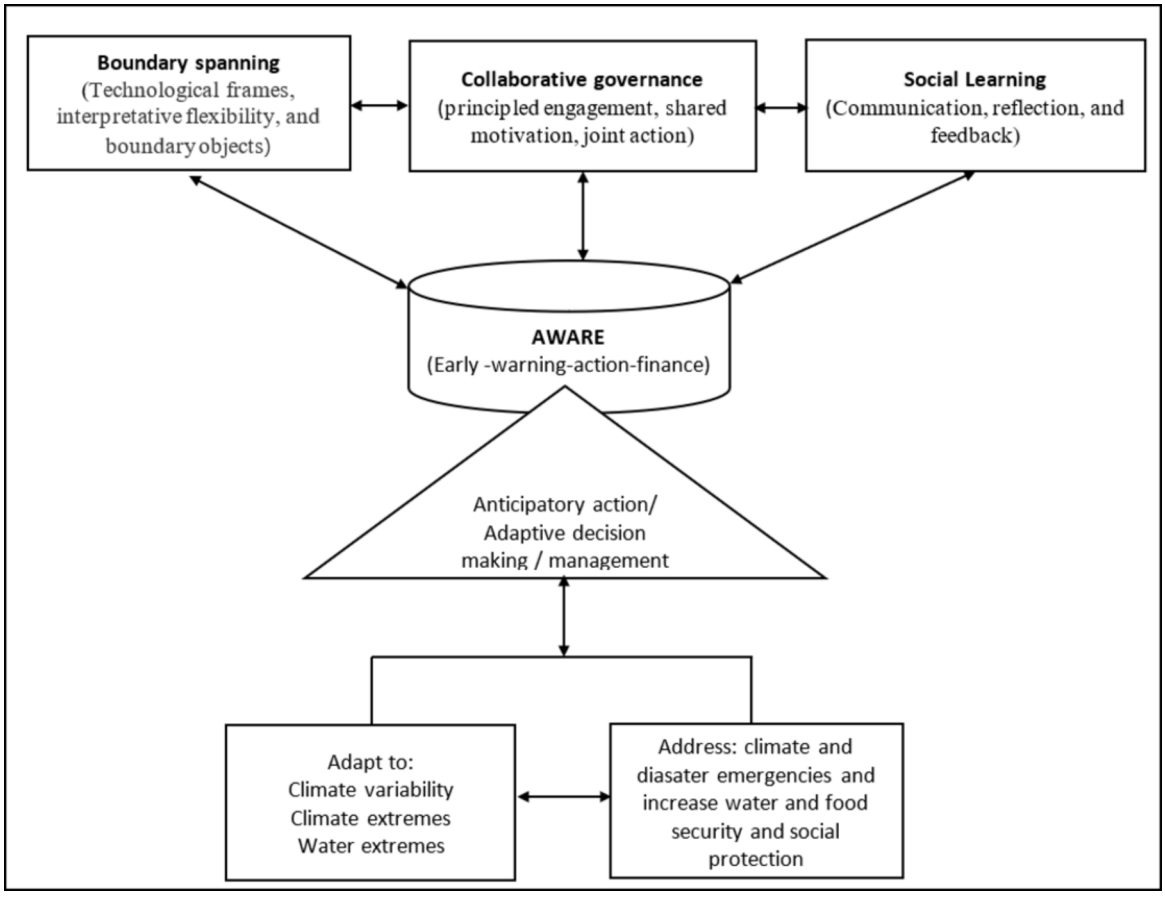


Fig. 1. Theoretical framework of the study. Source: Authors' construct.

Sättele et al. (2016) argue that an EWS's effectiveness hinges on its underlying framework. Therefore, the proposed Early Warning to Early Action and Early Finance (AWARE) platform and its framework, in this study, underscores the need for timely warnings linked to action and finance, supported by multiscale institutional responses (Loboguerrero et al., 2022). The Association of Southeast Asian Nations outlines three pillars for anticipatory disaster management: risk information and forecasting, planning and operations, and pre-arranged finance (ASEAN, 2022), which serves as a foundational entry point for this study. This article therefore proposes the AWARE framework, a digitally enabled multi-institutional governance mechanism that strengthens anticipatory action by fostering multiscale institutional responses and engagements among public agencies, humanitarian organizations, civil societies and communities. Also, AWARE, resulting from the ClimBeR project and part of CGIAR initiatives on Climate Resilience, promotes integrated responses to climate shocks and supports water and food security among vulnerable populations (Loboguerrero et al., 2022).

The remainder of this article is structured as follows: Section 2 provides a theoretical background of AWARE. Section 3 outlines the research methodology. Section 4 presents the findings of the study. Finally, Sections 5 and 6 respectively discuss the implications and key conclusions drawn from the study.

2. Theoretical background

At the core of EWS lie technological innovations, which are shaped by their social context and usage (Williams and Edge, 1996). Therefore, EWS must encompass not only technology but also the social processes and context in which they operate. This study employs the theories of technological frames, interpretative flexibility, boundary objects, social learning, collaborative governance and adaptive co-management, to elucidate the social context and processes involved in the development and use of AWARE (Fig. 1) (Bijker, 1987; Davidson, 2006; Forman and Haaugbølle, 2014).

Technological Frames describe individuals' or groups' perception of technology, shaped by their assumptions, beliefs, and values (Davidson, 2002; Kaplan and Tripsas, 2008). These frames can be explicit or implicit, conscious or unconscious, and influence how users evaluate and engage with AWARE. Orlikowski and Gash's (1994) framework of technological frames is applied to examine (i) the nature of AWARE, including its capabilities (ii) the strategy underlying its adoption and (iii) its practical use and consequences. Identifying areas of congruence or conflict in stakeholders' technological frames helps address discrepancies and refine AWARE's design. On the other hand, *Interpretative Flexibility* emphasizes the diversity in the meanings and uses of technology, allowing for different applications by different actors (Meyer and Schulz-Schaeffer, 2006; Huvila et al., 2017). This supports AWARE's adaptability to user needs and varying contexts. Factors such as user characteristics, social-economic conditions, and institutional and regulatory settings enable experimentation and learning, fostering innovative outcomes. For example, AWARE's features could be tailored to local contexts, maximizing relevance and usability. *Boundary Objects* are objects or concepts with different meanings and uses across social worlds, serving as bridges for communication and coordination among different groups (Harvey and Chrisman, 1998; Leigh, 2010; Huvila et al., 2017). AWARE as a boundary object, acts as a shared resource accommodating multiple interpretations, perspectives, goals, and languages. The AWARE platform aligns with these principles by creating a common space for stakeholders to share insights and align actions across sectors.

Further, *Collaborative Governance* focuses on integrating diverse actors for principled engagement, shared motivation, and joint action (Carlisle & Gruby, 2019; Thiel, 2017). AWARE incorporates this approach by fostering coordination among stakeholders, enhancing equity, and enabling collective problem-solving in complex scenarios (Emerson et al., 2012). For instance, AWARE implementation brings together governments, communities, and international agencies to co-create strategies for climate resilience. In this context, *Social Learning* underpins AWARE's capacity to co-create knowledge and build shared understanding among users. Drawing from Pahl-Wostl (2009), social learning connects diverse perspectives, promotes reflection, and generates feedback loops that strengthen adaptive responses. Mechanisms such as stakeholder workshops and feedback sessions facilitate this process, ensuring AWARE evolves in response to user needs (Pahl-Wostl et al., 2007). Finally, the study highlights the importance of *Adaptive Co-management*, advocating for flexible, multi-stakeholder and institutional engagement in managing complex and uncertain climate risks (Trimble and Plummer, 2019; Kovács et al., 2021). AWARE operationalizes this by promoting institutional coordination, addressing power imbalances, and integrating localized knowledge into decision-making processes.

3. Methodology

This paper introduces a digitally enabled AWARE platform that integrates early warning to action and finance to enhance multiscale institutional response to climate shocks and disasters. It uses data from literature and workshops and expert surveys to conceptualize and analyze its framework.

3.1. Data collection

(a) literature review

Using traditional literature review (Lacey et al., 2011) techniques, this study analyzed pertinent literature on the following topics: (i) The concepts of technological frames, interpretative flexibility, and boundary objects as derived from the field of science and technology studies, as well as the theory of social learning, collaborative governance and adaptive co-management. (ii) The evolution, significance, and challenges associated with EWS and anticipatory action. A list of consulted literature are shown in the reference section

We ensured rigor in our literature review by focusing on peer-reviewed, high-impact studies and credible grey literature, representing diverse regional perspectives while maintaining reliability and relevance to our study's objectives. The traditional literature review technique allows flexibility in synthesizing qualitative data, such as opinions, theories, and conceptual frameworks while also being useful when research aims to explore a broader topic area, generate hypotheses, identify research gaps, and inform the need for further investigation, rather than provide a conclusive answer to a specific research question based on the available evidence (Lacey et al., 2011).

(b) Stakeholders Workshop

This study also relied on the synthesis of data from stakeholder workshops organized in Senegal on the 19th July 2022, Zambia on the 26th July 2022 and Sri Lanka on the 6th June 2023.

The Senegal workshop was organized in collaboration with the Senegal Ministry of Environment and Sustainable Development (MEDD) and the National Agency of Civil Aviation and Meteorology (ANACIM) to bring together stakeholders to deepen their understanding of how to co-generate innovations like AWARE to contribute to building systemic resilience against climate variability and extremes in Senegal. The workshop also aimed at discussing and developing a common vision and an action plan around such innovations to strengthen climate adaptation efforts in Senegal. About 43 government and non-governmental organizations in Senegal were represented in this meeting with about 110 sample participants in person and at least five participants online.

The Zambia workshop served as a follow-up to initial introduction meetings in June 2022, involving key stakeholders from the Ministry of Agriculture, the Ministry of Green Economy and Environment (MoGEE), the Water Resources Management Authority (WARMA), and the Disaster Management and Mitigation Unit (DMMU). The workshop aimed to among others present AWARE as a digital decision-support system to be co-developed with and for stakeholders in Zambia to facilitate anticipatory resilience measures in response to climate shocks and disasters. Attendees included 49 national and regional organizations that have a presence in Zambia including delegations from Zambia and CGIAR institutions comprising developers, researchers, policymakers, and consultants. A total of 82 sample participants attended the workshop in person and 9 participants online. The discussions primarily focused on enhancing responsiveness beyond EWS, with a central question addressing how anticipatory disaster management operations could be improved to address challenges like floods and droughts.

The Sri Lanka workshop aimed to explore strategies for strengthening anticipatory action in disaster management. AWARE was presented and discussed from various perspectives during the workshop. Stakeholders from organizations such as the Asian Disaster Preparedness Centre, World Vision, University of Moratuwa, International Organization for Migration, Sri Lanka Disaster Management Centre, and International Water Management Institute participated in the event. In all, a sample of 52 participants from Government institutions, NGOs, United Nations agencies, and research for development institutes, attended the workshop.

The workshops were structured to foster active participation and discussions on the AWARE tool. To ensure reliability, each workshop followed a structured agenda with standardized guiding questions to foster consistent discussions and elicit comparable data. These workshops, thus, provide a representative cross-section of sectoral actors and capture genuine insights into local needs and priorities.

(c) Expert Survey

A survey was conducted to gather data on the experiences and perspectives of experts, including researchers and development practitioners, involved in EWS and climate information services. The survey, administered online using Google Forms (Vasantha Raju and Harinarayana, 2016), utilized open-ended questions to elicit qualitative responses. Rather than focusing on frequencies or inferential analysis, the survey aimed to collect real-life experiences and expectations for generalization purposes. We invited 38 experts (23 responses received) through purposeful sampling. The sample was chosen to reflect various professional backgrounds, ensuring a representative perspective of challenges and best practices. Reliability was enhanced by framing the survey questions into seven sections corresponding to the key concepts in the AWARE framework: (i) Background information on EWS, (ii) Technological framing of AWARE, (iii) Interpretative flexibility of AWARE, (iv) AWARE as a boundary object, (v) Social learning processes in AWARE, (vi) Collaborative governance in AWARE, and (vii) Biographical information. This allowed us to capture both general insights and specific qualitative data on the EWS system and to effectively capture the distinctiveness of AWARE compared to existing EWS, as well as its strengths and weaknesses. Some questions were framed in an ex-ante manner to analyze the potential outcomes of AWARE. To validate the survey tool, we conducted a pilot test with a small group of experts, refining questions for clarity and relevance based on their feedback.

3.2. Data analysis

The analysis of the literature involved two stages. In the first stage, literature was scanned and synthesized to gather relevant information from empirical and theoretical perspectives. In the second stage, a comprehensive examination of the compiled literature was undertaken by reading, extracting, and synthesizing key information about the identified theories and topics mentioned in Section 3.1.

The data obtained from expert interviews and stakeholder workshops were transcribed and coded using Atlas.ti (Hwang, 2008) based on themes and concepts. Some survey responses were evaluated and presented as figures using Excel (see Supplementary material). The analysis aimed to consolidate evidence that demonstrates the value of the AWARE platform and its framework for

facilitating anticipatory action.

We mitigated expert subjectivity by triangulating insights with literature review data and engaging a diverse, multidisciplinary group to capture varied perspectives, ensuring a holistic and validated assessment.

4. Results

The Supplementary material (Sections 1–4) provides detailed insights into AWARE platform, stakeholder needs, experts' EWS knowledge (Fig. S2 and S3), effectiveness of social processes in EWS (Fig. S3), rapid response triggers (Fig. S4), and examples of failed EWS cases (Box 1).

4.1. Proposed AWARE framework for promoting rapid response and multi-institutional collaboration

4.1.1. Description of AWARE framework

Fig. 2 presents the AWARE framework structured into four key settings: context, process, outcome, and feedback.

(i) Context:

AWARE is developed within the context of promoting collaborative governance to enhance systemic resilience against climate

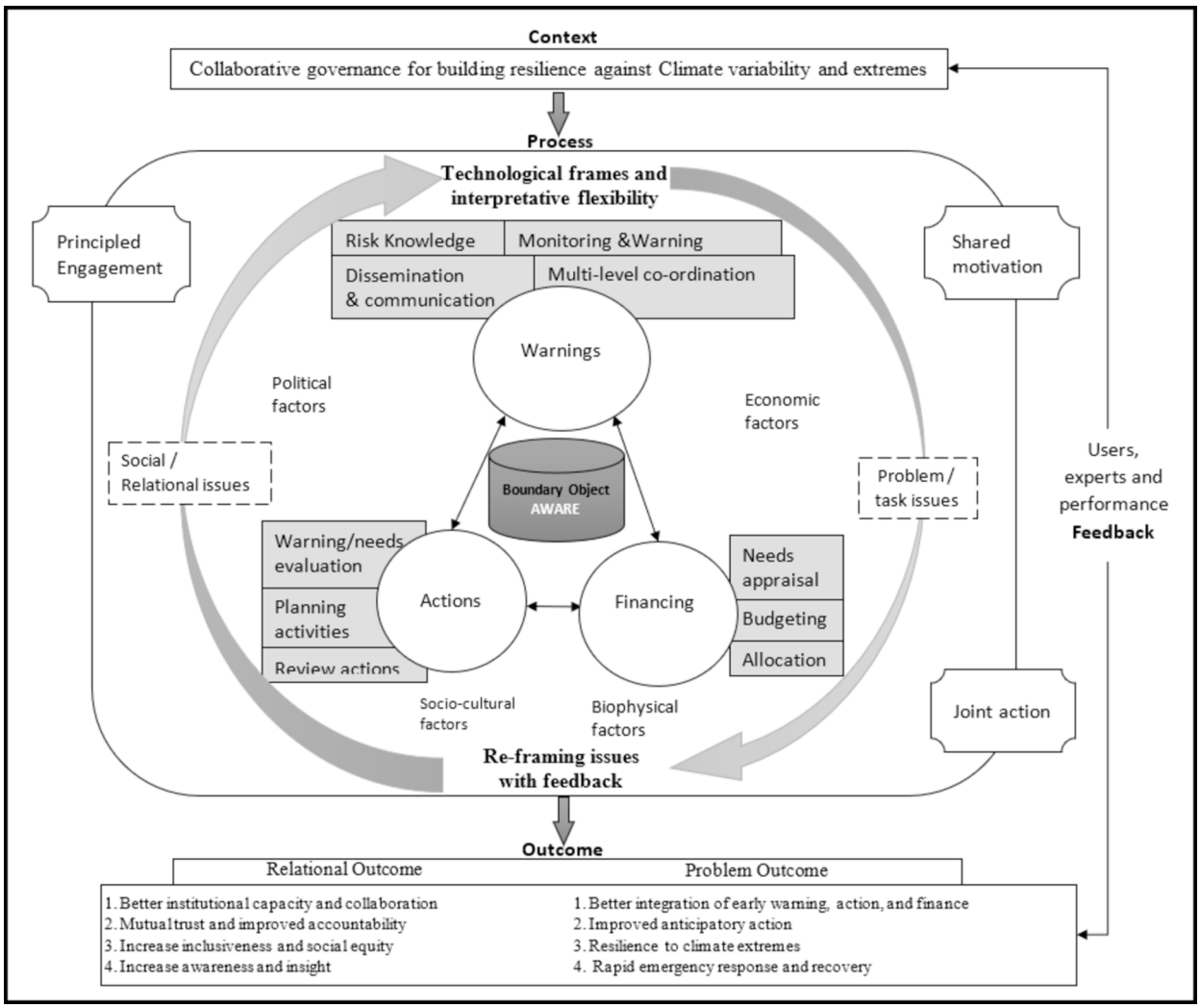


Fig. 2. A framework for improving the social processes of integrated early warning, action and finance (AWARE): illustrating the context, processes and outcomes of AWARE in reference to collaborative governance, social learning, technological frames, interpretative flexibility, and boundary objects. .
Source: Authors' construct, 2023

variability and extremes. By emphasizing multi-institutional collaboration, it fosters integrated planning, cross-sectoral partnerships, and joint monitoring of climate-related initiatives. AWARE engages diverse actors, including government agencies, NGOs, private sector, researchers, and communities, to co-develop strategies that leverage collective knowledge and resources. This collaborative approach ensures effective, equitable, and sustainable anticipatory solutions. Through improved information exchange, partnership building, and capacity enhancement, AWARE reduces vulnerability and enhances adaptive capacity, ultimately contributing to the broader goal of resilience against climate risks across communities, ecosystems, and economies.

(ii) Process:

AWARE integrate Early Warning, Early Action, and Early Finance components to enhance disaster mitigation and response through improved coordination and collaboration among stakeholders. (Fig. 2).

- **Early *Warnings*** focus on identifying risks, assessing hazards, vulnerability, and exposures at specific locations, using sound scientific methods. It ensures warnings are based on reliable indicators, and effectively communicated in understandable formats to those at risk.
- ***Early Action*** involves evaluating needs based on the severity and potential impacts of warnings, planning responses and allocating resources. This includes developing operational standards, establishing communication protocols, defining stakeholder roles, and regularly reviewing plans through drills and simulations.
- ***Early Finance*** identifies pre-financial needs for actions and warnings, conducts financial analysis and prepares funding plans. It allocates resources by prioritizing needs, budgeting for anticipated expenses, and seeking additional funding if required.

Detailed explanations of AWARE platform are provided in section 3 of the Supplementary material.

The AWARE framework recognizes the importance of contextual factors such as political, economic, sociocultural, and biophysical conditions for its effectiveness. *Political factors* including government support and investment, can shape the availability and effectiveness of AWARE. Political instability or conflicts can also hinder the AWARE implementation. *Economic factors* such as resource availability can impact the development and sustainability of the system. Economic conditions, such as poverty and inequality, can also affect the vulnerability of communities and their capacity for coordinating activities and responding to early warning messages. *Sociocultural factors* including local beliefs and practices and social networks affect community responses to early warnings. Language barriers and low literacy levels can limit AWARE effectiveness in certain communities. *Biophysical factors* like climate and geography influence the accuracy and timeliness of early warning messages, especially in predicting extreme weather events.

To ensure AWARE fosters multi-institutional partnerships for anticipatory action, three key elements are necessary: principled engagement, shared motivation, and joint action. *Principled engagement* involves active stakeholder involvement, including those at risk, throughout the development process to ensure that AWARE aligns with community needs. Shared *motivation* requires establishing a common understanding of risks and hazards, fostering trust, and cultivating collaboration among stakeholders to collectively mitigate potential threats. *Joint action* entails implementing AWARE through concrete measures such as protocol development, monitoring systems, and effective dissemination of hazard-related information. Ongoing coordination, monitoring, and evaluation are essential for maintaining AWARE in the long-term. Through collaboration, AWARE can be customized to meet beneficiary needs, delivering timely and accurate information to mitigate climate and disaster risks.

The AWARE framework also encourages the importance of social learning, which involves acquiring knowledge, skills, and values through stakeholder interactions and communication.

(iii) ***Outcome:***

The AWARE framework produces social learning outcomes that can be divided into two categories: relational outcomes and problem/task outcomes. These outcomes are crucial for fostering social cohesion, encouraging collaboration among institutions, and facilitating positive social change.

Relational outcomes encompass the social and emotional benefits that stakeholders derive from their interactions. These benefits include strengthened institutional collaboration and capacity, the establishment of mutual trust, heightened awareness of inclusivity, and the acquisition of valuable insights. Relational issues such as communication barriers and conflicts may also arise from interactions between individuals. By promoting effective communication, collaboration, empathy, and respect for diversity, AWARE can contribute to the development of these outcomes, which are vital for fostering positive relationships and successful collaboration among institutions.

Problem/task outcomes within the AWARE framework refer to the knowledge individuals gain through interaction and learning to address problems and achieve tasks. These outcomes include the improved integration of early warning, action, and finance, the enhancement of anticipatory action, the ability to adapt to climate and water variability and extremes, and the capacity for swift emergency response to climate shocks. Achieving problem/task outcomes requires critical thinking from various perspectives and a comprehensive understanding of specific topics or issues. Problem/task issues may also arise from the complexity, ambiguity, and uncertainty of the learning task or problem. These issues can hinder social learning by making it challenging to understand and solve problems.

(iv) Feedback

AWARE emphasizes feedback mechanisms for improving EWS adaptability and effectiveness. The feedback mechanism is indicated by double-ended arrows connecting the entire framework from context to outcomes (Fig. 2). Three types of feedback mechanisms are identified: user feedback, performance feedback, and expert feedback. *User feedback* involves collecting comments and criticism using online and in-person surveys, interviews, or focus group discussions with end-users to assess the effectiveness and utility of AWARE. *Performance feedback* involves monitoring AWARE's performance against predetermined metrics to identify areas for improvement such as the timeliness and accuracy of warning messages or the effectiveness of evacuation procedures. *Expert feedback* involves gathering insights from subject matter experts such as meteorologists, disaster management professionals, and researchers to enhance AWARE. This feedback can be obtained through consultations or expert interviews to enable refinement and enhancement of the framework by addressing issues, improving approaches, and incorporating expert knowledge and user perspectives.

4.1.2. AWARE framework: Addressing challenges in existing EWS

The literature review identified 12 key challenging areas of current EWS. Table 1 shows how AWARE will perform differently in addressing these challenges compared to current EWS.

Table 1
Differences between current EWS and AWARE.

Characteristics	Current EWS	AWARE
Framing Problem	Their approach focuses on reacting to and mitigating the consequences of climate and disaster events by addressing immediate risks and hazards to minimize their impacts (ISDR, 2010; Acosta-Coll et al., 2018).	AWARE frames the problem holistically, addressing underlying risk drivers, anticipating future hazards, and considering long-term climate uncertainties and vulnerabilities.
Goal	To deliver timely and accurate information to alert stakeholders about imminent hazards, enabling immediate response actions, informed decisions on evacuations, emergency response, and resource allocation (Acosta-Coll et al., 2018).	Goes beyond mere alerts, promoting proactive risk reduction and resilience-building. It facilitates anticipatory actions, early preparedness, adaptive capacity building, and fosters a culture of resilience to minimize hazard impacts and address underlying causes of vulnerability and risk.
Timing	Focus on detecting and alerting stakeholders about imminent or ongoing risks and hazards (Garcia and Fearnley, 2012; Jayasekara et al., 2023	Enable proactive preparedness and response measures by providing warnings and triggering actions before a hazard occurs.
Risk perception	Responding to past patterns and events. Often rely on historical data and established thresholds to determine risks (Patton et al., 2023).	They incorporate forward-looking risk assessment, climate and disaster risk projections, and consider emerging risks and uncertainties in seasonal climate change.
Action-oriented Approach	Lack emphasis on proactive actions, often leaving stakeholders to determine appropriate responses on their own (Perera et al., 2020).	Emphasize early actions, finance and response, bridging the gap between warning and action. Engage stakeholders to develop preparedness and response plans, ensuring actionable measures to mitigate risks and reduce impacts.
Collaboration	May involve multiple stakeholders, but lacks sectoral integration and collaboration (ISDR, 2010; Peek, et al., 2020).	Promote multi-sectoral collaboration and coordination, integrating knowledge, expertise, and resources across sectors and communities to enhance preparedness and response for locally-led adaptation strategies.
Technology and Data Integration	Does not fully leverage technological advancements and rely more on traditional data sources and communication channels (ISDR, 2010)	Leverage technology, data analytics, and communication tools to integrate and interoperate different data streams for timely and accurate risk information
User Friendliness	Have a traditional design, requiring specialized knowledge to interpret information, with complex interfaces and limited accessibility, especially for vulnerable communities (ISDR, 2010).	Aim to be accessible to a wide range of users, prioritizing clear communication, intuitive interfaces, and user-centric design.
Relevance of System	Focus on specific hazards or sectors such as meteorological events or natural disasters, providing valuable information within their scope. However, they may not address broader systemic risks or emerging climate change challenges (Basher, 2006; Wever et al., 2022).	Adopt a holistic and integrated approach, considering multiple hazards, climate projections, and socioeconomic factors to provide a comprehensive understanding of risks and their impacts across sectors
Outcomes	Focus on issuing alerts and warnings to inform stakeholders about potential hazards, with the ultimate outcome measured by the number and timeliness of the warnings issued (Ruhl, 2019; Rogers and Tsirkunov 2011)	Focus on tangible outcomes, aiming to trigger early actions, preparedness measures, and resilience-building initiatives based on the provided information. The success of AWARE is measured by its contribution to risk reduction, impact minimization, and adaptive capacity enhancement.
Communication	Typically employ one-way communication channels where experts or authorities disseminate information to end-users, limiting active community and stakeholder participation and engagement (Yasmin et al., 2023).	Prioritize two-way communication and stakeholder engagement, facilitating dialogue, feedback loops, and participatory processes. They aim to ensure that information is not only shared but also understood, contextualized, and acted upon collaboratively.
Resources	Require substantial resources, including infrastructure, technology, and human capacity. They often rely on centralized data collection and analysis, which can be costly and time-consuming (Perera et al., 2020; Twigg, 2021)	Utilize shared resources and technological advancements like remote sensing, satellite imagery, and crowdsourced data to enhance data collection and analysis. They emphasize integrating existing resources, knowledge, and expertise within a multi-stakeholder framework to maximize collective capacity and achieve resource efficiency in addressing risks.

Source: Expert survey and literature review, 2023.

4.2. Expert evaluation of AWARE

4.2.1. Technological frames

Results show that experts recognize AWARE as an important platform to promote anticipatory action, enhancing decision-making preparedness, response, advocacy, and resource mobilization for the climate crisis and disaster prevention. AWARE improves multidisciplinary collaboration, addressing institutional coordination gaps often in developing countries. AWARE's participatory and people-centered approach improves warning lead times and financial mobilization, supporting swift responses to climate change disasters. The platform will enable informed humanitarian decisions by providing real-time climate and hazard information and early warnings, strengthening local resilience systems. Its multidisciplinary framework ensures comprehensive sectoral coverage.

Experts have multiple expectations for AWARE. They emphasize the need for AWARE to enable prompt responses to climate change disasters, fostering multi-institutional collaboration through data and information sharing, coordination, and joint analysis. Its design and implementation should include diverse stakeholders including local communities, institutions, and authorities to address transboundary challenges. The platform must ensure data availability for effective decision-making and strengthen financing capabilities to enhance institutional collaboration and response effectiveness.

Specifically, experts anticipate that by embodying certain characteristics, AWARE has the potential to enable anticipatory action. AWARE is therefore expected to:

- Be responsive to specific needs
- Provide user-friendly information to stakeholders with limited technical knowledge of EWS
- Ensure alerts are translated into local languages
- Embrace inclusivity
- Connect with national systems to address real problems and provide solutions
- Promote participatory actions as a critical factor in making a difference
- Harness new information technologies and engage local communities in innovative approaches
- Prioritize reflexivity and collaboration to inform anticipatory action through multi-stakeholder involvement
- Deliver timely and tailored information, integrate multiple data sources, foster collaboration, integrate with financial mechanisms, and enable continuous monitoring and evaluation

4.2.2. Interpretative flexibility

Interpretative flexibility was analysed in terms of usability, design and collaboration concerns.

4.2.2.1. Usability concerns. Experts raised concerns about AWARE platform usability for users with limited technical knowledge and unfamiliar with jargon and lacking proficiency in digital tools. They recommend user-friendly interfaces, clear instructions, and intuitive design principles that simplify complex processes and empower users to navigate and access information.

Limited connectivity, especially in developing countries can hinder the dissemination of warnings from AWARE. Experts suggest leveraging mobile phones and messaging apps or SMS to reach users with minimal technical requirements. Prioritizing mobile-friendly design and accessible interfaces can enhance inclusivity and widen the reach of AWARE. This can also enable users to access important information, updates, and alerts especially as timely access to real-time data and information enables informed decision-making. Also, experts emphasized the importance of capacity building for end users, through adequate training and support especially those with limited technical knowledge. They also recommend using recognizable signs and symbols in the platform's indicators to for example represent different types of disasters. This visual representation aids user comprehension and decision making.

4.2.2.2. Design concerns. Experts stressed the need to address key design concerns for AWARE, including using universally recognized symbols and local languages and robust infrastructure to enhance d accessibility and usability. Customizing the platform to suit specific agro-ecologies and sociological contexts was also emphasized, avoiding a one-size-fits-all approach. Ensuring platform access, responsive technical support, and tailoring the platform to regional and community needs were critical for effective user engagement. Furthermore, experts also emphasized the importance of engaging all stakeholders, including community members and decision makers, in the design process. Tailoring the AWARE to different user needs, considering gender-specific concerns, and involving local communities ensures the platform's relevance, usability, and inclusivity.

4.2.2.3. Institutional/stakeholders' collaborative concerns. The experts emphasized the need for features in the AWARE that promote collaboration and active stakeholder participation. Sharing feedback, skills, knowledge, and resources and allowing stakeholders to contribute and be heard enhances inclusivity and fosters ownership, resulting in effective and sustainable climate crisis responses. Also engaging local organizations like NGOs, Faith-Based Organizations, and meteorological agencies is crucial for leveraging contextual knowledge and data. Building technical capabilities for secure information exchange on the AWARE platform enhances decision making. Experts recognized the value of educational institutions in training users on the AWARE platform functionality.

4.2.3. AWARE as a boundary object

4.2.3.1. Enabling collaboration among all relevant institutions and stakeholders. According to the experts, AWARE has the potential to

serve as a collaborative space for diverse stakeholders including government agencies, research institutions, NGOs, and community-based organizations, by promoting knowledge exchange and joint decision-making. However, for AWARE to function as a boundary object requires open, transparent data sharing to support evidence-based decisions, cross-sectoral communication and collaborative problem-solving.

The AWARE's user-centric design prioritizes usability, ensuring accessibility for all technical levels. The platform encourages broader adoption and engagement, facilitating collaboration and information sharing. Interactive features like forums, discussion boards, and virtual collaboration spaces allow stakeholders to contribute their expertise and experiences, fostering a sense of ownership and active participation. Real-time communication tools such as instant messaging and document sharing may also significantly enhance collaboration and facilitate the timely exchange of information, ideas, and feedback among institutions and stakeholders.

4.2.3.2. Participatory approaches to be adopted by AWARE. Experts emphasized co-production of knowledge to position AWARE as an inclusive boundary object. Involving stakeholders ensures the platform integrates diverse perspectives and local knowledge, fostering relevance and context. Dialogue features such as online forums and workshops were recommended to enable open discussions, mutual learning and collective decision-making leveraging collective intelligence and experiences for context-specific solutions.

4.2.3.3. The organizational benefit of AWARE-enabled collaboration. Experts agree that the AWARE platform could enhance organizational response to climate shocks and disasters by providing timely and accurate information for proactive action, particularly in agriculture. AWARE supports sustainable water management and serves as a research sharing repository, promoting collaboration and learning that ensure collective response to climate challenges.

Experts highlight AWARE's potential to improve livelihoods and resilience in climate-risk regions. They stress the importance of AWARE having a database of climate-resilient strategies, technologies, and practices for the action component. This enables organizations to access tested and proven approaches, facilitating informed decision-making and implementation of appropriate measures tailored to specific circumstances.

Table 2
Type of stakeholders to be involved in the different components of AWARE.

Stakeholders	Roles in AWARE
Early Warning:	
Meteorological and Hydrological Services	Collecting, analyzing, and disseminating weather and climate-related information. Their involvement ensures accurate and timely EWS.
International and national research institutions	International research institutions contribute a global perspective, advanced modeling techniques, and comprehensive data sets to hazard assessment and prediction. National research institutions provide local climate knowledge, vulnerability factors, and tailored early warning alerts. Collaboration with these institutions enhances EWS with cutting-edge research, robust data analysis, and context-specific understanding, leading to more effective and targeted alerts that save lives and minimize climate-related impacts.
Government Agencies	Government agencies responsible for disaster management, emergency response, and public safety play a vital role in integrating early warnings into national policies and coordinating effective response efforts.
Local Communities	Engaging local communities and community-based organizations is vital to ensure relevant, accessible, and actionable early warnings at the grassroots level. Incorporating local knowledge and understanding community needs enhances the effectiveness of EWS.
Early Action:	
Local Governments	Local governments are critical in implementing early action measures at the community level. They can develop and enforce regulations, allocate resources, and coordinate local response efforts.
NGOs and Civil Society Organizations (CSOs)	Non-governmental organizations and civil society groups are key in community mobilization, capacity building, and implementing early action plans. They have direct connections with vulnerable communities and can facilitate grassroots initiatives effectively.
Private Sector	Engaging the private sector, including businesses, industries, and financial institutions in early action efforts contributes resources, expertise, and innovation to implement climate-resilient practices and investments.
Early Finance:	
Development Finance Institutions	Regional banks, multilateral development banks, and international financial institutions can provide financial resources for climate adaptation and resilience-building projects. Their involvement is crucial in mobilizing funds and supporting the implementation of early finance mechanisms.
Climate Fund Institutions	Climate funds, such as the Green Climate Fund, Adaptation Fund, and Global Environment Facility, play a key role in providing financial support for climate adaptation and resilience initiatives. Engaging these funds ensures access to resources for early finance activities.
Donor Agencies and International (private) financing Organizations	Donor agencies and international organizations contribute to early finance by providing grants, loans, and technical assistance to support climate adaptation and resilience projects in developing countries.

Source: Expert survey, 2023.

4.2.4. Collaborative governance, social learning and adaptive management

(a) *Types of stakeholders/institutions and engagement in AWARE*

The anticipated engagement of stakeholders and institutions in AWARE, as indicated by expert responses, encompasses several key aspects. First, they are expected to contribute expertise, knowledge and data, and resources to enhance its accuracy and reliability. Secondly, they play a key role in sharing early warning information, translating warnings into local languages, and conducting awareness campaigns to promote preparedness and response actions. Thirdly, they should act on early warnings by implementing appropriate actions such as emergency plans, coordinating efforts, mobilizing resources, and supporting vulnerable groups. Furthermore, they should provide continuous feedback and evaluation of Warning's effectiveness, observed impacts and improvement suggestions for AWARE's success. Regular collaboration fosters learning, innovation, and adaptive management. Table 2 outlines the type of stakeholders and their role in AWARE.

(b) *Strategies for effective collaboration among relevant stakeholders/institutions*

Several essential factors for facilitating collaboration among relevant stakeholders/institutions in the development and implementation of AWARE were highlighted by the experts. These factors include:

Clear Communication: Establishing effective communication channels and mechanisms that facilitate information exchange, insight sharing, and feedback among stakeholders. Clear and concise communication aligns expectations, clarifies roles and responsibilities, and promotes a shared understanding of AWARE's goals. Transparent communication builds trust, enabling effective problem-solving, decision making, and collective stakeholder collaboration.

Shared Vision and Objectives: Stakeholders must share a common vision and understanding of AWARE's purpose and desired outcomes. This shared vision serves as a guiding framework for aligning efforts, generating consensus, and maintaining focus on improving preparedness and response to climate-related risks. Integrating AWARE into institutional plans ensures alignment with broader disaster risk reduction efforts and established procedures.

Inclusive Participation: Involving all relevant stakeholders, including government agencies, research institutions, local communities, NGOs, and other institutions, in the AWARE development and implementation process. Inclusivity ensures diverse perspectives, integrated knowledge systems, and addressing stakeholder needs. This promotes collaborative leadership, participatory learning, consensus-driven decision-making, and effective conflict management.

Collaborative Decision-Making: Adopting participatory and collaborative decision-making processes enables stakeholders to contribute their expertise, insights, and local knowledge. It fosters consensus, ownership, and contextually appropriate decisions while understanding stakeholders' interests, capabilities, and roles helps assign responsibilities and maximize impact.

Capacity Building: Building stakeholders' capacity through training and resources to enhance their understanding of AWARE, technical skills, and ability to interpret and utilize platform-provided information. Capacity building empowers stakeholders, increases trust, and strengthens collaborative efforts.

Institutional Coordination: Establishing coordination mechanisms, such as interagency platforms, working groups, and regular meetings, to facilitate collaboration among stakeholders and institutions. Effective coordination avoids duplication of efforts, enhances synergies, and streamlines AWARE's implementation.

Resource Mobilization: Mobilizing adequate financial and technical resources for AWARE's development, implementation, and maintenance. This includes securing funding for infrastructure, data collection and analysis, capacity building, and sustained system operation. Prioritizing resource mobilization ensures long-term sustainability and effectiveness of collaborative efforts.

Lastly, *establishing agreements or Memoranda of Understanding or Standards of Operations* that outline each institution's roles and responsibilities involved in the collaboration provides clarity, accountability, and a shared understanding of commitments and expectations.

4.2.5. AWARE for socio-environmental-technological outcomes

The potential outcome of AWARE was evaluated in terms of relational and problem/task outcomes of social learning.

4.2.5.1. Relational outcomes of AWARE. The experts emphasize the importance of trust in effective collaboration. AWARE can cultivate trust through transparency, inclusivity and data accuracy, addressing privacy concerns. It enhances credibility and builds stronger relationships while breaking communication barriers by serving as a centralized platform for diverse stakeholders to share information and collaborate. Furthermore, conflicts and power dynamics are significant relational issues that AWARE can address through its participatory approach. It promotes dialogue, collaboration, and inclusion of marginalized voices, reducing power imbalances and ensuring balanced representation to help stakeholders find common ground and resolve conflicts constructively. AWARE can also empower behavior change by providing reliable climate risk information and practical adaptation resources. It raises awareness, supports sustainable practices, and fosters knowledge exchange. By inspiring action, AWARE equips individuals and communities to implement adaptive strategies, promoting climate resilience and a culture of sustainability in response to climate challenges.

4.2.5.2. Possible problem/task outcomes of AWARE. The experts indicated that AWARE can provide clear, actionable and interpretable

climate information free from technical jargon, to support decision-making. AWARE has the potential to reduce uncertainties by delivering accurate, localized, and real-time data on climate risks and early action options. AWARE can also help reduce uncertainties, by enabling scenario planning, risk assessment, and collaboration to promote adaptive climate responses and bridge knowledge gaps. Furthermore, the experts recognized that AWARE offers information, including decision-support systems, risk assessment and monitoring and evaluation to help users manage climate adaptation tasks. AWARE also provides resources to provide practical guidance, support planning and overcoming challenges in implementing adaptation strategies.

4.2.5.3. Context specific issues or factors that influence AWARE outcome. Experts emphasized the need to understand geographic, climatic, and sociocultural contexts for optimal use of the AWARE platform. Tailored information, community engagement, and inclusive stakeholder involvement are essential for effective climate risk management and fostering ownership of adaptation actions. Also, data availability, quality, and reliability are key considerations, requiring assessment of the current data infrastructure. The platform should utilize existing data, address gaps, and provide accurate, timely information. Institutional capacity and governance should align with frameworks to ensure sustainability and collaboration. Furthermore AWARE should integrate local knowledge and data to provide context-specific information, fostering culturally sensitive communication and actions to enhance community engagement and address specific needs effectively.

5. Discussions

The results demonstrate the potential of AWARE as a boundary object, fostering social engagement and collaboration among institutions and stakeholders to collectively respond effectively to climate and disaster crises. This aligns with the boundary object literature, which discusses how technologies enable collective action (e.g. Bechky, 2003a; Carlile, 2004; Tim et al., 2017). AWARE connects multiple social worlds (Bechky, 2003b; Pawlowski & Robey, 2004), enabling collective action across them (Ritzer, 2004; Tim et al., 2017), and demonstrating flexibility across diverse contexts (Carlile, 2002; Star, 2010). As Levina and Vaast (2005) suggest, AWARE's effectiveness as a boundary object-in-use depends on its integration into local practices For AWARE to mediate effectively between different groups with their distinct perspectives, standards, norms, incentives, power structures, and infrastructures, it must be adaptable and involve active communication, collaboration, and a shared commitment to addressing climate hazards (Lainer-Vos, 2013; Winter & Butler, 2011). This approach enables mutual understanding and cooperation across social worlds.

The technological frame analysis reveals experts' assumptions, expectations, and knowledge of AWARE, highlighting how contextual factors impact its success(Lin and Silva 2005; Khoo and Hall 2013). Technological frames demonstrated challenges faced by current EWS in addressing climate and disaster crises, which AWARE seeks to resolve (Ayre et al. 2019, Nettle et al. 2018). AWARE offers a systematic and integrated approach to translating warning information into better decisions for effective anticipatory action (Eastwood et al. 2017; Ayre et al. 2019; Rijswijk et al. 2019; Loboguerrero et al., 2022). While AWARE addresses incongruent, conflicting, and contrasting frames (Keenan et al. 2019; Orlikowski and Gash 1994; Dewulf, 2013), it may struggle with frame ambivalence —where users shift between different cognitive frames based on the situation or context (Higgins & Bryant, 2020). Interpretive flexibility is however crucial in enabling stakeholder engagement and adaptability to uncertainties. Uncertainty in user adoption and fragmented knowledge may hinder anticipatory action, creating information asymmetry (Sutherland et al., 2013). For example, stakeholder concerns about AWARE's ability to capture unexpected climate changes may prompt reliance on other sources, causing fragmented knowledge and user confusion. Addressing this requires AWARE to account for uncertainties in adoption and future capabilities.

The interpretative flexibility of AWARE highlights diverse user perspectives, needs, and priorities based on expertise, responsibilities, and sociocultural contexts (Boin & McConnell, 2007; Cutter et al., 2008). Scientists prioritize technical accuracy, policymakers focus on political feasibility, while communities rely on local knowledge systems that may differ from mainstream approaches. Increased stakeholder interaction necessitates AWARE's adaptability, yet flexibility may decrease with rising interdependence (Cadili & Whitley, 2005). Continuous feedback and iterative improvements are essential to ensure usability, relevance, and acceptance. Failures in early warning systems often stem from poor communication rather than infrastructure limitations, emphasizing the need for sociotechnical design, user-centered features, and effective communication (Baudoin et al., 2016; Macherera & Chimbari, 2016; Brazzola and Helander, 2018).

The analysis also emphasizes the importance of social learning in framing user concerns, designing the platform, and facilitating collaborative outcomes. Incorporating insights from expert opinions and social-ecological systems literature, it underscores the need for multi-stakeholder collaboration and iterative social learning to build collective capacity for tackling complex issues like climate change (Haque and Doberstein, 2021; De Kraker, 2017; Reed et al., 2010; Armitage et al., 2009; Ison et al., 2007; Pahl-Wostl, 2009). To promote collaborative governance and social learning in AWARE, clear communication, shared vision, inclusive participation, collaborative decision-making, capacity building, institutional coordination, resource mobilization, and standards of operation are required to ensure accountability among stakeholders. The conceptualization of AWARE within the proposed framework with the call for system thinking and co-production of knowledge in addressing complex socioecological problems like climate change (Voulvoulis et al., 2022; De Souza,2022; Schneider et al., 2019; Slater and Robinson, 2020).

The AWARE framework identifies potential social learning outcomes by influencing attitudes and triggering actions, including relational outcomes such as enhanced trust, inclusiveness, awareness, and capacity. The AWARE framework identifies potential social learning outcomes through influencing attitudes and triggering actions, including enhanced trust, inclusiveness, awareness, and capacity. Task/problem oriented outcomes, such as integrating early warning systems, anticipatory action, emergency response, and

adaptation to climate extremes, align with adaptive management literature (Pahl-Wostl et al., 2007; Rai and Soni, 2019; Farahbakhsh et al., 2022). These processes strengthen decision-making by improving awareness of human-environment interactions, fostering relationships, and enhancing the problem-solving capacity of stakeholders (Armitage et al., 2009; Osifo, 2016). Social learning also boosts the adaptability of social-ecological systems (Pahl-Wostl & Hare, 2004; Ensor & Harvey, 2015). Cundill and Rodela (2012) stress empirically testing conditions for effective outcomes, highlighting tailored, context-sensitive approaches integrating stakeholder engagement, local knowledge, data quality, and institutional capacity.

The AWARE framework recognizes that the one-size-fits-all approach to EWS is ineffective, and that context plays a critical role in its success. These contextual factors such as political, economic, sociocultural, and biophysical factors can pose barriers to adoption (UNISDR, 2009; Eiser et al., 2012; Zia and Wagner, 2015; Haigh et al., 2020; Yasmin et al., 2023). Addressing these barriers is essential for AWARE's acceptance, effectiveness, and sustainability. Tailoring warnings to cultural norms, local knowledge, and hazard-specific factors, along with sufficient funding and political commitment, is vital for ensuring its success. AWARE framework also advances dialogue on anticipatory action and aligns with the broader landscape of disaster risk management, climate resilience, adaptation and financing. Its relevance aligns with the bold declaration by the United Nations on 2022 World Meteorological Day, stating that "within the next five years, everyone on Earth should be protected by EWS against increasingly extreme weather and climate change" (UNFCCC, 2022). This announcement not only underscores the urgent need for AWARE but its effectiveness, as an adaptation strategy as highlighted in all 18 chapters of the 2022 IPCC report (IPCC, 2022). AWARE contributes to the efforts to manage extreme hydrometeorological hazards through anticipatory action (Biagini et al., 2014; de Perez et al., 2022).

The proposed AWARE framework also aligns with the core principles and objectives of the Sendai Framework for Disaster Risk Reduction (SFDRR) 2015–2030, emphasizing disaster risk reduction and resilience building (Aitsi-Selmi et al., 2015; Bennett, 2020). It addresses the four priority areas of SFDRR by integrating early warning systems, action, and finance. For *Priority 1,* AWARE supports understanding disaster risk by assessing vulnerabilities and exposure by offering insights into how EWS, actions, and finance are interconnected and impact disaster risk. For P*riority 2*, it strengthens governance through multiscale institutional responses and highlights how governance structures can be enhanced to better integrate early warning, response, and financial mechanisms in disaster risk management. Aligning with *priority 3,* AWARE emphasizes financial strategies for resilience by offering strategies and insights on effective financial resource mobilization and allocation to anticipated actions that strengthen resilience. P***riority 4*** benefits from AWARE's focus on EWS and their interconnectedness with actions and finance, enhancing preparedness through timely and accurate information and coordinated responses, to effectively advance disaster risk management efforts. Despite advances in forecasting extreme weather, frustrations with delayed responses to climate hazards have increased thus raising increasing support for anticipatory action (Wilkinson et al. 2018). While sophisticated early warning systems (EWS) offer opportunities to prevent crises, they often fail to prompt action among humanitarian agencies, donors, and the public (Bailey, 2012). Leveraging platforms like AWARE can enable early action, but such initiatives must address political, economic, and institutional barriers, including governments' preference for reactive over proactive risk reduction (Wilkinson et al., 2020; Wilkinson, 2012).

Finally, our findings address the research question of how a digitally enabled AWARE platform can advance anticipatory action by promoting social processes that enable rapid multiscale institutional response to climate risk and disaster mitigation. While offering valuable insights, the study acknowledges its limitations. First, it focused on a selected number of theories that were found relevant in our case. It could benefit from further analysis with technology acceptance model (Raffaghelli et al., 2022; Taherdoost, 2018), diffusion of innovations theory (Dearing, 2009; Acikgoz et al., 2023) and social construction of technology (Bijker, 2009; Douglas, 2012) as well as analysing the side effects of social processes. Second, Challenges such as technical failures, and coordination of bottom-up actions require further exploration. Third, further empirical research is essential to refine AWARE's components, evaluate trade-offs in bureaucratic complexity from high institutional coordination, and assess AWARE's utility across diverse cultural, political, economic, and governance contexts to identify areas for improvement. Fourth, future studies should confirm these findings once AWARE is fully implemented. Nonetheless, this research this paper could stimulate interest among scholars to explore the potential of digital platforms to enable anticipatory action against climate shocks and disasters.

6. Conclusion and Recommendation

In conclusion, AWARE is a digital platform designed to promote anticipatory action by integrating early warning, action, and finance, while fostering multiscale institutional collaboration for rapid responses to climate and disaster risks. The findings demonstrate AWARE's potential to serve as a collaborative space for knowledge exchange, communication, and joint decision-making, bridging disciplinary and knowledge boundaries. Addressing assumptions, expectations, and contextual factors related to technological frames is crucial to overcoming incongruence, frame ambivalence and fostering a common understanding among stakeholders. Continued collaboration and social learning among institutions are deemed essential for triggering multiscale institutional responses to climate and disaster emergencies. AWARE is expected to generate valuable social learning relations and task/problem outcomes. The AWARE framework acknowledges the need to tailor approaches to specific contexts to overcome potential barriers to uptake and use. The application of the AWARE framework aligns with the Sendai framework priorities and expands the dialogue on anticipatory action, offering insights into disaster risk management, climate resilience, adaptation, and financing.

To advance the use of the AWARE platform for anticipatory action, the following recommendations are provided:

- Local Governments should integrate AWARE's climate data and anticipatory action protocol into municipal planning, such as for flood-prone zoning and to strengthen early warning systems through timely SMS alerts and community broadcasts.

- Communities should actively participate through local disaster committees or sub-groups in designing and implementing anticipatory action plans with AWARE'S localized risk alert to coordinate disaster preparedness such as evacuation drills and asset protection.
- International Organizations should promote AWARE adoption by funding capacity-building initiatives such as training local governments to use AWARE's real-time risk monitoring dashboard and providing financial support to build sustainable anticipatory action systems.
- Private Sector should utilize AWARE's drought or flood alerts to develop insurance products such as parametric crop insurance for smallholder farmers
- Academic and Research Institutions should collaborate with AWARE to improve predictive models and advance to advance research that informs evidence-based decision-making for anticipatory action.

CRediT authorship contribution statement

Emmanuel M.N.A.N. Attoh: Writing – original draft, Writing – review & editing, Investigation, Data curation, Formal analysis, Conceptualization. **Giriraj Amarnath:** Writing – review & editing, Project administration, Resources, Supervision, Conceptualization, Funding acquisition, Investigation.

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Declaration of competing interest

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

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Appendix A. Supplementary material

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Data availability

Data will be made available on request.

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