Flash flooding case studies to improve predictions and the communication of uncertainty

Final report

Carla Mooney[1] David Wilke[1] Karen Hudson[1] and Victoria Heinrich[2]

1. Community Services Group, Bureau of Meteorology, Victoria
2. Community Services Group, Bureau of Meteorology, Tasmania

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We acknowledge the Traditional Custodians across all the lands on which we live and work, and we pay our respects to Elders both past, present and emerging. We recognise that these lands and waters have always been places of teaching, research and learning.

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Table of contents

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- Case study partners, stakeholders and participants
- Survey participants (members of the Australian community and emergency management agencies)
- Bureau meteorologists, hydrologists, decision support and communications specialists
- Project Management Committee (including end-user representative)
- Project Reference Group (Flood and Severe Weather Intelligence Services Technical Group)
- Natural Hazards Research Australia, node research manager and communications team.

Executive summary

Flash flooding leads to adverse social, economic and environmental impacts, including loss of life, infrastructure and property damage, ongoing health effects and community disruption. Flash flood events are generally difficult to predict with much lead time, making it challenging to prepare, warn and take protective actions for flash flood in an effective and timely manner.

The primary responsibility for flash flood warnings in Australia sits with state and territory emergency services and local councils. The Bureau of Meteorology provides weather forecasts, nowcasts and observations and issues severe weather warnings for heavy rainfall that may lead to flash flooding. In contrast, jurisdictions issue targeted warnings for locations at risk, which provide the community with information about the impact of the flash flood and guidance on how to respond effectively. The effective communication of forecasts and warning information is critical to emergency services and public safety.

This mixed methods research project focused on gaining an overview of the public understanding of flash flood and the influence of forecast uncertainty on decision-making by emergency management and the public. The project components comprised:

- Case study analysis
    - Three case studies of flash flood events from New South Wales (NSW), Tasmania and South Australia (SA).
    - Examination of the full warning value chain and flows of information.
    - Testing of the warning value chain tools developed by the World Meteorological Organization (WMO) HiWeather project.
- Public survey
    - Baseline assessment of the understanding of flash flooding, including comprehension of uncertainty terms and rainfall language used in severe weather warnings.
    - Total of 1239 responses (31% emergency management sector, 69% general public; 55% with flood experience, 45% without).
- Collaboration and engagement
    - Collaboration with emergency management stakeholders through one-on-one interviews, steering group meetings, case study workshops, Natural Hazards Research Forum workshops and the AFAC Flood and Severe Weather Intelligence Services Technical Group (FSWISTG).
    - Ten presentations on the project at conferences and events, including the February 2025 Centre Hazardous webinar.

The warning value chain is core concept used in the case studies to describe the building blocks of information (e.g. weather forecasts), the actors (e.g. the Bureau and emergency management) and the flows of information (e.g. data) that operate to produce value (e.g. reduced harm from the hazard).

The project outputs comprise this final summary report, a detailed report on the three case studies and a manuscript submitted to the Australian Journal of Emergency Management discussing the survey results and implications.

Findings from this research will inform how future strategies, procedures, services and products can be developed to improve risk and uncertainty communication to emergency management and the public during flash flood events.

The research findings showed that the flash flood warning value chain is complex and includes many actors, information nodes, linkages and information flows. Uncertainty is endemic across the warning value chain, affecting all components individually to varying extents, and there are flow-on effects where uncertainty cascades from one component to another. The value of information can be enhanced or reduced by the way it is communicated along the chain.

The baseline survey highlighted that flash flooding is not well understood. People overestimated how much they know about flash flooding and there was little difference in knowledge between the public and emergency management. The survey also highlighted that the terminology used in weather warnings is confusing. Uncertainty terms such as 'likely' or 'possible' are understood differently, and there is limited understanding of the difference between 'heavy' and 'intense' rain.

Understanding the complexities involved and improving the communication of uncertainty will assist decision-making for these types of events. A multi-faceted approach of public awareness and education, use of best-practice communication strategies (such as consistent terminology, contextual information, use of words, numbers and visual prompts) and co-designed decision support (such as understanding of warning thresholds and response triggers for users) will yield the optimum benefits.

End-user statement

Steve Muncaster, Principal Advisor, Emergency Management Reform, Victoria State Emergency Service

The Victoria State Emergency Service (VICSES) welcomes the findings of this important research into flash flood understanding and uncertainty communication. Flash flooding presents one of the most challenging hazards for emergency management—characterised by rapid onset, short warning times and high potential for community impact.

This research provides valuable insights into how forecasts and warnings are interpreted by both emergency services and the public, and highlights the importance of clear, consistent and context-specific communication across the entire warning value chain. The findings reinforce that improving community understanding of flash flood risk, and the uncertainty that underpins forecasting, is essential for supporting timely and appropriate protective action.

For VICSES, the outcomes will directly inform how we design and deliver warnings, public education and operational procedures for flash flood events. In particular, the results underscore the need to:

- Strengthen collaboration between VICSES, the Bureau of Meteorology, councils and other partners to ensure warnings are locally relevant and clearly actionable.
- Enhance community engagement materials to improve understanding of flash flood dynamics, forecast language and uncertainty concepts.
- Integrate consistent terminology and visual communication methods into VICSES public messaging and training for emergency management personnel.
- Support co-design of decision tools and threshold-based response triggers that reflect both scientific uncertainty and operational realities

VICSES acknowledges the value of this research in supporting our mission to help communities understand their flood risk and make informed, confident decisions before and during emergencies. By improving how uncertainty is communicated and acted upon, we can strengthen community readiness and resilience to flash flooding across Victoria.

Introduction

Flash flooding is a significant risk to public safety, resulting in loss of life, casualties and disruption to communities and businesses (Coates et al. 2017).

Flash flooding typically occurs over small spatial scales within six hours of the onset of rainfall. It is generally difficult to predict, largely because of uncertainties in forecasting the intensity and spatial-temporal distribution of heavy rainfall and the resulting landscape response. This means that accurate forecasts of the timing and location of flash flooding are often not possible, with certainty, ahead of an event. Along with the many known hotspots across the country, flash flooding can occur in unexpected locations, ranging from rivers and creeks to the urban built environment. The magnitude of realised flood impacts varies significantly based upon the implicit flash flood risk of the catchment and the spatial and temporal distribution of rainfall across it. There is considerable uncertainty across the range of factors that contribute to the occurrence of flash flooding.

There is generally a poor understanding of these contributing factors, which presents a distinct challenge in the effective communication of risk by emergency management agencies to the public. The short timescales associated with flash flooding also mean that there is limited opportunity to trigger protective action during an event. These issues exacerbate existing communication challenges.

The *Flash flooding case studies to improve predictions and the communication of uncertainty* project was proposed following a Centre-convened research needs workshop with stakeholders from the Australian disaster management and emergency management sectors in 2023.

This final report provides an overview of the research findings and recommendations of the project. It explains the mixed methods approach, the results from the case study analyses and uncertainty survey and presents some preliminary guidance on the communication of uncertainty during flash floods. The report provides some recommendations for future areas of work and research.

The project outputs include a separate detailed report on the three case studies and a manuscript submitted to the Australian Journal of Emergency Management on the survey results and implications.

Background

Current approaches to flash flooding prediction and public information and warning are not yet sufficiently effective. The 2022 New South Wales Flood Inquiry highlighted the need for further research to improve predictions of extreme rainfall and associated impacts. Specifically, Recommendation 2 from the Inquiry outlined a need for the Bureau of Meteorology (the Bureau), Natural Hazards Research Australia (the Centre), National Climate Extremes Network, CSIRO and Australian Research Council Centre of Excellence in Climate Extremes to conduct research to '…understand the weather patterns conducive to extreme rainfall (including more detailed rainfall event attribution studies) with a view to increasing rainfall forecasting accuracy in time and location.'

To identify the relevant research needs in the Australian disaster and emergency management sectors, the Centre convened a project development workshop with stakeholders in 2023. The workshop identified two key priority areas for further research:

1. Communicating the uncertainty in forecasts and predictions—to enable EM agency preparedness and public safety messaging and warning to the community
2. Improving the Bureau of Meteorology's forecast guidance on the location, timing and intensity of heavy rain

These priorities are interlinked and highlight the importance of quantifying and communicating uncertainty in heavy rainfall forecasts and advice concerning the potential for flash flooding.

To address the identified priorities, two related projects were proposed.

The first project, as detailed in this report, is focused primarily on priority area 1, the communication of uncertainty. This project aims to identify knowledge and service gaps via a series of case study analyses and a short survey aimed at gauging public understanding of flash flooding, with a particular focus on uncertainty.

The Bureau issues severe weather warnings of conditions likely to lead to flash flooding and emergency management agencies issue flash flood warnings. In both cases, effective communication of uncertainty is important. The outputs of the project include the provision of preliminary guidance on the communication of uncertainty of relevance to both the Bureau and agencies with specific responsibility to warn for flash flooding.

The second project, *Developing an integrated predictive capability for extreme rainfall and inundation*, will build on this work, developing strategies to better use existing tools in line with priority area 2, and address the gaps identified in the case studies. This project plans to integrate tools and approaches to provide probabilistic guidance to Bureau and emergency management staff during extreme rainfall events likely to lead to flash flooding.

Knowledge gaps

The key knowledge gap to be addressed in this project relates to the communication of uncertainty during flash flood events. Flash flooding, by its nature, is typically 'high impact, low probability', and the current predictive capability limits the confidence with which the threat can be communicated. The communication of uncertainty therefore, becomes highly important to the successful mitigation of risk. Increasingly, probabilistic and ensemble-based data are expected to be utilised to quantify and communicate this uncertainty.

Flash flood events are typically quick to onset, often occurring with little prior indication that high-end impacts are likely. A key focus area therefore relates to response under escalating emergencies.

To address the above knowledge gaps and improve operational practices, it is important to have a strong understanding of the strengths and weaknesses of current operational processes. As such, the primary goal of this project is to identify outstanding issues in the prediction and communication of flash flood risk.

Research approach

The interdisciplinary and mixed methods research for this project comprised two key components: a case-study approach examining the operation of the current service, and a short survey aimed at gauging public and emergency management practitioner understanding of flash flooding. There was also extensive collaboration with emergency management stakeholders through one-on-one interviews, steering group meetings, case study workshops, Natural Hazards Research Forum workshops and the AFAC Flood and Severe Weather Intelligence Services Technical Group (FSWISTG). Examination of a research problem using mixed methods and the integration of qualitative and quantitative data provides multiple perspectives and contributes to a more robust understanding (Creswell 2021).

Case studies were chosen as the primary method of inquiry, as they provide a method for analysis of a real-world event in its context. The application of the warning value chain framework as the organising approach encourages the review to look at the end-to-end service provided by the Bureau and emergency management agencies. The warning value chain captures the sequence of interconnected people and processes, including observations, modelling, hazard prediction, warning generation and dissemination, that transform raw data into actionable information and user benefit. The chosen approach is multidisciplinary; focusing on how information, particularly uncertainty, is communicated through the warning value chain. This method has been used elsewhere to evaluate the performance of early warning systems (Golding et al. 2023; Neal and Titley 2024, Titley et al. 2024).

The survey was chosen as a second method to provide an analysis of the understanding of flash floods, to complement the case studies of current practice and to inform the gap analysis and potential strategies for communicating flash flood risk.

Case study events

The case studies were nominated by project stakeholders who considered the event to be notable and warranting closer examination. The support of key stakeholders for the research was critical given the collaborative nature of the study method.

The three events chosen for case study analysis cover a broad range of flash flood event types in Australia. They were:

1. Wallis Creek, NSW - July 2022
   - A high impact, relatively rare event extending over multiple days.
2. Hobart, Tasmania - May 2018
   - A high impact, exceptionally rare event of short duration.
3. Adelaide, SA - November 2023
   - A comparatively lower impact, more common event of short duration.

Case studies method

The research utilised a range of tools that were developed for the World Weather Research Program (WWRP) High Impact Weather Warning Value Chain project (Ebert et al. 2024). The case study method is valuable because it includes rich contextual data that facilitates insight into the complex interactions of systems and people in a real-world situation.

The project used the Warning Value Chain Questionnaire and Guide (Ebert et al. 2024-a) as the foundation for data collection, including use of the Rapid Assessment Template version. By posing targeted questions, it builds up a concise but comprehensive understanding of the warning system performance, identifying strengths, weaknesses and areas for improvement.

The questionnaire was designed to assist with the recording of information about a high impact weather event and can be used for any hazard. Part 1 records essential facts about the event, what happened, when, where, main impacts and overall response. Part 2 records more in-depth information about the different stages of the warning value chain including the weather system, hazards, impacts, warning communication and warning response, as well as the flow of information between the different components. Part 3 involves a subjective assessment of the effectiveness of the individual elements of the warning chain and its overall effectiveness.

The data collection methods include primary sources (weather, observation data) and secondary data (reports, media articles, event reviews and analysis). This is supplemented with informal interviews, discussions and a stakeholder workshop.

The focus of a value chain study of this kind is to bring together information from a range of sources across the whole event. This means that the involvement of key stakeholders is critical to the discovery and compilation of information. Value chain case studies differ from a post-event review or after-action review in that they are not intended as a forensic examination of events. The aim rather is to bring together information and people across the whole value chain to gather new insight into the flows of information, its use and the interdependencies of different players (actors).

To gather the required information and facilitate the completion of the value chain analysis, in-person workshops were held for each case study in Newcastle (for the Wallis Creek event), Hobart and Adelaide. Workshops had attendees across a range of agencies, including emergency management, local council and police and were facilitated by social scientists, hydrologists and meteorologists.

The workshops were an important part of the event analysis and included a presentation of a summary of the event, followed by the rapid assessment activity utilising the relevant template. The workshops provided a good opportunity for stakeholders across the whole warning value chain to come together and discuss the event and consider where it had worked well and where there is potential for improvement.

Survey method

The survey was developed to explore people's perceptions of flash flooding in the Australian context and focused on factors that influence warning response including flash flood knowledge, risk, uncertainty and terminology used in Bureau heavy rainfall warning messages.

For this exploratory study, the research questions were:

RQ1: What are the levels of knowledge of emergency management practitioners and the public about the causes, dangers, predictability and appropriate protective actions related to flash floods?

RQ2: Are there differences between emergency management practitioners and the public regarding their knowledge of flash flood?

RQ3: Do people understand the terminology used in forecasts and warnings?

The research design and survey materials were considered and reviewed by the research team following the guidelines of the National Statement on Ethical Conduct in Human Research (National Health and Medical Research Council et al. 2023) and criteria for low-risk research. The data collection and survey questions for this study were considered in line with the Australian Privacy Act 1988 and the Bureau's Privacy Threshold Assessment Tool (low level risk). No private, sensitive, identification nor personal information was intentionally solicited or collected in this study. All respondents were over 18 years and participation was anonymous. Before starting the survey, participants were provided with information about the study and gave informed consent. The consent included permission to store and use deidentified data for future related research.

Participants were asked to rate their flash flood knowledge (perceived knowledge) and this was measured against their assessed knowledge of flash flood. Factors assessed included the importance of various environmental risk factors, predictability, causes and definitions of flash flood and rainfall terms, including those that infer likelihood used in warnings, and knowledge about protective actions and impacts.

Research findings

This section presents a high-level overview of the research findings from the three case studies analysed and the survey results. More detailed reports on the case studies and survey are available as stand-alone documents (refer to Appendix 1).

Case studies

Case study 1: Wallis Creek, New South Wales

In July 2022, the Wallis Creek catchment in the Hunter Valley region of NSW recorded significant flash flooding resulting from the passage of an east coast low. The flash flooding, which occurred within a larger rainfall and flood event affecting eastern NSW, caused numerous impacts across the region. This included extensive property damage and resulted in more than 5000 people being isolated for up to 12 days in the Maitland local government area (LGA). The event was marked by various factors that contributed to significant uncertainty. These included initial model variation in the forecast rainfall, limited observations within the catchment area, complex interactions between riverine and flash flooding, and concerns regarding the structural integrity of Maitland's main levee system.

Case study 2: Hobart, Tasmania

During the evening of Thursday, 10 May 2018 and overnight into Friday, 11 May, severe thunderstorms brought intense rainfall across the Hobart area, causing widespread flash flooding and destruction. The worst affected areas were the southern suburbs of Hobart and the elevated areas directly inland. Total estimated losses attributable to the event were greater than $135 million, with extensive damage to bridges, roads, buildings and other infrastructure and significant agricultural impacts including stock and crop losses.

The event was challenging due to its rarity and volatility which significantly hampered preparedness and response activities. The last time flooding of a similar magnitude or severity occurred in Hobart was in 1960, therefore the community memory of the potential impacts of extreme rain events was considerably diminished. In addition, the location and intensity of the heaviest rain was not well modelled, resulting in limited warning time ahead of impacts occurring. It was a difficult forecast situation, not suggested by the guidance, with flash flooding initially considered a lower probability than damaging winds.

Case study 3: Adelaide, South Australia

During the early morning of Tuesday, 28 November 2023, the Adelaide CBD and surrounding areas experienced very heavy rainfall from thunderstorms causing significant flash flooding and storm damage. This area is susceptible to flash flooding and is often impacted during heavy rainfall, at thresholds below those used by the Bureau for issuing warnings (10% Annual Exceedance Probability (AEP) for heavy rainfall; 2% AEP for intense rainfall).

The event was caused by a complex weather system, being a cut-off low, which brought higher uncertainty than usual in the rainfall totals and areas of impact. It was also unusual in that the weather pattern was from the northeast rather than the more common pattern of moving across from the west. This added to the uncertainty and resulted in the State Emergency Service not being confident enough to provide public warnings ahead of the event.

Key challenges during this event were the rapid development of storms, a succession of severe thunderstorm warnings issued (at unsociable hours and with no/limited ability for response), and urban flash flooding in a highly populated area that occurred during the morning rush hour.

Warning value chain scoring

A key benefit of the warning value chain approach is that it provides a framework for assessing the relative performance of each component in the warning process. During the case study workshops, participants were asked to score each component on a scale of 1 (poor) to 5 (excellent). While these scores are subjective, they can highlight areas where the chain performed well and where improvements are needed. The scores were taken individually and then averaged across the participants for each case study.

Refer to Figure 1 for a schematic representation of the warning value chain, as a sequence of information nodes (mountains) and associated actors (including national meteorological and hydrological services) who exchange data, knowledge and resources (bridges) (Ebert et al. 2024). This figure also highlights the scoring results from the workshops.

The value chain scoring for each case study revealed several clear patterns. Most components of the chain received modest scores across all case studies. The overall scores are relatively consistent (3.1 for Wallis Creek, 2.9 for Adelaide, and 2.3 for Hobart). Observations ranked highest in all cases. The events occurred in relatively populated areas with good networks, particularly in the urbanised centres of Hobart and Adelaide. These observations were not significantly impacted by outages or disruptions, contributing to a positive assessment. Conversely, impact forecasting ranked lowest in all cases, primarily because this capability is not mature in any of the study locations. Impact predictions are often based on past experience and are affected by uncertainties from each of the earlier components in the warning value chain. Interestingly, the response to warnings was mixed across all events. The Wallis Creek event ranked higher than the other events likely due to the longer lead time available for warning, whereas the other events had shorter lead times and therefore the response was reactive to the event onset.

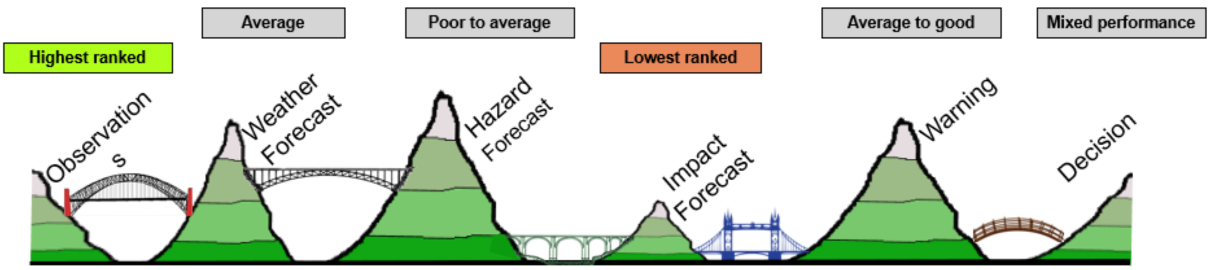

FIGURE 1: SCHEMATIC REPRESENTATION OF THE WARNING VALUE CHAIN

Survey

The study surveyed a total of 1,239 participants from across Australia, with 31% of these having some form of experience or role in emergency management, to assess knowledge of flash flood causes, risks, impacts, protective actions and definitions, as well as interpretations of likelihood terms in rainfall warnings. Over half of the participants had experienced some form of flooding, 38% in an urban environment and 31% in a rural setting.

Knowledge of flash flood

Key findings related to these survey questions were:

- Most participants rated their perceived knowledge of flash flooding, rainfall terminology and protective behaviours as higher than their actual knowledge.
- Most participants disagreed with the statement 'flash floods are easy to forecast'.
- Our hypothesis that emergency management practitioners had more knowledge relating to flash flood than the general public was only partially supported. The results showed some consistent gaps in understanding across both groups. This also applies to the likelihood of flash flood impacts.
- Participants mostly correctly defined flash flooding as 'flooding of short duration and relatively high flow' but there was less understanding for the item 'flooding that happens within 6 hours of rain falling'.
- Overall, the public have lower knowledge of appropriate protective actions in response to flash flooding than emergency management participants.

Interpretations of uncertainty terminology

The verbal probabilistic terms 'likely' or 'possible', used in rainfall warnings, were interpreted inconsistently.

Participants were randomly allocated to one of four groups. Each group received two of four warning messages where the uncertainty term of likely/possible and weather hazard heavy rain/flash flood varied: 'You receive the following warning message for your location: 'HEAVY RAIN which may lead to FLASH FLOODING is [likely/possible]. What do you think the likelihood (per cent chance) of [FLASH FLOODING/HEAVY RAIN] is?' A follow up question asked respondents to indicate their confidence in the likelihood value reported.

Figure 2 highlights the spread in responses, with participants assigning values ranging from 0% to 100% for both 'likely' and 'possible'. While 'likely' was generally interpreted as indicating a higher probability than 'possible', there was substantial overlap between the two, highlighting ambiguity in understanding. In the warning scenarios participants generally reported higher likelihoods for the occurrence of heavy rainfall than for flash flood events.

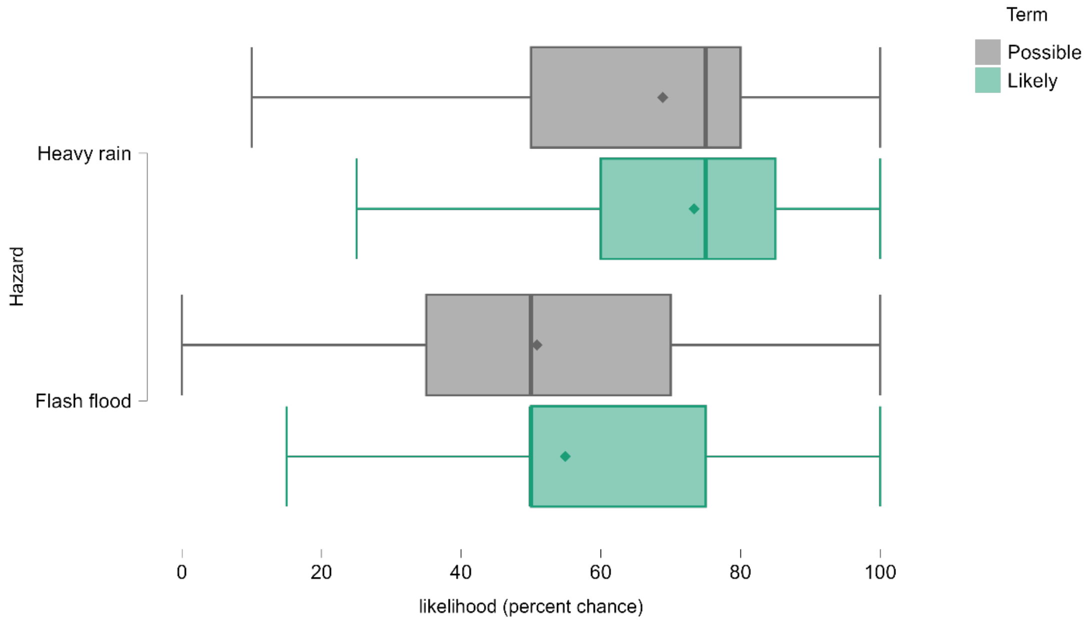

FIGURE 2: BOX PLOTS HIGHLIGHTING A WIDE SPREAD IN PERCEIVED LIKELIHOODS DEPENDING ON WARING MESSAGE WORDING AND HAZARD TYPE (JASP SOFTWARE 2025).

Discussion and implications

Sources of uncertainty

Uncertainty is endemic across the flash flood warning value chain, affecting all parts of the chain with influences that propagate from one component to another. For example, uncertainties are common in the rainfall forecast, which are then compounded by uncertainties around the landscape response and ultimately produce uncertainties in any hazard forecasts of potential flooding. While uncertainty exists at all points in the chain, some uncertainties can be more easily quantified. Modern ensemble prediction systems allow for some estimation of uncertainty in the rainfall forecast. However, it is not currently possible to quantify the landscape response in a similar way, especially in urban areas. The decisions authorities make, combined with organisational constraints and human behaviour factors add further uncertainty into the warning value chain, as it is difficult to model and predict people's warning response, choices and actions. This section considers the key sources of uncertainty in each component of the flash flood warning value chain.

Observations

There are uncertainties associated with the observations taken in the warning value chain.

Rainfall observations are important for situational awareness and knowledge gaps can be a key source of uncertainty. The density of the rain gauge network, which can be sparse, especially in rural areas, influences the confidence of inferring rainfall at a location. This is especially problematic in flash flood events when intense rainfall can exhibit high spatial variation.

Radar can be a good alternative when rain gauge data is limited. While coverage is extensive, it is concentrated around urban areas and airports which can mean it is not a viable alternative in rural areas.

Water level observations are even sparser and are only available in regular watercourses. They are generally not available in urban flash flood events. Agencies will often rely on manual or subjective visual observations for response, as seen in the Wallis Creek case, which introduce their own uncertainties.

Antecedent conditions and soil moisture significantly impact the landscape response in flash flood events; however, these can be difficult to assess.

Finally, gaps in the observation network impact the initial conditions used in weather forecasts. An accurate portrayal of the initial state of the atmosphere is important because it influences the Numerical Weather Prediction (NWP) outputs.

Weather forecasts

NWP models often provide key intelligence ahead of the development of flash flood events. They are also a significant source of uncertainty in the warning value chain and the effects propagate downstream to all other components.

Weather models typically depict a range of potential spatial, temporal and quantitative rainfall scenarios for a given event. However, they rarely predict the extreme totals that lead to flash flooding, and when they do, there is often a high level of uncertainty around the location and timing of the rainfall. For example, in the Wallis Creek case study, models indicated the potential for heavy rainfall, but the predicted location varied by hundreds of kilometres along the east coast of Australia. When thunderstorms are present, such as in the Hobart case study, the uncertainty is amplified as large spatial gradients may develop due to the formation of specific storms, which are currently not explicitly resolved by existing NWP models.

Ensemble NWP systems provide a powerful method to quantify the probability of rainfall. However, current ensembles are not capable of fully resolving extreme rainfall in most cases, which is often a 'worst case scenario'.

Hazard and impact forecasts

Flash flooding and its impacts are generally not forecast in Australia, except for a few key locations. In other areas, where tools such as flood studies, flash flood inundation maps or operational flash flood forecasting systems are unavailable, rainfall forecasts and warnings are used instead to identify areas at risk. While this method is useful, it introduces uncertainties as the link between rainfall and flash flooding is complex.

The Bureau issues severe weather warnings based on the forecast rainfall exceeding climatological rainfall thresholds (defined by AEP, i.e. forecasts of rainfall that are relatively rare) for a specific location. This approach is based on the understanding that common rainfall usually doesn't cause significant issues, but flooding may develop in rare rainfall events.

However, this is not always the case. Some locations, as highlighted in the Adelaide case study, can experience flash flooding at lower thresholds than those that trigger current warnings, while other locations may only see flooding at extremely rare rainfall rates. Whether flooding occurs at a location can also vary based on environmental factors. For example, soil moisture levels can affect run-off; the same amount of rainfall might not cause flash flooding one week but could do so the following week if the soil has become saturated or hydrophobic after a long period of dryness. Urban drainage systems can become blocked by debris or rubbish, or even downstream water levels in the receiving river or inlet. This means that a catchment that in one event flowed freely, may flood in another event of similar rainfall magnitude, making prediction of flooding even more uncertain.

Once flooding starts, uncertainties often emerge about the extent of inundation. These uncertainties are associated with factors like topography, the effectiveness of any flood mitigation strategies, and the impact of any concurrent riverine flooding. For instance, in the Wallis Creek case study, uncertainties regarding the structural integrity of the Maitland levee, along with the complexities of coincident riverine flooding, significantly contributed to the difficulty in predicting flash flood effects and hence impacts.

Warnings and communication

The institutional arrangements for warning for flash flood comprise a shared responsibility across the three levels of government: Commonwealth, state and territory and local councils. The high level of dependency between each of the actors has been recognised through the total flood warning system which aims to detail roles and responsibilities across the warning value chain for flood.

Using a warning value chain perspective, the complexity of information networks and flows of communication can be highlighted including agency-to-agency, agency-to-public and individual-to-individual communication. For example, briefings by the Bureau may trigger regional SES response protocols where information is on-shared to response agencies. Similarly, media by the Bureau may be paralleled by media releases and social media posts by agencies which combined aim to create public awareness of the pending hazardous weather. The flows of information are two-way, and the value of local intelligence was highlighted in two of the cases.

Along with the agency briefings and routine weather forecasts to the public, which include forecast rainfall, several other communication tools were utilised in the three events. They included severe weather outlooks, flood scenarios and specific briefings to agencies along with the public facing flood watch, severe weather, severe thunderstorm and flood warnings. As the events intensified specific and targeted media including press releases, media briefings and social media were used to amplify messaging and build awareness. This overarching messaging is very effective at creating broadscale awareness, but its effectiveness seems to be constrained by relatively low levels of awareness by the public of the nature of flooding and flash flooding and the lack of specificity about impact locations and timings.

Formal warnings by the Bureau are an important tool during flash flood events, but their effectiveness in creating situational awareness may be constrained by the style and language. In particular there is a need to consider whether the current language allows meaningful communication of risk and uncertainty. Warnings are also frequently issued with minimal lead time and during inconvenient hours, which can hinder the public's ability to receive a warning and respond effectively. There are only a handful of locations in Australia with targeted flash flood warning systems and so the importance of other tools is heightened.

Following the three case study events documented in this report, the Automatic Weather Station (AWS) has been introduced and implemented by emergency management agencies and is proving a useful mechanism for delivering responsive, location-specific warnings to communities that work in addition to Bureau warnings. However, the nature of the flash flood hazard and the uncertainty around the rainfall forecast mean that situations will continue to occur in which flash flooding occurs and warnings can only be issued reactively.

Response and decision

The uncertainties involved in forecasting flash floods, together with the usually rapid onset, make flash floods difficult to warn for and reduce the ability of agencies and the public to take timely and appropriate actions. Responses to the hazard are often reactive as the flooding starts to occur. This underscores the importance of increasing public awareness of flash flood potential and its hazardous nature so that people can take the appropriate actions to avoid danger. For example, being prepared to respond at a lower level of likelihood, keeping up to date with the latest forecasts and conditions, and avoiding unnecessary travel. In the Adelaide case study, cars became trapped in floodwater and the number of cars on the road during the rush hour exacerbated flooding.

To keep the community safe, emergency management agencies have clearly defined and well-practised processes and procedures in place for responding to events. In all three case studies, the response was multi-agency, with Incident Management Teams set up and several hundred requests for assistance in each event. Evacuation centres were established for the Wallis Creek and Hobart events.

The level of preparedness for the severity of flooding in the case study events was limited by the uncertainty in the weather, hazard and impact forecasts. In all three cases, there was some indication of heavy rainfall in the days ahead, but there was significant complexity and uncertainty in predicting the location and magnitude of the localised impacts that occurred. Additional certainty in the forecast could have triggered a larger predeployment of resources for response and, in the Adelaide case, full activation overnight rather than on-call rosters. In NSW, the nature and extent of the severe weather and flooding surrounding the Wallis Creek event meant that resources were likely already stretched.

An understanding of key rainfall and water level thresholds for decision support, including the required certainty and lead time, could help in pre-positioning of resources and faster response, for example for closing susceptible roads quickly. Ensemble guidance (% chance of a certain rainfall intensity and duration) could be linked to impacts as part of an action plan for response in these situations.

Communication of uncertainty

Uncertainty is a well-recognised and inherent aspect of flash flooding, but significant challenges remain for its effective communication. This was evident in each of the case studies. The primary method for conveying uncertainty surrounding heavy rainfall and flash flood risk to the public was through Bureau warnings, such as the severe weather warning or the severe thunderstorm warning.

The tools available to provide the community with information about the potential risk of flash flooding are limited. The severe weather warning primarily communicates the risk of heavy rain and is often the only warning describing flash flood risk ahead of hazard onset. These warnings are cancelled when the heavy rain risk ceases. However, the flash flood risk can persist for up to six hours as the landscape responds. AWS warnings now issued by states and territories can be used to fill this gap and can provide more locally responsive communication to the public than was the case in the past.

The baseline survey highlighted the participants' varied interpretations of the uncertainty terms 'likely' and 'possible', as used in severe weather warnings. Results suggest inconsistent understanding across the community and a need for targeted education and improved practice and standardisation in communicating forecast uncertainty.

In addition to public communications, interagency communications play a critical role in managing uncertainty during events. For instance, briefings conducted between the Bureau and state and territory emergency services are essential for conveying and clarifying the uncertainty surrounding various potential outcomes. While these briefings are highly valued, there remains room for improvement in the consistency and clarity of language and the communication of uncertainty across agencies.

Uncertainty manifests differently across spatial and temporal scales, adding layers of complexity for those conveying and interpreting information. This dynamic highlights the tensions between the necessity for sufficient certainty to trigger warning issuance and response actions and the limitations of current forecasting systems.

The next section of this report provides some preliminary guidance on how to improve the communication of uncertainty, essential for effective and timely decision-making and action.

Preliminary guidance on the communication of uncertainty

The project examined the role of uncertainty information in the warning value chain for flash flood in Australia. This section highlights key findings and provides preliminary guidance on how to improve the communication of uncertainty.

Communication is a key factor that influences risk interpretation, decision making, actions and responses to hazard risks, and thus preparedness, outcomes and consequences to severe weather and natural hazard events (Khan et al. 2017).

How weather information is communicated, including presentation, language, framing and visualisation, can influence risk perceptions and resultant decision making. Users need both a forecast and an indication of how confident they can be in it, to enable more decisive actions and reduce the need for extensive contingency planning (Fischhoff 1994). If uncertainty is not expressed in a forecast, people do not have information relevant to their decision making and will guess the certainty/confidence (Joslyn and Savelli 2010; Fischhoff 1994; Morss et al. 2008). Guessing the certainty/confidence incorrectly can lead to exceedingly cautious or highly risky actions (Fischhoff 1994).

Probabilistic information and probabilistic forecasts are becoming more readily available and as such, qualitative and quantitative descriptions of probability are more likely to be included in future weather services and risk communications (Ripberger et al. 2022; Stuart et al. 2022). Appropriately communicated uncertainty or probability information can improve people's decision making proficiency and lead to greater trust in the information (Joslyn and Savelli 2021; National Research Council 2006; Ripberger et al. 2022).

Uncertainty plays a critical role in shaping risk perception, decision making and preparedness (Carr et al. 2016; Doyle et al. 2019; Lipshitz and Strauss 1997). From the perspective of natural hazards and science communication, there are three sources of uncertainty: the data, the actors and the known and unknown unknowns (Doyle et al. 2023). For example, uncertainty about forecasts, such as the expected height of floodwaters or the timing of an event, can influence public and emergency management behaviour, complicating decision making, planning and emergency response (Doyle et al. 2023; Haynes et al. 2018; Waring et al. 2020). Conflicting information in warning messages, contradictory environmental cues and forecast inconsistency or inaccuracy may also create increased uncertainty, making it harder for people to act decisively (Dootson et al. 2022; Joslyn and LeClerc 2013; Su et al. 2021). Uncertainty about a situation can lead to delayed decisions, especially when individuals have poor situational awareness, engage in maladaptive coping strategies or behaviours such as 'milling' - looking for further information or confirmation (Lipshitz and Strauss 1997; Waring et al. 2020; Wood et al. 2018). These delays can result in negative outcomes during emergencies. Therefore, effectively communicating uncertainty is essential for reducing risk and ensuring public safety.

Finding	Guidance
Many people and organisations are involved in sharing flash flood information. These processes are diverse and use different mechanisms in the transfer of information along the warning value chain. The survey found that people interpret common terms about rainfall severity and forecast uncertainty differently.	Communication of uncertainty information is improved when it is combined with contextual information, words and numbers and visual prompts. For qualitative terms, providing definitions helps to constrain the range of interpretations that will be applied.
The survey results demonstrated a false dichotomy between public knowledge and emergency management expertise. Each group is made up of experts and non-experts who need and use information to inform decision making. The way information is interpreted is contextual and dependent on application, pre-existing knowledge and experience.	Good practice suggests that understanding the audience, their level of knowledge and need for information is fundamental to the design and delivery of effective communication and impactful products. Understanding the need for uncertainty information and particularly relevant thresholds is important.
There are many sources of uncertainty across the flash flood warning value chain. These include local factors which vary in space and time, inherent uncertainty caused by dynamic atmospheric systems, the limitations of models and predictions, the ways in which forecasts are interpreted and the human factors which influence how people will interpret, respond and behave. Uncertainty around some of these aspects can be quantified and others not. The different types of uncertainty (quantifiable and unquantifiable) create different challenges for communication. The research found that quantifiable uncertainty is not communicated consistently and this presents challenges to information users.	Comprehension of unquantifiable flash flood risk factors can be increased by efforts to build understanding of these elements through provision of information, education and training. Communicating the limit of forecast capability can assist decision making and facilitate realistic expectations about the value of information at different points across the forecast timescale. Consistent communication around quantifiable uncertainty will be beneficial to understanding. There is a rich body of literature about the effective communication of probabilistic information (refer to Ripberger et al. 2022; Doyle et al. 2019) and this should be utilised to improve current practice.
We found that many formal and informal tools were used to transmit information between actors across the warning value chain. The need for consistency to aid comprehension is vital.	Maintaining consistency is challenging however, robust processes which include standard procedures and documentation, for example, standard operating procedures and checklists, will help to address this challenge.

TABLE 1: COMMUNICATING UNCERTAINTY—KEY FINDINGS AND PRELIMINARY GUIDANCE

Closing remarks

Findings from this research will inform how future services and products can be developed to improve risk and uncertainty communication by emergency management agencies across the warning value chain and to the public during flash flood events.

The interdependencies across the flash flood warning value chain were highlighted in this project. While there is clarity about roles and responsibilities, there is scope for improving the flow of information between the different parts of the warning value chain. Opportunities to optimise practice through existing initiatives and arrangements should be sought.

Understanding the complexities involved and improving the communication of uncertainty will assist decision-making for these types of events. A multi-faceted approach of public awareness and education, use of best-practice communication strategies (consistent terminology, contextual information, use of words, numbers and visual prompts) and co-designed decision support (understanding of warning thresholds and response triggers for users) will yield the optimum benefits.

The research findings highlight several areas where targeted education and professional development are needed. Improving public understanding of flash flood definitions, risk factors and appropriate responses, especially in high-risk or newly urbanised areas, could enhance community resilience and reduce response delays during critical events.

The case studies identified several areas across the flash flood warning value chain where improvements could be made, in addition to the communication of uncertainty. These included observation coverage, predictive tools, shared understanding of roles and responsibilities, faster dissemination of warnings and support for the development of flash flood forecasting systems.

A related Centre project, *Developing an integrated predictive capability for extreme rainfall and inundation,* is developing a predictive capability for heavy rainfall and inundation, utilising the same case studies and addressing gaps in the weather and hazard forecast space.

The insights of this project could be used to inform future directions, and ongoing research including:

- examining verbal probability terms, use of numerical probabilities with verbal probabilities and the use of defined probability ranges to see if they are understood by the community as intended by the forecast provider or warning authority/organisation
- investigating the thresholds of concern and the required levels of certainty and lead time required for meaningful action
- developing guidelines and standardised procedures for the communication of uncertainty within and across all the agencies in the flash flood warning value chain

Project approach

This project greatly benefited from the multidisciplinary and collaborative approach undertaken. The expertise and input of the key stakeholders was highly regarded, and it was clear that there is an appetite for ongoing and collaborative evaluation of the end-to-end warning value chain.

Data collection for the mixed methods approach (comprising desktop analysis, interviews, workshops and baseline survey) was time consuming but valuable, yielding some rich results and insights. The warning value chain approach and use of the associated templates as developed by the HiWeather project, worked well in framing the data to collect and questions to be answered.

Reflecting on the project, the research team suggest that the following activities would be of value for future similar studies:

- Evaluate the effectiveness of recent improvements across agencies in preparedness, warnings and response by undertaking case studies of more recent events. Improvements include updated administrative arrangements, updated flood intelligence, introduction of the Australian Warning System and state-based warning platforms.
- Review the data collection methods used:
    - Test having a series of shorter workshops with more targeted conversations with individuals for the case study analysis.
    - Conduct the survey with a sample more representative of the Australian community (rather than the snowball sampling used here).
    - Refine the survey instrument to improve potential for further insights.
- Undertake analysis of case studies across all states and territories and include deeper dives into specific challenging events.
- Commence the warning value chain evaluation as soon as possible after the event where this is practicable, as data collection will be easier and the events fresh in peoples' minds.

A combination of the above activities would enable a more detailed examination of flash flood events to assess if improved communication of uncertainty in warnings leads to more efficient and informed decisions that enable timely actions to reduce risk.

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Appendix 1: Related publications and presentations

Publications

- T2-A2 Case Study Reports (stand-alone report on the three case studies)
- Flash flood knowledge and uncertainty communication in warnings—An Australian study (manuscript submitted to the Australian Journal of Emergency Management)

Presentations (oral)

- Flash flooding case studies to improve predictions and the communication of uncertainty (Natural Hazards Research Forum, June 2025)
- Communication of uncertainty across the flash flood warning value chain (Floodplain Management Australia National Conference, May 2025)
- Flash flooding case studies: Improving predictions and the communication of uncertainty (Centre Hazardous Webinar, February 2025)
- Effectiveness of the flash flood warning value chain: case study analysis of three recent high impact events in Australia (European Meteorological Society conference, September 2024)
- Examining the flash flood warning value chain in Australia: An interdisciplinary and mixed methods approach (WMO HiWeather Final Conference, September 2024)
- Flash flooding case studies to improve predictions and the communication of uncertainty (Natural Hazards Research Forum, May 2024)
- Communicating uncertainty in flash flood events (Floodplain Management Australia National Conference, May 2024)
- Communicating uncertainty in flash flood events (Australian Meteorological and Oceanographic Society, February 2024)
- Flash flooding case studies to improve predictions and the communication of uncertainty (Natural Hazards Research Forum, May 2023)

Presentations (poster)

- Communicating uncertainty in flash flood events (Australian Disaster Resilience Conference, September 2024)