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Research gaps and challenges for impact-based forecasts and warnings: Results of international workshops for High Impact Weather in 2022

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A R T I C L E I N F O

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A B S T R A C T

The World Meteorological Organization (WMO) has called for more meaningful warnings to help reduce the impacts of weather-related events. Impact-based forecasts and warnings (IBFW) are being developed by forecasting agencies globally to meet this call. However, there are many challenges facing those implementing such systems. The WMO World Weather Research Programme High Impact Weather project sought to understand the future direction of research on IBFW systems. This research involved a virtual workshop series in late 2022 with over 350 international registrants to identify and analyse challenges that people are facing in developing IBFW systems, and potential solutions.

We found that challenges relate to ten themes, in addition to defining the measures of success of an IBFW system Examples of key research gaps are to develop evaluation methods to explore the value of multi-hazard IBFW, in terms of collating data at appropriate scales, and including avoided losses, behavioural responses, and unconventional observations. We need to explore the value of using quantitative approaches in comparison to more efficient qualitative approaches, as well as of dynamic exposure and vulnerability data sets, and tailored warnings. We must investigate how to effectively communicate uncertainty and explore the governance of underpinning data.

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Further research on these topics will assist with the successful implementation of more meaningful warnings globally, whilst considering the feasibility and effectiveness of the efforts involved. This is our contribution to reducing the impacts of future hazards, at a time where climate-related events are expected to increase in severity.

1. Introduction

In March 2022 the United Nations Secretary General called for everyone in the world to be protected from natural hazards by early warnings by 2027 (termed the 'Early Warnings for All' initiative), building on the universally accepted commitments contained in the Sendai Framework [1].[1] In recent years, state-of-the-art hazard warning systems (principally for hydrometeorological events) have begun to shift from warning about what the hazard may *be* (hazard-focussed), towards warning about risks associated with what the hazard may *do* (impact-focussed). The intent is to make the warning more relevant and meaningful to the recipient thus increasing their likelihood of taking protective actions. At the same time many responder organisations, especially humanitarian non-governmental organisations (NGOs) working in developing countries, have been shifting their priorities from responding after a disaster to early action that reduces the impact of the hazard, potentially preventing disaster. Understanding, anticipating and communicating the impact of natural hazards is a common thread that brings these two initiatives together. The impetus for change has come from clear deficiencies identified in the warning and response to historical disasters [2,3]. However, practical implementation of impact-based forecasts and warnings (IBFWs) for early action can be complex and costly. It is therefore important to understand which aspects are necessary to achieve an effective response. While research on the response to warnings has grown in recent years, there remain many unanswered questions about the production, use, and realized societal value of IBFWs.

Various social and behavioural science methods, including surveys, interviews, focus groups, and controlled experimental studies using hypothetical scenarios and role-playing exercises, have been employed with users and issuers of warnings to examine the efficacy of IBFW systems. From this work, key overarching knowledge gaps identified include: continuing to better understand the value and effectiveness of IBFW; effectively communicating impact-related information (including uncertainty); exploring measures and relationships along the multi-hazard warning value chain for multiple simultaneous or sequential risk events; and characterising uncertainty (e.g. Ref. [4–9]). More specific knowledge gaps within these overarching gaps are provided in Table 1.

Other researchers attempt to objectively formalize hazard-impact relationships or forecast impacts, often as an extension of traditional weather or hydrometeorological predictions, by analyzing and modelling interrelationships among hazard, exposure, vulnerability, response and risk outcome or impact variables (e.g., Ref. [4–9,11–14]). Key knowledge gaps, also represented in Table 1, include: a lack of impact data for quantifying certain types of losses and damages (e.g. Ref. [15]); the need for an evaluation of datasets and sources for verification and comparison of methods to construct and verify formal risk and impact models (e.g. Ref. [12,13]); and the need to develop methodologies for quantifying and integrating vulnerability and exposure into impact forecasts (e.g. Ref. [16]).

In the grey literature (including guidance documents, comprehensive reviews, and 'state-of-practice' syntheses (e.g., various chapters in Ref. [2,17–19], [3]), key identified knowledge gaps related to governance and how to co-produce IBFW systems, clarifying roles and responsibilities; data requirements; clarifying the objectives of IBFW systems; how to tailor IBFWs; and how to translate research into practice. Additionally, researchers have identified areas of opportunity in exploring the application of new technologies in the development of IBFWs. This includes exploring the role of Artificial Intelligence (AI) in impact forecasting, and people's perceptions of trust in the use of AI (e.g. Ref. [20–22]); and deepening our understanding of how to integrate modern technology and local needs for emergency communication [23].

There remains a need to bring people together from the operational meteorological and hydrological services, research, and forecast user communities to address improvements in forecasts [24]. Towards this end, the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO) initiated the High Impact Weather (HIWeather) research project to increase societal resilience through improved forecasts and their communication.[2] Over the past decade, this project has drawn together a wide variety of diverse research and experience on forecasting, warning, communication and decision-making relating to high impact weather and its consequences. Outputs have included a special issue [5], a book on bridging disciplinary gaps through partnerships [18], as well as workshops[3] [25] and webinars. The purpose of the present article was to understand what the key gaps and challenges are relating to IBFWs, and what solutions have been found worldwide that could be shared. Deliberations from a series of global interactive workshops held in 2022 were analysed using a structured process developed by the authors. This paper lays out our findings on the research gaps and priorities that need to be addressed to establish a secure foundation for the widespread implementation and use of IBFW systems. While the focus is on weather-related hazards and impacts (where most previous work has been conducted), the findings are applicable generally in a multi-hazard context.

[1] Target 'G' of the Sendai Framework specifically refers to increasing the availability and access to multi-hazard early warning systems while the first four targets relate to reduction of the socio-economic impacts of disasters.

[2] www.hiweather.net, accessed on 1 July 2024.

[3] http://hiweather.net/article/18/1.html, accessed on 1 July 2024.

Table 1
Knowledge gaps identified from reviewing academic and grey literature (derived primarily from Ref. [2,3,10]).

ACADEMIC LITERATURE GAPS, CHALLENGES, AND NEEDS	GREY LITERATURE GAPS, CHALLENGES AND NEEDS
Explore and better understand the value of IBFW ● Evaluation and understanding of the social value of impact-based relative to traditional warnings. ● Application and assessment of social and economic theories and constructs in explaining anticipated and realized effects of different types of warnings on risk-mitigating behaviour. ● Ethical dimensions and issues associated with IBFW. ● Understanding the effects and extent of spatial, temporal, and social precision of warning information required to influence decisions and actions. **Communication of impact information** ● Communicating likelihood/probability/uncertainty and people's interpretations; sensitising people for uncertainties in modelled forecasts of impacts; what is the acceptable level of accuracy in impact forecasts? ● Communication and presentation of qualitative and quantitative vulnerability and exposure information for IBF decision-making. **Explore measures and relationships along the multi-hazard warning value chain** ● Characterization, qualification, quantification, validity and reliability of empirical measures and relationships among weather, warning information, decisions and behaviour, and particular types of physical, social, economic or environmental risk/impact. ● Better understanding and treatment of multiple simultaneous or sequential risk events in IBFW, including those unrelated to weather, climate or hydrology. ● Improved characterization and understanding of uncertainties in all aspects of risk and implications for development of impact forecasts. ● Integration of cascading/consecutive/secondary/compounding hazards in hazard and impact forecasts. **Explore methods and data for verification** ● Comparison of methods to construct and verify formal risk and impact models for particular sectors, issues, and outcomes. ● Accessibility, reliability and utility of data required to construct and validate risk models. **New technologies** ● Perceptions of trust in Artificial Intelligence (AI), exploring AI for enhancing mitigation, applying AI for impact analyses ● Deeper understanding of how to efficiently integrate technological applications and local needs for emergency communication.	**Governance and co-production** ● Understanding benefits and drawbacks of different forms of operational IBFW governance, including co-production models and institutional arrangements with various partners and constituents. ● Identification, assessment and application of co-production techniques with users/decision-makers to design, construct, and use of IBFW services. **Roles of public and private sector actors** ● Relative roles of private and public sector actors in designing, building and applying IBFW models and systems. ● Better understanding of the roles of 'intermediary' actors in the value chain (e.g., media, social media influencers, partner organisations) at influencing public behaviour in relation to IBFW. **Level of support and data required** ● What forms of training, new expertise/skills, and technical infrastructure are necessary to support IBFW systems within National Meteorological and Hydrometeorological Services (NMHSs) and partner organisations with varying levels of resources? ● Identification of minimal exposure, vulnerability, and impact or risk outcome data necessary to support IBFW systems and contingencies to bridge gaps. **Clarify the objectives of IBFW** ● Clarification across NMHSs and with international organisations about the explicit goals and objectives of IBFW and measures that define success. **Extent of standardisation and automation** ● Extent to which IBFW systems or aspects therein (e.g., warning production, impact observations, verification, etc.) can and/or should be standardized and automated. **How can IBFW be tailored?** ● How and to what extent given available resources can IBFW systems be used to target and tailor information to priority populations (e.g., exposure/vulnerability, language, special needs requirements). **How to translate research to practice?** ● How best to translate or incorporate evolving IBFW research into operational warning systems of NMHS and/or other responsible agencies, organisations? **Differing interpretations** ● Understanding the different interpretations of IBFW products and services (such as risk matrices) among users/decision-makers. **Analysing experiences** ● Compilation and analysis of various user/decision-maker experiences during events or for particular hazards.

2. Method

Three themes frequently noted from the initial literature review and deemed most relevant in project organiser discussions were identified for further exploration during a series of virtual IBFW workshops: 1) Impact-based warnings: Underpinning data and model integration, 2) People-centred impact-based warnings, and 3) Multi-hazard impact-based warnings. The intention was to deliberate, build upon, prioritise, and identify new gaps.

2.1. *Impact-based forecasts and warnings workshops*

For attendee recruitment general advertisements were distributed publicly through social media, via e-mail, and through partner lists (e.g., WMO HIWeather newsletter). Over 350 people registered for one or more workshops, most having professional roles as hazard (physical) scientists, operational hydrometeorologists/meteorologists, and social or risk scientists. While registrants represented 52 different countries, over half were from seven, mostly English-speaking, nations (Australia, Canada, India, New Zealand, Nigeria, United Kingdom and United States). Consent from registrants and clearance through the host organisation's (Aotearoa New Zealand's GNS Science) Low Risk Human Ethics procedure were obtained to record and use participant remarks, opinions, and suggestions with guarantees of anonymity and acknowledgement in this paper (if desired). An information sheet was sent out to all registrants prior to the workshops with further information about the HIWeather project, the workshops, and their rights as participants (Appendix A).

Workshops were held on October 25 (06:00 UTC), November 1 (12:00 UTC), and November 9 (19:00 UTC) 2022, with variable timing intended to enable participation from all time zones and regions. The 2-h-long workshops were conducted and recorded using MS Teams. Each workshop followed the same format, but focussed on one of the three themes. They included a 10-min overview by workshop facilitators, 3–4 invited 5-min panel presentations, and a 45–60 min interactive digital whiteboard session. The whiteboard sessions used 'Mural' (Mural.co) online software, and began with participants identifying on a map where they were from as an exercise to become familiar with how to use the software. In the second activity they were asked to identify pertinent gaps and challenges relating to the workshop theme (e.g., underpinning data and model integration for IBFW for Workshop 1) on post-it notes, and to cluster common entries together and name the theme (30–40 min). The common themes were then transposed to activity three, with possible solutions described by participants (10–15 min). Finally, definitions of success and potential indicators and ways to measure it were captured in activity four (5–10 min).

2.2. Workshop data analysis, expert workshop, discussions and collaborative writing

Five project team members thematically coded participant data derived from the Mural Board interactive session, in a manner similar to that described by Braun and Clarke (2006). Raw entries were exported from Mural into an MS Excel spreadsheet, and cleaned to cull duplicates and any irrelevant comments. They were then assigned unique alphanumeric references to distinguish between the three workshops, activity (gaps and challenges, solutions, measures/success), and whether the comment was a detailed entry or a participant-suggested synthesis theme. Three separate rounds of inductive ('bottom up') coding/recoding ensued for the 'gaps and challenges' topic which occupied the majority of workshop participants' time. In round one, coders read through Workshop 1 'gaps and challenges' data and identified and assigned codes. The coding team then met and reviewed code definitions and assignment decisions for consistency and determined a common set of codes. The second round of coding saw the assignment of those common codes across the dataset. A consensus set of 11 common themes (each containing multiple codes) was developed after the second round and used to re-code all 'gaps and challenges' entries across the three workshops as well as the 'solutions' data. Memos (notes and comments relating to themes) were documented during this process, which later helped inform the description of the themes and discussions. Given a much smaller set of entries, one coder was assigned to review and synthesise results for the 'measures/success' activity across the three workshops. Due to the relatively low number of data entries, inter-coding reliability metrics such as Cohen's kappa were not appropriate for this analysis.

An in-person[4] meeting of the authors was convened 18–20 April 2023 at the UK Met Office in Exeter, United Kingdom, to craft the substantive elements of the analysis. Deliberations focused on identifying missed or underrepresented gaps and challenges as well as areas of agreement/disagreement with the workshop results. Iterative rounds of group breakouts were then used on the final two days to further examine the themes and additional gaps, distil the essence of discussions, develop the paper outline, and begin preparing specific sections of the paper.

Following the writing workshop, team members self-assigned to complete and edit various sections of the paper, with a final round of editing to improve flow and consistency conducted by a core writing team. The expert consensus method used in this project and described here is consistent with the approach used by others to identify issues in risk communication and produce 'state of the art' summaries (e.g., Refs. [26,27]).

3. Results and discussion

Eleven themes were identified during data analysis. We first describe participant perspectives on the definition of warning success and methods of measurement. The next ten themes are then presented with the associated 'gaps and challenges' and 'solutions' that were identified by workshop participants. The theme of 'uncertainty' was discussed across nearly all themes, but comments particularly aligned with theme 3 (Communication) and it has therefore been covered there.

3.1. Measures and success

Participants were asked what defines 'success' for IBFW and how this might be indicated or measured. Success was primarily expressed as saved lives, livelihoods and properties, and people taking appropriate and timely action. Other forms of success were mentioned, such as when communities feel empowered by understanding their risks, user satisfaction with decisions they make, or that collaborators are rehearsing their operational settings in the lead up to an impactful event.

> "The different actors know what actions to take, and should agree [on] the emergency level set in the IBW." (W1-MS-17)

Participants suggested a number of different measures and instruments to assess IBFW success. The former include the degree of correlation between weather and impact variables, quantitative comparisons of events and outcomes with and without IBFWs, and measuring the avoidance or mitigation of losses due to behaviour change. Instruments suggested include social science and evaluation

[4] One person joined remotely but participated in all discussions.

studies, citizen science and crowdsourcing methods, tracking mobile phone movement data and recording peoples' actions via an app. Post-event surveys or social media users reporting to have received, understood, and acted upon the IBFW were also suggested.

The degree to which IBFWs are used by various actors in the disaster risk reduction value chain, or more generally the level of engagement with the National Meteorological and Hydrometeorological Service (NMHS), were identified measures of success. For example, receiving a request to extend IBFW testing to other areas, sectors, or community groups, and to start utilising Common Alerting Protocol (CAP) data to generate their own warnings, were highlighted as unconventional measures of IBFW success. Another example given by a participant reflected success being in the sustained trust in the service:

> "To be able to acknowledge 'poor' performance of the service but not lose trust from your users." (W2-MS-12)

Participants suggested that in order to implement a successful warning, we need awareness across sectors and society, government and multi-agency support for collaborative action, and a common understanding between impact-based forecast producers and users. In addition, the need for a warning system that accommodates cascading and compounding hazards and that successfully communicates this risk and appropriate protective measures to the warning audience was highlighted. Continued investment was deemed essential to realise and sustain such improvements, especially in a multi-hazard context.

Our findings are in alignment with the description of a 'perfect' warning as "one that prevents all [negative] consequences that are avoidable" as defined by Golding [28], p. 258). To do so, the warning must enable the recipients to make the right decisions to protect themselves and others [5]. Perspectives may vary on what is understood as a successful warning [29], thus, strong collaboration between providers and recipients of warnings is important [30]. Despite the identification of the indicators, workshop participants felt that the definition and measurement of success remain key open questions, and this is likely to differ according to context.

Several of the gaps and challenges identified by our participants link back to the perceived purpose, audience, and expectations of the IBFW system being developed. This is demonstrated through IBFW for the public (and also individuals vs society) being differentiated from IBFW for dedicated users. Different expectations around what an IBFW system should provide are also apparent in the literature [31–34]. These differences affect the data and methods required to support IBFW development, but also have implications for implementation and governance. Workshop participants also identified the importance of balancing user needs of IBFW against what is possible given the available data.

Researchers, funders, and agencies should be clear on what they consider to be key characteristics of a successful IBFW in order to choose the most appropriate research foci from the areas identified below. For the purposes of this article, however, we assume that protection of lives, livelihood and property is the ultimate goal of IBFW, contributed to by the empowerment of individuals to take appropriate actions.

3.2. Evaluation and verification

The evaluation theme encompassed challenges relating to both forecast verification and measurement of IBFW success. Several comments identified data availability for verification as a challenge (e.g. spatial, impacts, multi-hazard), in particular the dearth of data from disaster management agencies and insurers necessary to quantify realized impacts. Lack of techniques to verify IBFW across multiple hazards and dimensions (e.g. likelihood, severity, duration) and to measure harm reduction were noteworthy gaps raised by participants. Comments identified a need for methodologies to explicitly quantify avoided losses (i.e. lives lost, financial costs), as well as more general processes for measuring success:

> "How to measure the effectiveness of the information – e.g. verification of impacts, assessment of lives saved or financial value …." (W1-GC-21)

User input to the assessment of success was deemed necessary to address these concerns, however, participants highlighted difficulties in obtaining this information and sustaining engagement.

One participant noted a need to better understand how cultural norms affect responses to warnings (i.e. identifying whether certain practices work better in some contexts than others). Another comment questioned how much the public uses lower level warnings derived from risk-matrix approaches (e.g. 'yellow' warnings).

One suggested approach for calculating avoided impacts was to compare losses associated with events where current warnings were issued with those associated with historical events, though challenges around attributing differences to the warning were acknowledged. Another participant proposed assessing the ratio of damage that can be mitigated against, to damage that cannot.

Pre- and post-event review management scoring was also suggested as an approach for identifying where greatest benefit for effort could be realized. Post-event user surveys were offered as a means to obtain data for effectiveness evaluation, ideally part of a structured effort to collect reports for future use:

> "Collecting feedback from stakeholders in a structured way so that the data can be used in future analysis (e.g. collecting structured feedback with dates, locations, impacts, and mitigating actions clearly reported)" (W2-SO-13)

In summary, evaluation of IBFW has been identified as a major theme within which several research gaps have been identified, including (1) performance and (2) value. Evaluation is particularly complex for IBFW due to its multi-dimensionality (hazard, vulnerability, exposure), coupled with the need to understand the causal influence of protective actions taken on the impacts observed. Additional research gaps arise when considering that both qualitative and quantitative evaluation approaches can be used to demonstrate the performance and value of IBFWs. WMO guidelines recommend that accuracy is assessed using traditional numerical verification comparing warning forecasts statistically to observations. However, Meléndez-Landaverde et al. (2022) postulate that the evaluation of IBFWs requires a different approach to traditional verification of weather forecasts. The benefit of IBFW over traditional forecasts is often cited as 'IBFW systems add value by helping users understand the impact of the hazard, enabling better decisions and preventative actions to be taken' [3]. One must also contextualise the value of IBFW in terms of its value relative to other baselines, such as the absence of any system, to traditional hazard-based systems, and to more informal community-based systems. While IBFW practitioners and users can perform rapid estimations of the benefits of action and the cost of inaction in response to IBFWs [3], our findings suggest that the quantitative demonstration of value remains a research gap.

IBFW performance relies on observations of impacts (and responses) against which IBFW can be compared. There is, however, a challenge regarding what is meant by an observation and what are appropriate impact observations (e.g., true impacts; proxies of impact; responses and mitigating actions). The use of impact observations for IBFW evaluation has been recommended by the WMO (2021), and although collection practices exist (as illustrated earlier), workshop participants and the literature continue to recognise this as a gap [13,35–39]. While many sources of impact data have been previously identified ([3,31], Annex 3), obtaining these data can be challenging without established partnerships [29,30,40]. Furthermore, impact data are rarely created for the purpose of IBFW verification and often requires further processing, particularly where multiple data sources are used to provide a more holistic observation [33]. Systematic and standardised impact data remains a data gap limiting IBFW evaluation [36–38]. Research shows that publicly available impact data suffers from bias [33], requiring impact data sources be reviewed for data quality, completeness and bias.

Approaches to harmonise, consolidate and aggregate impact observations across data sources remains challenging [41]. This is particularly pertinent when trying to assess whether the impact severity of an issued IBFW was correctly forecast as a system or if an event-based approach is required to aggregate observed impacts. This involves defining and identifying unique events within multiple impact data sources, assigning individual impact observations to a unique event, and consolidating impact observations to determine an impact severity classification. It also requires procedures to link observed impacts back to the hazards that cause them, which remains challenging in many instances. Furthermore, Jenkins et al. [42] discuss the difficulties and implications of translating quantitative impacts of weather events into qualitative severity categories (e.g. low, medium and high) and suggest that future research focus on improving the consistency and accuracy of this process to support IBFW evaluation. Our findings suggest that there is a need to further investigate and develop methods (e.g., that define and identify unique events across impact data sources; compile and consolidate disparate impact observations; attribute impacts to the responsible hazards) that will ensure impact observations, from variable sources, are appropriate for IBFW evaluation (see subsection 3.7 on Input variables).

Both qualitative and quantitative evaluation approaches can be used to demonstrate the value of IBFWs [2,3]. Given that the value of IBFWs depends on the decisions and actions taken by users of the forecast, it is important to consider how actions taken reduced the observed impacts resulting from the forecast hazardous event. This requires collation of data documenting or quantifying behavioural response to warnings, mitigating actions taken, and avoided losses, in addition to impact observations. The identification of appropriate data sources and methodologies that can be employed to calculate avoided losses remains a knowledge gap within a verification workflow. Recent research has demonstrated that social media, crowdsourcing and citizen science may offer opportunities to gather both impact observations and evidence of mitigating actions and avoided losses [20,24,43–50]. Additionally, it may be possible to leverage existing processes and work flows to obtain data required for verification, for example by modifying post-event damage assessments to include descriptions of the causal hazard or including categorical damage ratings [19]. There is a need to research the role of unconventional and opportunistic observations of impacts, mitigating actions, and avoided losses for the purpose of IBFW evaluation.

3.3. Communication and uncertainty

Of the many gaps and challenges relating to communication and uncertainty raised in the workshops, several related to 'public communication', while others addressed interactions with technical audiences, or across a range of audiences. The discussion around uncertainty included the problems in distinguishing between (hazard) forecast uncertainty and additional sources of uncertainty by including impacts, and how to balance expectations of precision and possible accuracy of data available.

Workshop participants suggested that warnings should be consistent, coherent and localised in order to be meaningful and useful for the recipient, citing it as a solution to a range of challenges, as well as a challenge in itself. Where variations in sub-national warning content were identified, participants recommended they be assessed across a range of hazards to provide greater national consistency. Maintaining message consistency when multiple different agencies were involved in the warning communication process was also a perceived challenge. Questions surrounding the risk of perceived (in)consistency were also raised with respect to tailored messaging (i.e. whether it was possible to avoid this being viewed as inconsistent), as well as communication under uncertainty (e.g. high-impact/low-probability events, especially emergency situations and under the associated constraints) and possible false alarms:

> "How do you deal with low probability but [very] high impact events being seen as providers of data not knowing what they are talking about? This is made worse when you have multiple large scale hazards." (W3-GC-28)

Information on uncertainty is (currently) not usually explicitly included in IBFWs, whereas the likelihood of an event often is. Participants identified problems distinguishing uncertainty associated with hazard forecasts with that involved in forecasting subsequent impacts. An example is that it is unclear whether 'likelihood' in risk matrices is referring to the likelihood of the hazard or the impacts occurring. It is recognised that uncertainty pervades the whole IBFW system and accumulates or propagates across the chain. For example, in developing an impact-based forecast for pluvial floods, Rözer et al. [51] observed a high variability and uncertainty of damage estimates resolved at the property scale. They attributed a large part of this uncertainty to the rainfall forecasts and predictions of the maximum water level. Lack of detailed exposure information also contributed to the deviation and uncertainty.

Participant comments touched on whether and how probabilistic information should be communicated (e.g., should the risk matrix be provided? Is use of colour coding sufficient?). Communicating probabilities has been found to be useful for many people in a context of decision-making (e.g. Ref. [52]). Probabilistic information could be framed as absolute or relative risk, with the latter being shown to increase perceived risk of low-frequency events (e.g. Ref. [53]). The merits of absolute versus relative risk representations were raised as a knowledge gap; with advocates on both sides, there is need for additional evidence.

A further challenge relating to communicating uncertainty is how to communicate risks and impacts in a changing climate,

> "When people may never have experienced anything like it before." (W2-GC-17)

For evaluation, a large element of the uncertainty relates to the identification of the causal influence of protective actions taken. Causal modelling (e.g. Ref. [54,55]) is a tool that may help to overcome this challenge, for example, by quantifying if effective mitigations were taken due to the IBFW. Thus, there remains a research gap around how to include the uncertainties of forecasts into IBFWs, as well as how individual risk tolerance is linked to accepting uncertainty and what forecast users actually need for decision making.

The need to understand how IBFWs are currently interpreted and responded to was emphasised by the participants in respect to communication with public audiences, highlighting the need for guidance in translating concepts of vulnerability and exposure into appropriate action statements. Defining what effective responses to warnings would be for the general public (i.e. against which evaluation could take place) is necessary to address these challenges. This may be different from a high-probability event, where a protective behavioural response or change in plans would be appropriate versus low-probability, high-impact events where remaining informed of updates may be the appropriate initial response for the general public.

Other challenges relating to public communication included questions of how to sustain engagement whilst limiting warning fatigue, and of risk communication in contexts where intended recipients cannot easily access communications:

> "Risk communication/information dissemination to the end users has always been a difficult task with limited access to communication or areas with topographical challenges." (W3-GC-16)

Participants recommended addressing accessibility issues by using multiple communication channels. While the question of how to engage with intermediaries (e.g., the media) was indicated as a challenge, it was also highlighted as a path to successful communication, as mentioned in a case summary from one participant:

> "… working with and using appropriate intermediary agencies to help - in Pakistan for an IBF on agromet - using Agricultural extension workers who have the connection with individual farmers to tailor the message to their crops/farming practice e.g. lack of rain warning for rainfed crops" (W2-SO-33)

Post-event surveys, mental models approaches, and cognitive process tracing were suggested as techniques to evaluate and improve communication.

Comparatively few comments specifically addressed the challenges of communication with technical users, beyond broader questions of data sharing and interoperability. Participants did highlight the questions of how to communicate based on large quantities of data, how to improve understanding of forecast inputs for expert users, and how to foster interdisciplinarity in the context of communication development.

3.4. Responsibility

Several participant comments concerned issues of responsibility, with a few making specific reference to the role of an 'authoritative voice'. A general underlying tension was observed between participants' acknowledgement that IBFW were likely more effective than traditional hazard warnings and concern over various aspects of responsibility. The comments picked up on nuanced types of responsibility concerns and challenges including liability and authority, both formal (i.e., no or limited legislative or institutional mandate) and informal (limited recognised expertise among public, partners, clients, users). For example, in terms of formal authority, one participant noted:

> "We often hear NMHSs say 'we're not allowed to do impact-based forecasting' because the responsibility for impacts and response lies elsewhere." (W3-GC-02).

Identifying who would take on roles to obtain, build and maintain the skills, tools, and other resources required to prioritise and sustain IBFW services were also mentioned.

Solutions offered by participants to address responsibility challenges included adopting a co-production framework in which multiple agencies representing several lines of authority would be co-located, supported if possible with formal working agreements. Another suggestion involved the embedding of external expertise within existing agencies and centres, presumably to complement and expand knowledge and responsibility for weather-sensitive/impacted sectors.

There is a key question around which data governance structures facilitate data usage in the way(s) that we want to use it for IBFW systems. Differences in the perceived purpose of IBFW, as discussed earlier, naturally result in questions relating to the scope and scale of the IBFW, which in turn are influenced by the availability of supporting data. The participants and literature agree that there are challenges associated with the quantity, quality, access, sharing, interoperability, resolution, type (e.g. hazard, societal, avoided loss, response), and coverage of data needed for IBFW development (e.g. Ref. [56–59]). These perceived challenges or gaps relate to data governance, which refers to "the organisation and implementation of rules and responsibilities, which enforce decision making and accountabilities regarding an organisation's data assets" ([60] p. 299). Lack of data governance continues to plague data accessibility and usability [58,59]. There is a research opportunity to explore agencies' perceptions and current activities for collecting, managing, and otherwise governing 'risk data' so that we can deepen our understanding of the social, organisational, cultural, and power dynamics at play to help identify ways forward to facilitate data governance, access, and sharing.

Results spoke mainly to the 'system' scale and authority to implement an IBFW program. Many other questions of responsibility rest within specific components of, and fundamental inputs to, the system, ranging from data to aspects of modelling and communication (e.g., action statements). When looking across the value chain it is evident that there are many areas where responsibility will influence the effectiveness of the IBFW system. First is the need to increase user engagement to ensure that those at risk are involved in designing the warning system [24]. Responsibility issues are problematic at different points in different warning agencies depending on the current status and extent (quality and quantity) of adoption of IBFW. Some of this issue depends on the form of governance and mandate as well as the perceived skills and resources among staff.

As the complexity of an IBFW system increases, the responsibility issues will necessarily change and typically increase commensurate with the number of partner agencies, data sources, models, areas of expertise, communication channels, hazards, user groups, etc., involved. This naturally leads to the question, what are the potential limits to IBFW, whether in terms of number of hazards, scale, scope, interoperability, or data management infrastructure? At what point do we see diminishing returns on complexity investment? Are there critical points when diminishing returns make it less worthwhile to pursue IBFW? Does this vary by the type or extent of risk, vulnerability or exposure? Developing an IBFW system that accounts for multi-hazard risk may require redeveloping existing warning systems to deliver a consistent user-focused message in the most effective way [61]. Value chain approaches can be used to examine data, communications, relationships, and other system elements to achieve this end [24].

3.5. Scale and resolution of IBFW

Spatial resolution, temporal scale, social scale, urban bias over rural, and accuracy versus precision topics were many of the gaps and challenges described by participants. Looking at these in more detail, some challenges are aspects that determine or condition IBFW resolution, for example the relationship between the scale of the warning and the level of accuracy and precision of the input data, and the importance of the scale of the data in relation to the scale of the impact. Related to this is the appropriate aggregated scale of impacts to assess severity and the availability of information. Other concerns include how to address the coverage of large-scale jurisdictions, personalised or local detailed information, and a bias of highly populated urban areas over sparsely populated rural areas. If crowdsourcing is used, for example, it can be expected that the density of crowd observations will be higher in urban regions [62].

The selection of a decision-making approach (e.g., threshold/matrix, risk modelling, discussion-oriented) may depend on the scale or use of application. The dynamic nature of risk affects the scale of the IBFW too. The attribution of thresholds to impacts in a diversity of terrain/environments is seen as a challenge, as is implementing IBFW near and across border regions with different vulnerability characteristics. Infrastructure characteristics (i.e. vulnerability and exposure) can affect the temporal scale of the impact. One of the participants illustrates this concept:

> "For example in a very poor area, if people's homes and livelihoods have been destroyed the impact may be over months/years, compared to a road being closed for a week. Also, a large event could result in a country being impacted for years, which could vary depending on vulnerability and infrastructure." (W3-GC-05)

Issues around social scaling of IBFW also emerged from workshop discussions. Participants noted a disconnect between user expectations and existing or potential resolution of warnings. This is exacerbated by efforts to further personalise and tailor information without enough knowledge to discern important variations in vulnerability and differential responses to warnings and interpretations of 'loss'. Finally, regarding the temporal dimension, other questions included how to define the beginning or end of an 'event', and how to ensure a seamless approach in IBFW. Spatial scale of the forecast will be conditioned by the scale and uncertainty of the input data.

To address these gaps, participants suggested the use of a criterion to select a bounded area, for example, selecting where you have more information or skills, or where users have higher needs, or focus on urban areas. Another recommendation involved layering the data to facilitate flexible verification at different spatial scales.

It became clear that research must investigate how to ensure that marginalised, vulnerable, and/or rural communities are not further disadvantaged by biases in the data, and how additional emphasis on understanding vulnerability and coping abilities could mitigate or exacerbate biases. Other solutions proposed in the literature include developing careful messaging to ensure that the target users' perceptions are considered when describing the forecasted impacts [37], and developing user-defined thresholds that consider the vulnerability and capacities of the target users [37,63–65]. More investigation is needed to develop methodologies and tools to integrate these user-defined thresholds, and to evaluate the threshold performance.

One of the identified challenges is the need to balance user desires of IBFW against what is possible, given the available data that can be used to create IBFW products and services. Related is how to determine the appropriate scale and resolution for evaluation, as discussed earlier in this paper. An important consideration is whether the observations are at sufficient granularity and scale to support evaluation and verification, or if it is necessary to aggregate the observations to match the scale of evaluation. There is a research need to investigate and test different scales of IBFW evaluation and verification, and to develop methodologies to aggregate or disaggregate impact and response observations to support evaluation at different spatial scales.

While some expectations of IBFW may be for tailored warnings that incorporate dynamic impact, vulnerability, and exposure data at fine spatial and temporal resolutions, the system is limited to the data and knowledge available, as identified by the participants and in the literature [31–33,35]. A common theme in the literature is the suggestion that community-based approaches and sustained engagement with local users can facilitate the exchange of localised knowledge both for tailored thresholds and for the creation of highly localised datasets (e.g. Ref. [66,67]).

3.6. Interoperability

Challenges identified relating to interoperability included cooperation between agencies, data sharing and standardisation, interagency communication, and system and model interoperability.

Participants noted that technical standards for the exchange of cross-border impact data are largely missing or have not yet been defined. There is a lack of a simple way to store and exchange different information in an accessible format in a timely manner. This makes interoperability of data difficult, including, for example, how to create a (cross-border) inventory of existing impact databases, or how to integrate data from other agencies (health, transport, police, energy, agriculture, etc.) and insurance. A challenge is feeding data from impact modelling into the same operational system used by those issuing the warnings. Workshop participants suggested avoiding contradictory advice and establishing a common set of standards for classification of different natural hazards or different sectors in a single notice format or platform.

Regarding the challenges of inter-agency communication, it was highlighted that it requires reaching agreement between several organisations with different responsibilities (and competing views), which is particularly challenging in the case of cascading and compounding hazards. Open questions relate to the role of re-users, redistributors, and communication through intermediaries (media, emergency managers). Participants expressed concern that these partners are becoming critical communication channels yet are not bound to carry the original NMHS message or preserve its sentiment. How to effectively work with these groups or, as the quote infers, sustain positive, productive interactions, remains challenging:

> "*How can we best maintain stakeholder engagement in the IBFW development process*?" *(W2-GC-44)*

Partnerships of multiple agencies responsible for (different) hazards, and collaborative multi-agency organisations improve interoperability. Changing competitive behaviour to cooperative behaviour enhances inter-agency communication. However, these behaviours are often system-defined. The integration of multiple (scientific) disciplines could also help to address the challenges of interagency communication (e.g. Ref. [61]). Co-production [68] across disciplines is increasingly used for warning system development and to ensure products are targeted and tailored to user needs [29,30,69]. To understand common data needs and areas where model integration would be beneficial, there is the potential to use systems thinking approaches, such as conceptual models to investigate interactions between different hazards and impacts.

One reason for this challenge of sustaining multidisciplinary partnerships across organisations is the cost and feasibility, particularly where capacities within a country/region are limited [40,70,70]. Tools to support countries to advocate for investment into IBFW could help to address this challenge, particularly if interoperable systems could be set up and funding can be leveraged across countries. It is likely that an important part of advocacy for sustained investment is to provide evidence from successful IBFW implementations. Therefore, it is essential to work to measure and evaluate IBFW systems, such as through the value chain approach [18] and post-event surveys that incorporate responses and impact information. Platforms to share experiences with warning systems that promote cooperation and communication between countries would also be useful.

Additional reasons for the challenges associated with interoperability and sharing data identified in the literature relate to the complex human relationships, power dynamics, trust, communication obstacles, and competition (such as for resources), which influence how partnerships are formed and maintained [71–74]. The importance of informal relationships is often understated but should be recognised and is a potential solution to strengthening formal relationships and partnerships [75]. Ways to increase partnerships include co-location, holding joint training activities, and collaborating to define warning thresholds [40]. Deep operational partnerships are foundational to interoperability; without operational partnerships, accessibility to and interoperability of required data and knowledge can be impeded, and sometimes prevented [32].

3.7. Input variables

Participant comments were coded to this theme if they related to input data required for IBFW development and verification. However, they were also often coded to other themes, demonstrating the importance of data across all elements of an IBFW system. The sub-themes described below relate to types of data (hazard, exposure, vulnerability, impact, and behavioural response data), the amount and accessibility of that data, the quality and acceptability of data, and the scale of data (explored more thoroughly in the scale and resolution section).

Challenges relating to hazard data and models including integrating antecedent conditions; the lack of a historical hazard database to correlate to impacts; for some participants the verification of warnings when they are a function of both likelihood and severity. Accounting for the complexity and variability of terrain was a challenge for both hazard data and models, and in developing vulnerability functions.

Exposure and vulnerability are identified in the results and literature as key datasets for IBFWs, yet having enough data to support the issuing of warnings, as well as for verification, was seen as a challenge. Specifically, difficulties were noted in getting vulnerability data at various spatial scales (local to national, including over very large areas) and from historical events, and getting vulnerability and exposure data at different timescales (from dynamic and live, to between forecasts, to seasonal variations), along with associated quality and confidence information (also noted for hazard data). Further vulnerability challenges are how to incorporate capacity modelling and redundancy in systems, as well as the acceptability of using vulnerability to describe socioeconomic groups. Accessing these data requires direct connections to the data sources, particularly for live data, and an exposure database.

It was seen to be particularly challenging if the datasets needed are dynamic to reflect the changes in exposure and vulnerability over space and time [32,76,77]. However, this builds from the premise that dynamic vulnerability and exposure are needed to ensure that the warning levels are appropriate to the current social, environmental, economic, and infrastructural conditions [8,32,77,78]. The desire to include dynamic data may jeopardise quantitative risk analysis, as identified by one participant:

> "I see a tension between inclusion of preceding and co-occurring hazards, exposure, vulnerability. and our ability to remain quantitative in our overall risk assessment" (W3-GC-15).

This challenge may be due to increasing complexity and uncertainty of the data as it becomes dynamic over different time and spatial scales, causing difficulties in integrating it into the risk analysis. The requirement of these detailed, dynamic datasets is still in question and depends on whether the effectiveness of IBFW systems are significantly increased when they are used, compared to those without such information. A cost benefit analysis of investing in the creation, collection, and maintenance of dynamic exposure and vulnerability datasets is required. This will also address the challenge of assessing the cost and feasibility of developing IBFWs. Conducting sensitivity and uncertainty analyses were also cited as means to further understand the value of dynamic vulnerability and exposure data. Other participants noted that it is a challenge for each nation to determine the correct balance and progression between using a qualitative subjective approach to determine potential impacts and using risk modelling.

Participants wanted to access more impact data from various sectors, as outlined in the evaluation and verification section. They desired impact data collection to be inclusive, from a range of sources, and consideration given to including data on how people and agencies respond to the warning, as part of the impacts of the event. There is difficulty in having objectivity in the impact data, and getting it at local scales. Forecasters preparing the warning may lack the knowledge about what happens as a result of the weather and need feedback from the disaster management agency on this. Whether indigenous knowledge (defined by Johnson [79] as the "*body of knowledge built up by a group of people through generations of living in close contact with nature*") should be included to help define warning thresholds is an outstanding question, and likely needs to be determined on a case-by-case basis according to the aspirations of the indigenous group.

Participatory research approaches have been utilised to develop early warning systems that are community-based (e.g., Ref. [38,46,80,81]). Crowdsourcing, citizen science, social media data [43–48,82], and volunteered geographic information are other tools for incorporating local knowledge into an early warning system where applicable and deemed appropriate by the knowledge owners [43,46]. There are research opportunities to explore the legal, ethical and cost considerations around the collection of impact data by the public, stakeholders, and scientists during an event. For example, what are the legal and liability implications for collecting public hazard and impact observations during an event, which may put people at risk if the action of submitting a report contradicts with the protective actions they should be taking? How can the Beneficence Principle and Distributive Justice Principle both be applied in this context (e.g. Ref. [83,84])?

An alternative source of impact data is through automated means, however:

> "Automated impact data collection for [impact-based forecast] verification [is a] bigger challenge than we'd initially thought" (W1-GC-58).

Monitoring behavioural changes as a result of the warning can help provide useful input to the issuance of warnings and verification. However, it can be a challenge to obtain timely feedback from stakeholders about what actions they took or decisions they made. Conversely, a participant also stated that managing and communicating the vast quantity of data is a challenge. Quantifying the data quality and confidence was seen to be useful, and it was desired that inputs to impact models need to be transparent to the user.

Solutions offered by participants include inventorying existing transboundary impact databases to see what is already available. The literature agrees that data often exists, however, they are often not well connected to or suitable for the issuers of forecasts and warnings [33]. Thus, a scan of available sources and developing partnerships and interoperable systems can help connect the data [31,57]. Developing such impact databases was deemed desirable, but guidance was wanted from our participants on how to go about doing this. Guidance was also sought on the historical impact record length required to support issuing impact-based warnings and, as noted below, content to facilitate understanding:

> "Impact data collection at a level of detail that enables […] attribution and contextual understanding of the social and environmental antecedent conditions." (W3-SO-32)

Existing guidance includes De Groeve [85], Corbane et al. [86] and UNDP [87], and example databases include Gourley et al. [88], Aldridge et al. [89], and the US National Weather Service Storm Data Database.

Interagency coordination was suggested to allow for agencies responsible for verifying warnings to have an influence over what impact data are collected. It was suggested that post-event survey interview protocols can help collect useful impact data. Templates could also be used to gather stakeholder feedback, to collect data (such as on dates, locations, impacts, mitigation actions) that can be used in future analysis. As previously mentioned, making use of local and indigenous knowledge through mapping could help to understand local impacts. The collected impact data needs to be accessible for both research and operations.

Response appropriateness could be enhanced by enabling users to personalise and tailor information using individual exposure and vulnerability aligned with the hazard(s). It was highlighted that assessing the appropriate scale to warn at is a balance between user needs and what is currently possible, as well as uncertainties. Finally, it was suggested that improving the understanding of risk concepts by the meteorological agencies and those issuing the warnings may be a solution.

Further research is required to understand how different data and approaches are effectively embedded within an IBFW system to help fill data gaps. This includes automated options; mobility data (e.g. Ref. [90]); agent-based modelling [8,8,91,92,93]; collaborative/participatory vulnerability mapping [94,95]; vulnerability indices development and assessment [96–98]; and data collected by emergency management and response agencies in the form of situational awareness (e.g. Ref. [48]).

3.8. Tailoring

Tailoring (or personalization) of warnings to individuals through to sectors of the population - including at various spatial and societal scales - remains a key challenge in implementing IBFW, as identified in our workshops. The first associated challenge is how to personalise information to incorporate user and community specific thresholds, how to ensure that IBFW can be incorporated into user-specific decision-making processes.

Warnings and forecasts targeting the response sector may already have well-defined decision thresholds, including what the impacts are relating to (e.g., power outages vs. life safety), and developed decision support tools. The attribution of thresholds to impacts in diverse terrain and the use of local knowledge to determine thresholds are still gaps to be researched, however, as thresholds differ across communities and individuals. Community-based approaches can help to address this gap by incorporating local knowledge about response capacities into the definition of thresholds [67]. The use of local and indigenous knowledge to determine thresholds is often context-specific, and how to appropriately do this remains a challenge (discussed further in the next section).

The development and provision of tools to enable people to customise forecasts according to their needs was suggested by some participants as a tailoring solution to facilitate better integration of forecasts into decision making (e.g. incorporating individual vulnerability and exposure). Using the same format or platform to display different sectors' thresholds was identified as one way of tailoring to specific user needs that might go some way to addressing concerns regarding inconsistency. Other participants highlighted the importance of tailoring the channel of message delivery to include a range of platforms and sources that could ensure inclusivity. Geiger et al. [99] describe how the underlying service architecture needs to be modular and flexible in order to provide tailor-made products.

Co-production was highlighted as a way to ensure that forecasts can be tailored to meet the needs of their intended audiences, with responses emphasising the importance of obtaining 'buy-in' for the co-production process to ensure engagement and the ability to obtain reliable data from different sources.

A key research question to be addressed is the degree to which tailoring warnings is effective at influencing risk perceptions and behavioural responses of the public and key users. How useful is it to have a highly personalised warning, in comparison to a general warning issued at a much larger scale? This is particularly relating to the vulnerability and exposure of the individual or community groups to determine individual risk, as well as their risk tolerance thresholds and suggested actions - encompassing both thresholds and messaging. Although this need has been mentioned from a cost-benefit perspective (e.g. Ref. [3]), there is still a gap related to the need to ensure the diversity of interpretations are all identifiably from the same underlying authoritative content. Solutions suggested by the workshop participants relate to user-led personalization, potentially using a common platform. As an example, Fdez-Arroyabe et al. [100] developed a mobile application through which users set their own thresholds based on their health-related vulnerabilities to meteorological changes. The users then receive personalised alerts about meteorological changes that pose a risk to their health. However, personalised messaging may introduce the perception that the warnings are inconsistent between people. This concern was raised within the workshops, necessitating the need for:

> "Finding the right balance of tailored warnings and information alongside reaching the broadest audience" W2-GC-06

3.9. Knowledge translation

Many participant comments reflected concerns about how risk and impact knowledge developed by different actors/sources can be successfully conveyed through the warning value chain.

Participants spoke to a number of potential barriers or challenges associated with exchanging knowledge across institutional, disciplinary and occupational boundaries. These included difficulties imposed by language, goal and methodological differences among physical and social sciences, over experiential and quantitative approaches, between research and operations, and among different types of practitioners. Questions concerning the merits of - and issues associated with - incorporating Indigenous knowledge into warning systems were also raised. Also problematic was a perceived dearth of platforms from which to share even basic experiences, advice, and suggested steps from countries with established IBFW programs to those just starting out.

Another group of participant comments focused on the content and reach of warning messaging, noting gaps in translating or at least connecting risk and impact knowledge with actionable directives, suggested courses of action, and preventive behaviour. For example, one participant stressed the need for:

> "Translating warnings into actions so that people do something and making sure impacts reviewed are inclusive." (W2-GC-32)

Such difficulties were thought to be magnified in multi-hazard or cascading situations when the initial contributing or primary hazard event is dislocated in time or space from where the impact occurs due to the vulnerability and exposure (e.g., desert flash floods). More generally, participants identified a need for development of tools to translate and tailor knowledge to individual circumstances, as discussed in the previous section.

Participants provided several ideas to at least partially address gaps and challenges, including taking advantage of opportunities to educate and inform primary/secondary schools students about the role, use and merits of IBFW. This was thought to be especially beneficial in communities with older populations that may be less likely to speak the official languages of the IBFW provider. Another suggestion, offered to bridge disciplinary, technical, and practitioner divides, was to develop risk and uncertainty training from different perspectives across the value chain. Explicit efforts to (respectfully) identify and learn from Indigenous sources of knowledge was also mentioned as a potential solution.

Participants identified a number of challenges relating to knowledge translation for the development of an IBFW, including experiential (qualitative) vs quantitative (model-based) approaches, methodological differences among physical and social sciences, the merits of incorporating indigenous knowledge into warning systems, and a perceived lack of platforms through which to share and access resources from countries with established IBFW systems.

Developing an impact-based forecasting and warning service involves different methodological approaches, including both quantitative and qualitative [2,19]. Quantitative approaches use models, such as risk models, to quantify the potential impacts using vulnerability functions and exposure datasets combined with the hazard dataset/layer [13,101,102]. Alternatively, qualitative approaches can rely on discussions across partners/stakeholders, the use of a risk matrix, decision support systems, and/or spatial overlays to incorporate tacit knowledge about impacts, vulnerability and exposure and support the decision-making process [32,64,65,103]. There are benefits and limitations for both approaches and there may be a tendency to prefer the more 'sophisticated' quantitative, model-based approaches (e.g. Ref. [19]). However, the quantitative model-based approach may require more resources and capacity than the qualitative approaches. Furthermore, recent research suggests that both approaches have value and the most effective approach may be to use them together [32,32]. There is a need to perform a cost-benefit analysis and evaluation of the approaches to determine which approach is most feasible and effective for the intended purpose of the IBFW system in different contexts; what is a minimum viable product that is achievable and not resource-intensive?

The integration of indigenous knowledge was identified by workshop participants as an opportunity for gathering localised knowledge of impacts, and for determining community-specific warning thresholds for tailored warnings. This finding aligns with priorities in the Sendai Framework to ensure culturally appropriate knowledge exchange and co-production with indigenous communities for disaster risk reduction and early warning systems (e.g. Ref. [104,105]). However, there is no single solution or approach to this. It is clear from the literature and best practice that enduring partnerships with indigenous communities are crucial [106], and success occurs when knowledge and solutions are co-produced and indigenous communities directly benefit from the initiatives (e.g. Ref. [106,107]). Community-based approaches and methodologies are increasingly applied to achieve these objectives (e.g. Ref. [80,108]).

Beyond implementation tools and advocacy, Sendai Target F (United Nations Office for Disaster Risk Reduction 2015) relates to substantially increasing international cooperation to developing countries, and this could include supporting the quality of real-time warnings (Target G). Global initiatives such as the WMO Severe Weather Forecasting Programme have already shown potential in this regard, as the system seeks to connect the improving quality of global and regional numerical prediction and professional insights to impacts on users, creating a continuous feedback loop.

3.10. Cost and feasibility

Cost and feasibility concerns cut across the entire spectrum of activities involved in developing and implementing IBFW.

A significant overlap existed between many of the cost and feasibility gaps and challenges raised by participants and those associated with 'responsibility'. Essentially these boiled down to 'how can NMHSs afford, obtain or develop the human resources (expertise in new domains), multi-hazard data sets, modelling tools, and communication platforms required to fully support an IBFW system?' More fundamentally, should this be the sole or primary remit of such organisations and, if not, what other forms of governance, co-production, and collaborative partnerships can be created to achieve the same end? IBFW cost and feasibility challenges were noted by participants as being particularly daunting in countries with fewer financial resources, where the hazards were particularly complex, the area covered is large, and population served is sparsely distributed. Within this context, establishing priorities, such that marginalised, highly vulnerable groups receive adequate attention and service, was identified as an important challenge.

Solutions included introducing measures to increase efficiency, prioritise effort, and find new resources to support IBFW implementation in developing nations. For instance, efficiencies might be gained through collaboration and combining resources from multiple agencies into a single, multi-hazard operations centre. Priorities could be established to assign limited resources to locations or sectors experiencing concentrated or relatively greater levels of risk. Finally, new investments, for example in the development of more complex tools capable of modelling dynamic vulnerability and exposure, could be formally assessed for value-added before being implemented.

Bringing together experiences and expertise from different organisations easily and effectively appears to be seen as a barrier to IBFW development and implementation. However, co-production [68] is increasingly used for warning system development and to ensure products are targeted and tailored to user needs [29,30]. Perhaps the gap is associated with the cost and feasibility to sustain partnerships with multiple and different organisations, particularly where capacities within a country/region are limited. There might be a need to calibrate an IBFW effort to the sustainable resources available. Most capacity development projects fail, but failure is more likely if the developments are unrealistic [109]. IBFW implementation must have a low barrier to entry and have multiple potential successful stages in the developing process. Tools to support countries to advocate for investment into IBFW could help to reduce this gap. It is likely that an important part of advocacy for sustained investment is to provide evidence from successful IBFW implementation. Thus, work to measure and evaluate IBFW systems will also support resolving the challenge of cost and feasibility.

3.11. Multi-hazard complexity

It is a challenge to deal with multiple hazards, which often have complex requirements. Many of the data concerns associated with multi-hazard warnings were also linked to other themes. Challenges related to dealing with the complexities of cascading or compounding hazards given the dynamic nature of risk, particularly determining the scope of the IBFWs, managing collaboration between agencies with different responsibilities, managing the communication of multi-hazard warnings, and multi-hazard verification. Comments relating to interoperability in a multi-hazard context are reported in the 'interoperability' section.

The dynamic nature of risk was succinctly captured in one participant's statement:

> "discrete events are a myth; there's just a continuum of multi-hazards with peaks" (W3-GC-11).

This creates complications for getting enough up-to-date data, such as on how to accommodate seasonal variance in vulnerability, how to integrate antecedent conditions, how vulnerability and the landscape change between forecasts, and how to calculate compound return levels of multiple hazards. Obtaining sufficient data for multi-hazard models is more difficult than getting enough for a single hazard. Knowing when to draw the line about including cascading or compounding hazards in a warning highlights the need to define the temporal edges of an 'event'.

Taking a multi-hazard approach may require several authorities with different legislated responsibilities coordinating across different levels of government, which can lead to jurisdictional challenges. Additionally, the collaboration that needs to occur for multi-hazard warnings may require bringing multiple disciplines together that "*don't have a strong history of talking*" (W3-GC-06).

It was seen as difficult to build appropriate technology platforms to create and deliver complex warnings for multiple hazards. It was acknowledged that we do not want to produce systems or models that are siloed within meteorology, but rather can integrate with non-weather-related hazards.

The few solutions suggested to address some of the multi-hazard challenges relate to agency coordination for setting operational activation thresholds; using consistent and standardised messaging across regions/nationally and for classification of hazards; conducting research to identify the most effective actions to take to minimise impacts in multi-hazard situations; and conducting post-event surveys that identify what messages people recalled during the event to help to explore the role of multi-hazard warnings.

On a positive note, warnings may be better integrated across hazards if they are based on a foundation of impacts [20]. Impact-focused communication will draw together the multi-hazard narrative in a way that speaks to the potential impacts, including crossing disciplinary lines, moving from 'what the weather may do', to 'what the combination of hazards may do'. Ideally the organisational arrangements behind the multi-hazard early warning system would support this (i.e., a deep partnership approach), but at minimum there cannot be competing discipline or organisation-specific voices; there must be a coherent set of voices speaking in the language(s) of the people. This relates to the challenges of governance and responsibility, discussed earlier. Additionally, more work is needed to support the technical integration of cascading and compounding hazards into hazard and impact forecasts and monitoring [20,110].

Participants queried how communication should be developed for multiple hazards, and with whom this should occur. There was a suggested need to ensure the messages avoid contradicting advice, and that formatting of the messages is compatible but still aligns with user needs. Additionally, there were concerns around communicating probabilistic information in a multi-hazard impact assessment. Further research should be conducted into which actions are effective at reducing the risk of each hazard, including how to prioritise the statements in a variety of multi-hazard contexts. Perceptions on how effective the suggested actions (or 'hazard adjustments') are at reducing risk ('response efficacy') are an influence on behavioural response to warnings [111], and should be investigated further to help inform guidance messages. Collaboration and agreements amongst agencies help to communicate consistent messages where multiple agencies communicate the hazard, impact, risk and action statements. In this way, an agency who warns of the hazard can amplify guidance messages that may need to be issued by an emergency management agency. Findings could be integrated into the development of a behavioural advice framework (i.e. a list of consistent messages). Research and guidance on how this can be done is needed, including to understand the degree of similarity or difference between statements across hazards.

Finally, verifying multi-hazard warnings was identified as a challenge, particularly attributing impacts back to specific hazards, and given the perceived lack of impact data. One participant pointed out that if one part of the warning was done well, and the other part not so well, there are difficulties in verification. An example is that a warning is given for impacts caused by ashfall downwind of an erupting volcano. If the severity of the forecasted impacts do not occur as expected, this could be due to inaccuracies in how damaging the ash was going to be, in the ashfall model, in the eruption forecast, or in the meteorological forecast for wind direction and speed. Each part of this chain would need to be verified, potentially using a value chain approach to articulate the qualities of each component of the chain [112].

There is a need to evaluate the utility of the multi-hazard IBFW from the user perspective (e.g. Ref. [113]). We must develop and test impact event definitions and identify methodologies that can be adopted in multi-hazard situations in order to do this. Additionally, the new evaluation approaches should complement and support the formal evaluation process of the Sendai targets (specifically Target G to 'substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030').

4. Limitations

We acknowledge that the benefits of improved warnings may pale in comparison to the improvement that could be made in reducing people's longer term vulnerability and exposure to the hazard. For example, improved building standards, restricting development on at-risk land, and other similar policies may save many more lives than whether the warning is based on hazard or impacts. Nonetheless, as severe weather and flooding continue to increase in severity under a changing climate, more meaningful warnings will help to reduce the impacts.

Our study sought to identify and explore challenges and potential solutions relating to developing IBFW across a broad range of countries and experiences, and in a snapshot of time (late 2022). It was out of scope to undertake a global, large-scale quantitative assessment (such as a survey) to analyse statistical significance of the issues identified. We also focussed on gaps that can guide research directions in alignment with the priorities of the WMO World Weather Research Programme. Practical guidance on implementing IBFW is produced elsewhere (e.g. Refs. [2,3]). Nonetheless, some of the identified research gaps are also operational gaps and will be solved through practitioner experiences.

5. Conclusion

Through a series of international workshops, we found there is a need to support IBFW implementers to identify measurements of success, and that the key areas of research to support the development of IBFW are:

- Conduct a cost-benefit analysis of investing in the creation, collection, and maintenance of dynamic exposure and vulnerability datasets
- Explore the legal, ethical, and cost considerations for the collection of impact data during and immediately after an event
- Develop evaluation methods to explore the value of multi-hazard IBFW, in terms of quantitative data at appropriate scales, avoided losses, unconventional observations, and to ensure it has a robust, repeatable design
- Determine the value of the appropriate mix of quantitative and qualitative approaches to IBFW in different contexts
- Develop platforms to share experiences with warning systems that promote cooperation and communication across countries and regions
- Develop methods and tools to evaluate the effectiveness of user-defined threshold approaches, integrate them into functioning systems, and determine impacts on perceived consistency of the warnings
- Determine multi-hazard appropriate guidance messages
- Understand the role of intermediaries in communicating IBFW
- Explore effective ways to communicate uncertainty of hazard and impacts in IBFWs
- Explore the governance of risk data for IBFW to enable access and sharing
- Determine the potential limits to IBFW in terms of number of hazards, scale, scope, interoperability, and data management, which will inform the return on investment.

Several solutions have been described to help meet some of the identified challenges. For example, against expectations, sometimes vulnerability and exposure data to support IBFW can exist and identifying the sources and developing partnerships can provide access to that data. Additionally, we could be developing consistent post-event surveys (and taking a value chain approach) that capture impacts, avoided losses and behavioural responses, in an ethical manner.

The results of this study are feeding into the new WWRP research programme work plans, and can inform research proposals and plans globally, for a variety of hazards. This will fill important knowledge gaps and help to produce more meaningful warnings to mitigate against the impacts of hazardous events.

CRediT authorship contribution statement

Sally H. Potter: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Thomas Kox:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Brian Mills:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Taylor:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Joanne Robbins:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Carolina Cerrudo:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Faye Wyatt:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Sara Harrison:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Brian Golding:** Writing – review & editing, Writing – original draft, Investigation. **Will Lang:** Writing – review & editing, Writing – original draft, Investigation. **Adam J.L. Harris:** Writing – review & editing, Writing – original draft, Investigation. **Rainer Kaltenberger:** Writing – review & editing, Writing – original draft, Investigation. **Stefan Kienberger:** Writing – review & editing, Writing – original draft, Investigation. **Harold Brooks:** Writing – review & editing, Writing – original draft, Investigation. **Andrew Tupper:** Writing – review & editing, Writing – original draft, Investigation.

Research data for this article

Data collected and used in this article have been anonymised and are available from Mendeley Data (https://data.mendeley.com/datasets/p5znfxv6ty/1, Potter (2024).

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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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Data availability

Data collected and used in this article have been anonymised and are available from Mendeley Data doi: 10.17632/p5znfxv6ty.1.

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