Natural Hazards Research Australia

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

Case study reports

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Australian Government
Bureau of Meteorology

Version	Release history	Date
1.0	Initial release of document	18/03/2026

Australian Government

Natural Hazards Research Australia receives grant funding from the Australian Government.

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.

Publisher:
Natural Hazards Research Australia

ISBN: 978-1-923057-54-8

Report number: 71.2026

March 2026

Cover: Ajax9, AdobeStock

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Acknowledgements

The project was funded by Natural Hazards Research Australia (the Centre) with contributions from the Bureau of Meteorology and partner agencies.

The project team would like to thank everyone who was involved in and assisted with this project. It was a collaborative approach and benefited greatly from the expertise and input of the following groups:

- Case study partners, stakeholders and participants
- Bureau meteorologists, hydrologists, decision support and communications specialists
- Project Management Committee (incl. end user)
- Project Reference Group (FSWISTG)
- Natural Hazards Research Australia, node research manager and communications team

Introduction

This document presents the case study analysis completed as part of the *Flash flooding case studies to improve predictions and the communication of uncertainty* project. Case studies have been 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 value chain framework as the organising approach encourages the review to look at the end-to-end service provided by the Bureau of Meteorology (the Bureau) and emergency management agencies. 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).

Aims

The primary aims of the case study analysis are to:

1. Document and analyse how information flows through the warning value chain during selected flash flood events, including how uncertainty is communicated by the Bureau, local councils, emergency services and the police to inform the public.
2. Identify service gaps and potential strategies to improve communication of flash flood risk, both to emergency management and the public.

In examining the operation of the current service, this report aims to provide a baseline of practice and its effectiveness to inform the development of improvement strategies. In particular, the project will inform the future utilisation and communication of probabilistic information, which is expected to increase in importance.

The relevant objectives and core outputs are listed in Table 1.

Table 1 – Project objectives and Core outputs addressed in this report.

Objectives	1. To determine, via case study analysis, how information and particularly the communication of uncertainty, flows through the warning value chain during flash flood events. 2. To identify service gaps and potential strategies to improve communication of flash flood risk, both to emergency management and the public.
Core outputs	Core output 1: Analysis of the key issues and priorities in forecasting and predicting heavy rainfall and flash flooding in three case studies, including the influence of uncertainty on warning for these events. Core output 5: Case study reports for three events.

The report is structured as follows:

First, the method of case study analysis, centred around the warning value chain approach, is described.

Second, an overview of the warning value chain for flash flood is presented, outlining the generalised operation in Australia.

Thirdly, the case study analysis is presented for each event, beginning with Wallis Creek in New South Wales (NSW) (July 2022), followed by Hobart, Tasmania (May 2018) and then Adelaide, South Australia (SA) (November 2023).

Finally, a cross-case analysis is provided to identify key issues and sources of uncertainty in the flash flood value chain.

The case study reports contain information often provided directly via a series of workshops or from personal communication with agencies. Direct references are supplied where appropriate, data is obtained via these sources or directly from the Bureau of Meteorology.

The value chain approach

The case study approach follows the guidelines used in the World Meteorological Organisation (WMO) World Weather Research Programme (WWRP) High Impact Weather Warning Value Chain project, as outlined in Ebert et al. (2024). This approach examines the end-to-end function of the warning service and provides a powerful method to examine the strengths and weaknesses of a given service, at various points in operation. Considering a warning system as a value chain offers a systematic method for breaking down and analysing its key components and processes. It encourages a focus on the value of the warning system – typically measured in terms of reduction of human losses and livelihood impacts (Šakić Trogrlić et al., 2022).

The approach involves constructing an 'information value chain' to represent the service, including the contributions of partnerships. This 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, refer to Figure 1. Considering the warning value chain in this way enables analysis of the value added at each stage and the identification of gaps, inefficiencies, or bottlenecks that may weaken the system.

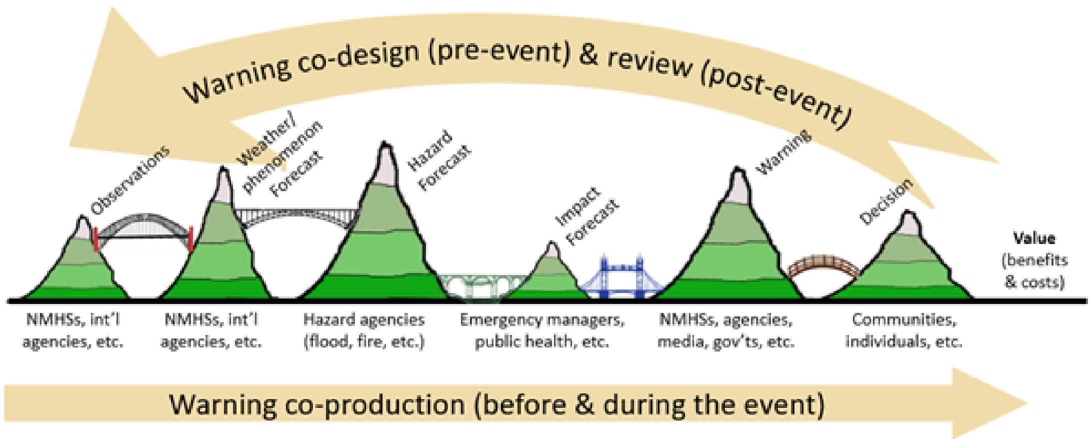


FIGURE 1 - SCHEMATIC REPRESENTATION OF THE WARNING VALUE CHAIN AS A SEQUENCE OF INFORMATION NODES (MOUNTAINS) AND ASSOCIATED ACTORS (INCLUDING NATIONAL METEOROLOGICAL AND HYDROLOGICAL SERVICES -NMHSS) WHO EXCHANGE DATA, KNOWLEDGE AND RESOURCES (BRIDGES) (EBERT ET AL. ,2024)

This approach requires a multidisciplinary effort combining physical and social science with practitioner perspectives. Therefore, a range of data is required, including:

- weather and hazard observations and forecasts
- societal, economic and environmental impacts
- warning and forecast communication, including advice provided to emergency services and public forecast and warning information by the Bureau, local councils, emergency services and police
- warning response.

The practical benefit of using a value chain to describe an existing service as we have done in this research is that it helps tease out the nature and benefit of information exchange and where value is being generated and lost.

Case study method

The research utilised a range of tools that were developed for the 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, observations data) and secondary data (reports, 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 important to the discovery and compilation of information. It is important to note that the study is unlike a post-event review or after-action review in that it is not intended as a forensic examination of events. As such they do not aim to provide a definitive review of all the information that is available about the case study area. The aim 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 and meteorologists.

The workshops were an important part of the event analysis and brought together a range of stakeholders in each case study area. They included a presentation of a summary of the event developed from the information collected through the Value Chain Questionnaire, 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.

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 were selected based on stakeholder feedback to cover a broad range of flash flood event types in Australia. They are:

1. **Wallis Creek, New South Wales** - 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, South Australia** - November 2023
    - A comparatively lower impact, more common event of short duration.

Key stakeholder agencies represented at workshops

- NSW State Emergency Service
- NSW Local Land Services
- Maitland Local Government
- NSW Department of Planning and Environment
- NSW Reconstruction Authority
- NSW Police
- Tasmania State Emergency Service
- Tasmania Networks
- City of Hobart
- Department for Environment and Water (South Australia)
- South Australian State Emergency Service
- Brown Hill Keswick Creek Stormwater Project
- City of Adelaide
- City of West Torrens

The flash flood value chain in Australia

The responsibility for flash floods in Australia is shared across different levels of government and the institutional context is important to understanding the flash flood value chain.

The Bureau of Meteorology (The Bureau) has responsibility for meteorological observations, the forecasting of weather and the issue of warnings, among other things, for weather conditions likely to give rise to floods (Meteorology Act 1955 (s.6)). This broad responsibility is further conditioned by The Intergovernmental Agreement on the Provision of Bureau of Meteorology Hazard Services to the states and Territories (Council of Australian Governments, 2018), which provides that the 'responsibility for Flash Flood warnings and systems lies with the States and Territories in partnership with local government (where appropriate) within their jurisdictions'. The responsibility of the Bureau is 'to provide forecasts and warnings for severe weather conditions and potential heavy rainfall conducive to flash flooding'. Specific quantitative flash flood warning services are not broadly available and only provided at localities determined to be at risk of flash flooding by flood studies as part of a formal risk assessment process.

In this section, a broad overview of the warning value chain for flash flood is provided. This description is generalised and serves to provide context for the case studies presented in subsequent sections. A schematic of the value chain is shown in Figure 2. While the warning value chain is depicted as an idealised linear progression between each component, in practice there are various interactions along the chain. For example, weather forecasts often directly inform warnings without hazard or impact forecasts. Furthermore, observations may themselves lead immediately to warnings or response during an event.

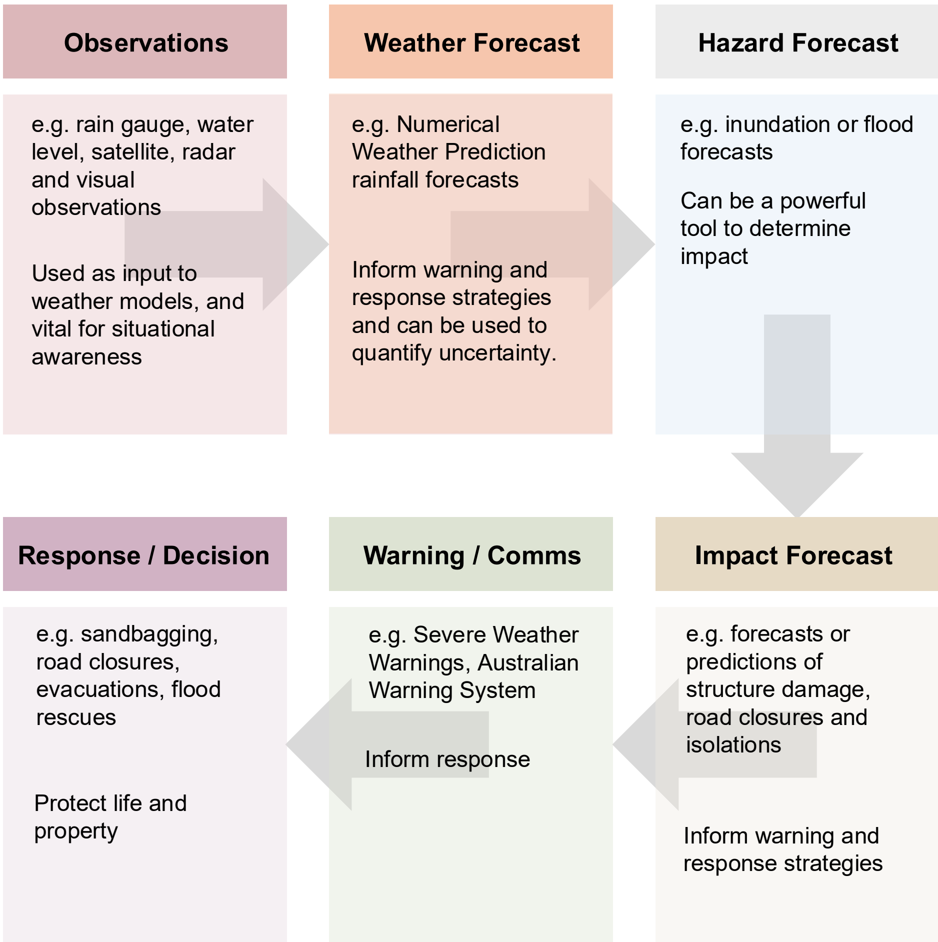


FIGURE 2 - GENERALISED WARNING VALUE CHAIN FOR FLASH FLOOD IN AUSTRALIA, LISTING TYPICAL EXAMPLES AND USES FOR EACH COMPONENT.

Observations:

Observations play an important role in the flash flood value chain through assimilation into numerical weather prediction (NWP) models to form weather forecasts. For situational awareness during an event, however, observations of rainfall (for example, radar or rain gauge) are the most relevant. These observations can help to indicate where significant rainfall and hence flash flooding may be occurring or about to occur. River height gauges are also useful, though this network is sparser and cannot identify flooding outside of a regular watercourse, for example, urban flash flooding.

Weather forecasts:

Rainfall forecasts are usually the first indicators for the prediction of flash flooding. Forecasts are typically developed from NWP models, often post-processed to remove bias and increasingly utilising forecast ensembles which provide a spread of possible outcomes. This data is then fed into a range of products, including public forecasts and warnings issued by the Bureau. Often, flood-producing rainfall is relatively unlikely and so may not be represented in the official, routine forecast for a location. In such cases, this higher-risk rainfall is primarily communicated through decision support to partner agencies and via public warning products as the rainfall develops.

Hazard and impact forecasts:

There is a body of literature examining flash flood forecasting techniques, refer to for example Zanchetta and Coulibaly (2020), but there remain limited operational flash flood forecasting tools used in Australia. Some agencies in flash flood-prone areas have set up operational or trial flash flood forecasting systems using a variety of techniques. These systems typically use the local network of rainfall and river gauges in hydrological modelling, often together with Bureau gridded forecast rainfall data – such as Rainfields (Seed et al., 2008) or NWP output. Some systems then incorporate hydraulic models to provide flood hazard forecasts in near-real time. Others use the forecast flood levels to interpolate between a library of pre-prepared static hydraulic flood maps to provide an indication of the flood inundation. Examples include City of Parramatta, Townsville City Council, Ipswich City Council, Brown Hill and Keswick Creek (Adelaide). In addition to flash flood forecasting systems, there are numerous other examples of flash flood alerting or warning systems that provide direct push notifications to residents based on rainfall and river/drain level gauge alerts, for example, Melbourne Water's Flood Alert System.

Explicit impact forecasts, which provide predictions of the potential damage or disruption caused by flash flooding, are limited. Instead, estimates of the consequence of flash flooding are typically based on past events.

Warnings and communication:

The warnings landscape for flash floods is complex. The Bureau issues a range of products that may indicate the potential for flash flooding, including severe weather warnings, severe thunderstorm warnings and tropical cyclone warnings. Flood watches and warnings may also indicate the generalised risk of flash flooding; however, these products are primarily focused on riverine flooding over a longer timescale.

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 Australian Warning System (Australian Warning System, n.d.) has recently been implemented by emergency management agencies as a nationally consistent approach to warnings with defined colours, icons and protective actions. This system replaces the predecessor approach that varied by jurisdiction and included evacuation warnings and evacuation orders.

To support warning and response decisions, interagency communication is critical. For example, in most states and territories, the Bureau provides decision support expertise which includes regular briefing and liaison services ahead of and during events. Bureau forecasts and warnings also commonly inform warnings from emergency management agencies.

In addition to forecasts and warnings, a range of public communication is conducted by agencies, including press conferences, media interviews and other public information strategies to enhance community risk awareness. Individuals, communities and other intermediaries have an important role in the communication of information about hazardous events and routinely share information that extends the reach of formal communication and warnings.

Response and decision:

Decision making by individuals and organisations is informed by the public information and warnings provided about a flash flood event, in addition to a range of other relevant considerations including knowledge of the hazard, past experience, perception about exposure and capacity to act.

The scale of the response in flash flood events is dependent on the impact. In some events, response may amount merely to minor strategies aimed at mitigating damage and disruption. For example, police and emergency services may consider road closures to prevent people from driving through floodwaters. For larger-scale events, more significant response actions may be necessary, including evacuations and rescue operations. Such events often require coordinated, multi-agency response.

Value chain scoring

A key benefit of the 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 necessarily subjective, they nonetheless highlight areas where the chain performed well and where improvements are needed. The scores were taken individually and then averaged across the participants for the case study. The results for all three case studies are shown in Table 2. Over the following sections, each case study is examined in detail.

Table 2 - Value chain scoring for the three case studies - The cells are shaded according to rank with dark green being the highest and light green the lowest rank.

	Wallis Creek	Adelaide	Hobart
How well do you think the event was observed?	3.2	4	4.1
How well do you think the weather was forecast?	2.5	3.2	2.1
How well do you think the hazards were forecast?	2.7	2.5	1.6
How well do you think the impacts were predicted?	2.3	2.3	1.6
How well do you think warnings were communicated?	3.1	2.8	3
How well do you think the warnings were used?	3.2	2.5	2
How well do you think the entire warning value chain performed overall?	**3.1**	**2.9**	**2.3**

Case study 1: Wallis Creek, NSW

Event overview

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 twelve 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.

Focus area

This case study focuses on parts of the Maitland LGA impacted by flash flooding within the Wallis Creek catchment. Wallis Creek is a waterway in the Hunter Valley region with headwaters around the Watagans, refer to Figure 3. The creek meanders northeast past Gillieston Heights to South Maitland and eventually into the Hunter River, which discharges into the Pacific Ocean at Newcastle. When Wallis Creek floods, it swells to engulf a much larger area of low-lying, predominantly farmland, which can lead to road closures and isolation. Flooding in Wallis Creek typically occurs on short timescales and there is no official flash flood warning service.

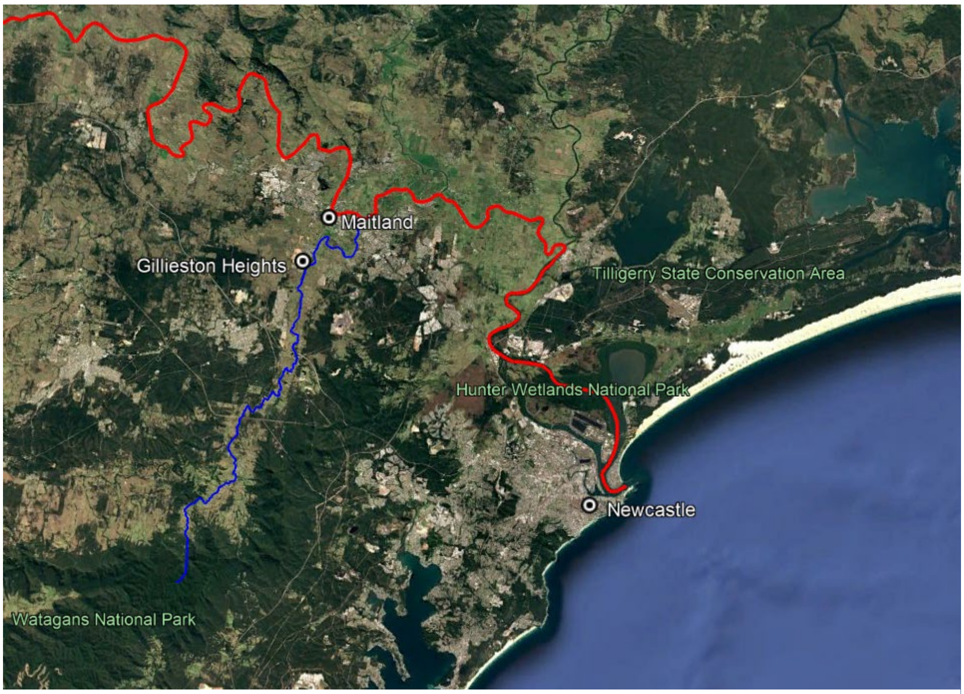


FIGURE 3 - A MAP OF THE AREA OF CONCERN INDICATING THE RELATIVE LOCATION OF MAITLAND, NEWCASTLE AND GILLIESTON HEIGHTS. WALLIS CREEK (BLUE) AND HUNTER RIVER (RED) ARE OVERLAYED.

Event timeline

Refer to Figure 4.

The broader event commenced in early July when rainfall developed over parts of coastal NSW due to the passage of a trough and the eventual formation of an east coast low. Heavy rainfall was first recorded in Maitland on Sunday, 3 July, resulting in the first of numerous road closures. By Wednesday, 6 July, the region faced significant impacts, including the closure of the New England Highway, a critical roadway in the Hunter Valley. At this time, the township of Gillieston Heights was surrounded by floodwaters from the expanding Wallis Creek, isolating nearly 5000 residents for nine days. On 7 July, Maitland was declared a natural disaster area (Australian Government, 2022), with jointly funded Commonwealth–State disaster assistance available. The following day, SES issued evacuation warnings due to the potential breach of the levee in Maitland and peak flooding on the Hunter River and Wallis Creek occurred on 9 and 10 July, respectively.

The initial recovery meeting of the Local Emergency Management Committee (LEMC) took place on Monday, 11 July, marking the beginning of coordinated efforts to address the impact of the flooding.

Key Event Timeline: Wallis Creek

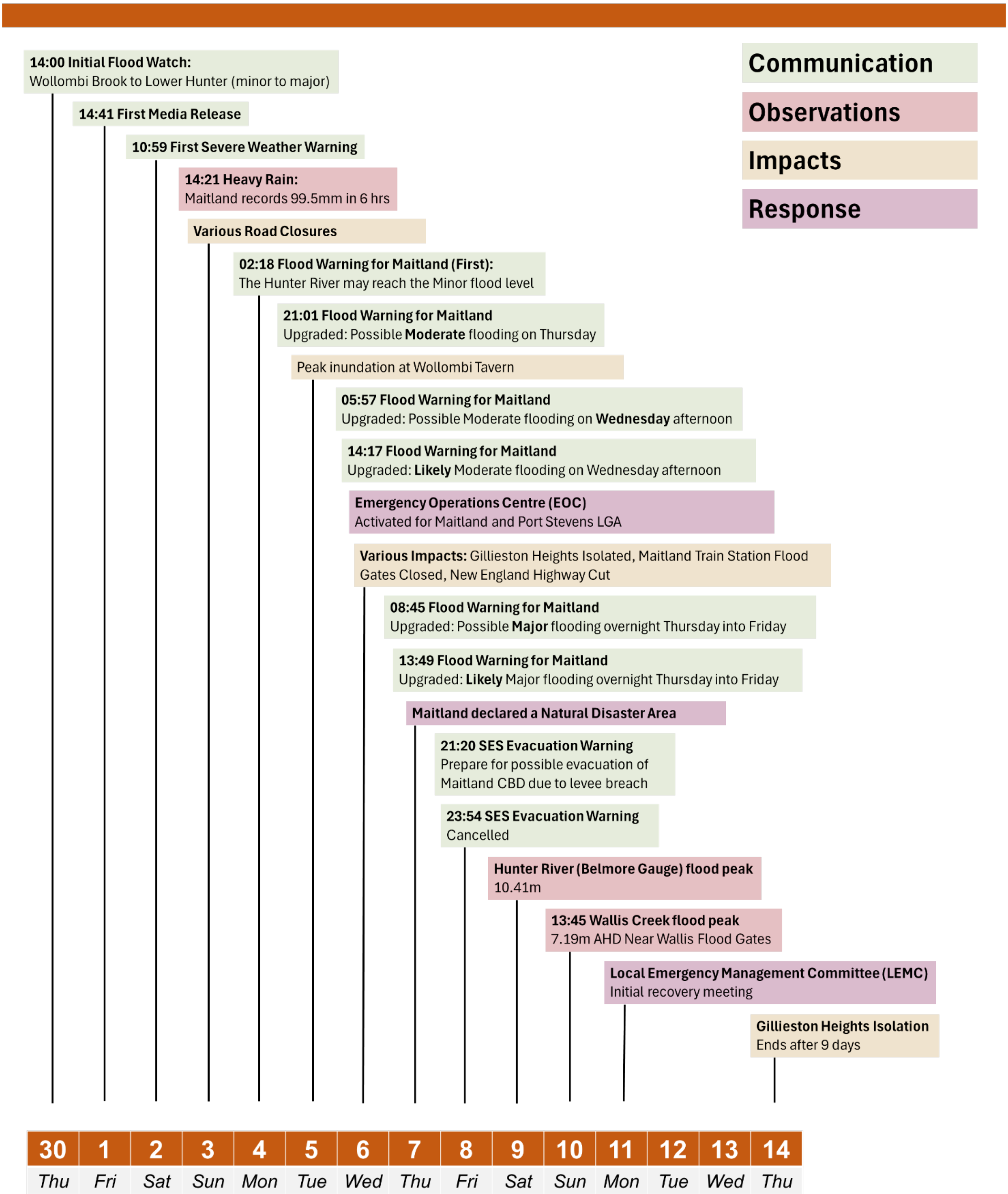


FIGURE 4 - KEY EVENT TIMELINE FOR THE WALLIS CREEK EVENT FROM THURSDAY, 30 JUNE TO THURSDAY, 14 JULY 2022.

Antecedent conditions

The antecedent conditions around Maitland in late June and early July 2022 acted to prime the environment for the flash flood event that unfolded. Firstly, rainfall anomalies over the preceding months had been high, contributing to high soil moisture throughout the Hunter Valley and ensuring catchments would respond quickly to further rainfall. This is illustrated by the plot of root zone soil moisture in Figure 5 which shows some drying over the preceding month, from a widespread above average level of soil moisture in June. Additionally, many rivers and creeks in the region were already at relatively high levels due to flooding earlier in the year, leaving little capacity to accommodate further flows.

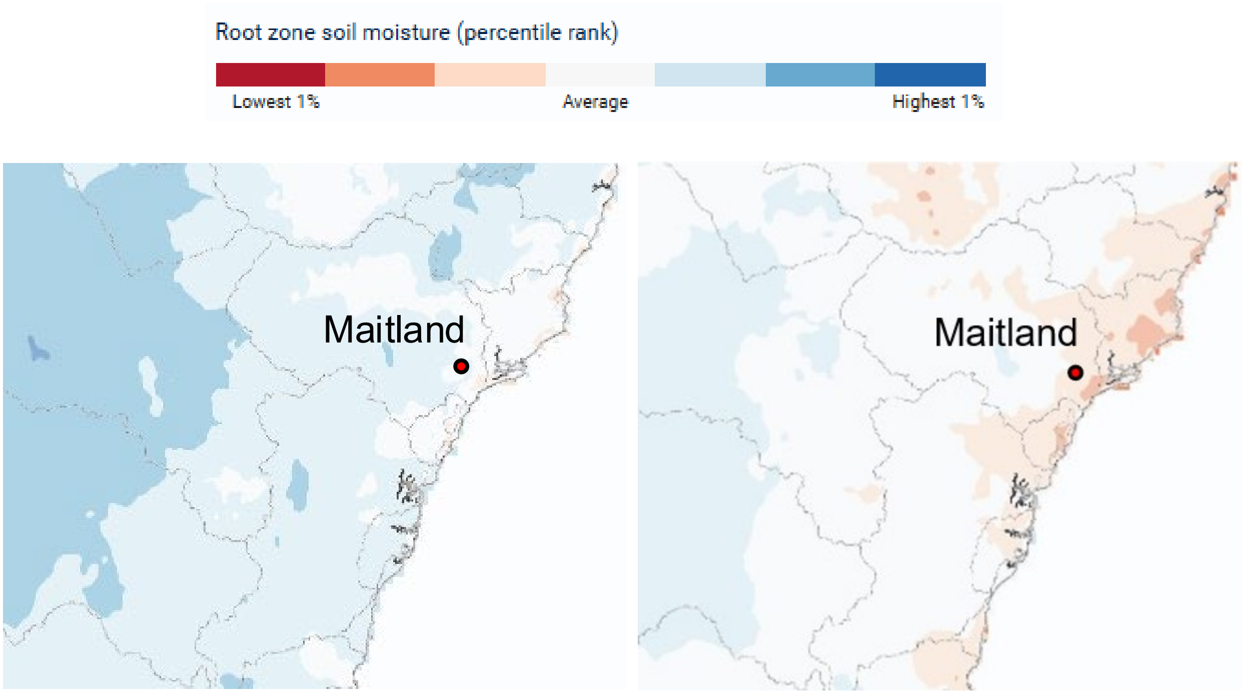


FIGURE 5 - ROOT ZONE SOIL MOISTURE FROM 1 JUNE 2022 (LEFT) AND 1 JULY 2022 (RIGHT). AUSTRALIAN BUREAU OF METEOROLOGY (N.D.-A).

Synoptic overview

Synoptically, the event was relatively typical for NSW. Following the passage of a cold front on 1 July, a trough deepened along the coast, forming a low-pressure system from 3 July, refer to Figure 6. This system lingered near the coast for several days, with multiple centres developing and dissipating during the period. On 6 July, the low deepened further as another cold front with an associated upper-level trough passed to the south. The low then tracked away to the southeast across the Tasman Sea during 7 and 8 July. This synoptic pattern brought persistent, moist, onshore flow to areas south of the low centre with heavy rain, gale-force winds and damaging surf developing along the coast. Rain fell over multiple days over much of eastern NSW, with the focus of the heaviest rainfall initially about the Illawarra region during 1-2 July, before a gradual shift northward to Sydney and the Hunter Valley by 3 July. The rain persisted about the Maitland region for several days, before abating during 7 July as the low tracked into the Tasman Sea.

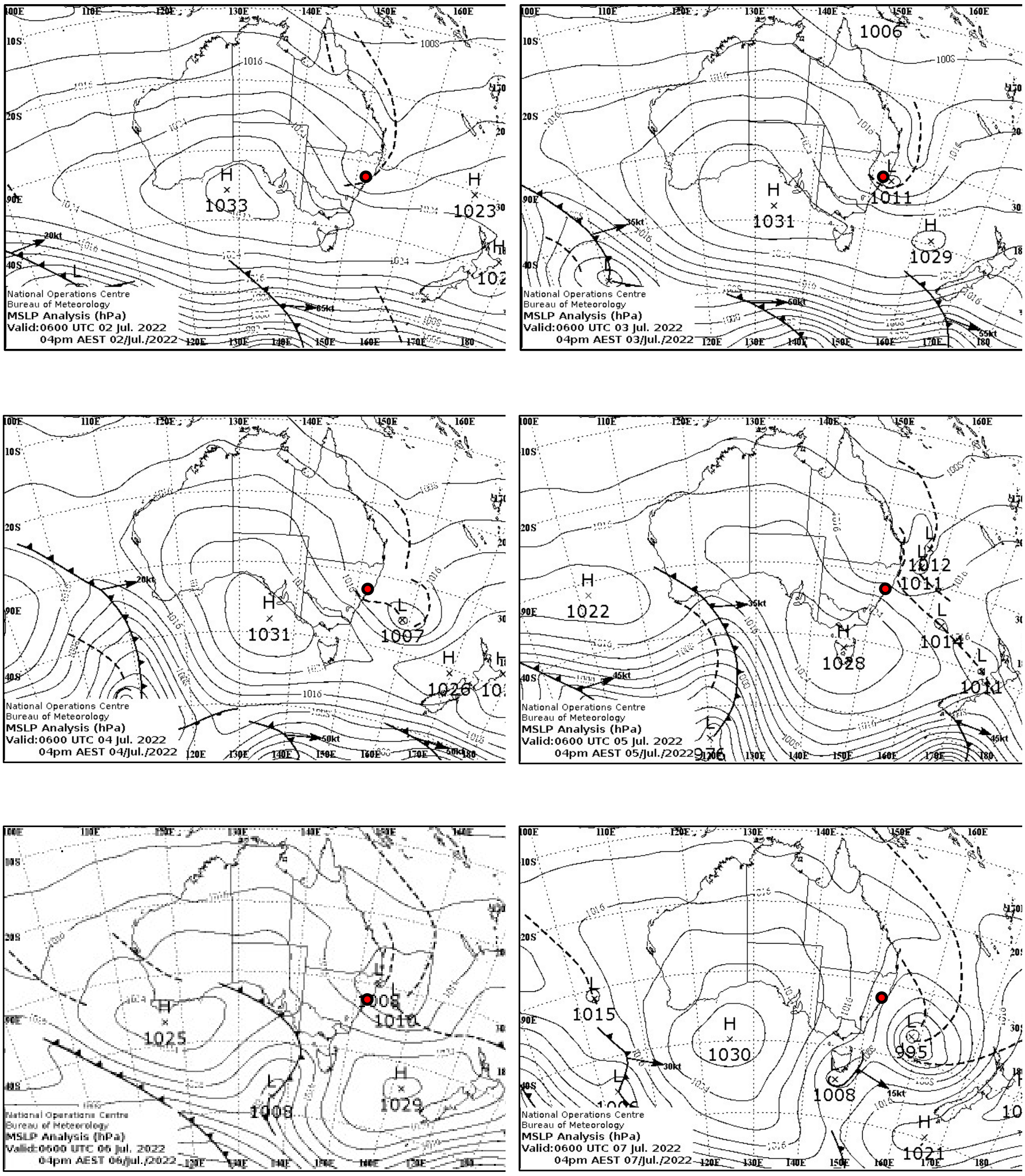


FIGURE 6 - EVOLUTION OF MEAN SEA LEVEL PRESSURE (MSLP) DURING 2-7 JULY, SHOWING THE DEVELOPMENT OF THE LOW-PRESSURE SYSTEM AND ITS EVENTUAL TRACK INTO THE TASMAN SEA. THE LOCATION OF MAITLAND IS INDICATED BY THE RED MARKER.

Weather forecasts and event detection

East coast lows are notoriously challenging to forecast. The primary difficulty for meteorologists lies in accurately predicting the location, movement and intensity of the low's centre (Dowdy et al., 2019). Consequently, the accuracy of rainfall forecasts is largely dependent on these factors. Given that east coast lows are synoptic-scale systems, rainfall forecasts can often vary significantly based on the low's location.

There was significant variation among the models in the days leading up to the Wallis Creek event. While most models indicated the potential for heavy rainfall somewhere along the NSW coast as early as 28 June, the exact location varied considerably. This variation is illustrated by a four-model comparison of rainfall from the late evening of 28 June, shown in Figure 7. In this comparison, the 24-hour (deterministic) forecast rainfall to

10:00pm AEST on 4 July ranged from as little as 0 millimetres to upwards of 20-30 millimetres across the Wallis Creek catchment. This is largely driven by the variation in placement of the low-pressure system. Despite these differences, all models consistently indicated a peak of 100-150 millimetres somewhere along the coast on this day, raising the concern of potential flooding.

Despite this, the models showed relatively good consistency during the event. The four-model comparison, illustrated in Figure 8, again depicts the 24-hour forecast rainfall to 10:00pm AEST on 4 July, this time as issued the day prior on 3 July. At this shorter lead time, each model indicated the potential for significant rainfall over central parts of the NSW coast and ranges, including the upper parts of the Wallis Creek catchment. However, as is often the case in flash flood events, the deterministic models did not capture the observed extreme rainfall.

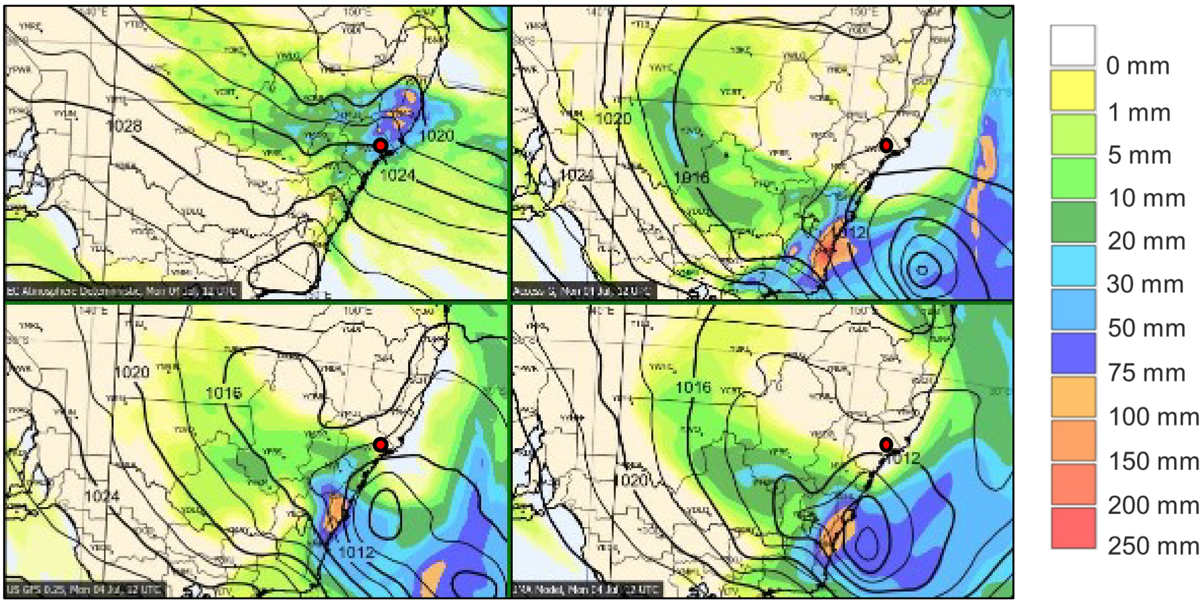


FIGURE 7 - 24HR RAINFALL FORECAST TO 10:00PM AEST 4 JULY 2022 (RUN ON 28 JUNE 2022) FROM FOUR GLOBAL DETERMINISTIC MODELS. CLOCKWISE FROM TOP-LEFT; ECMWF, ACCESS-G, JMA, US GFS. THE LOCATION OF MAITLAND IS INDICATED BY THE RED MARKER.

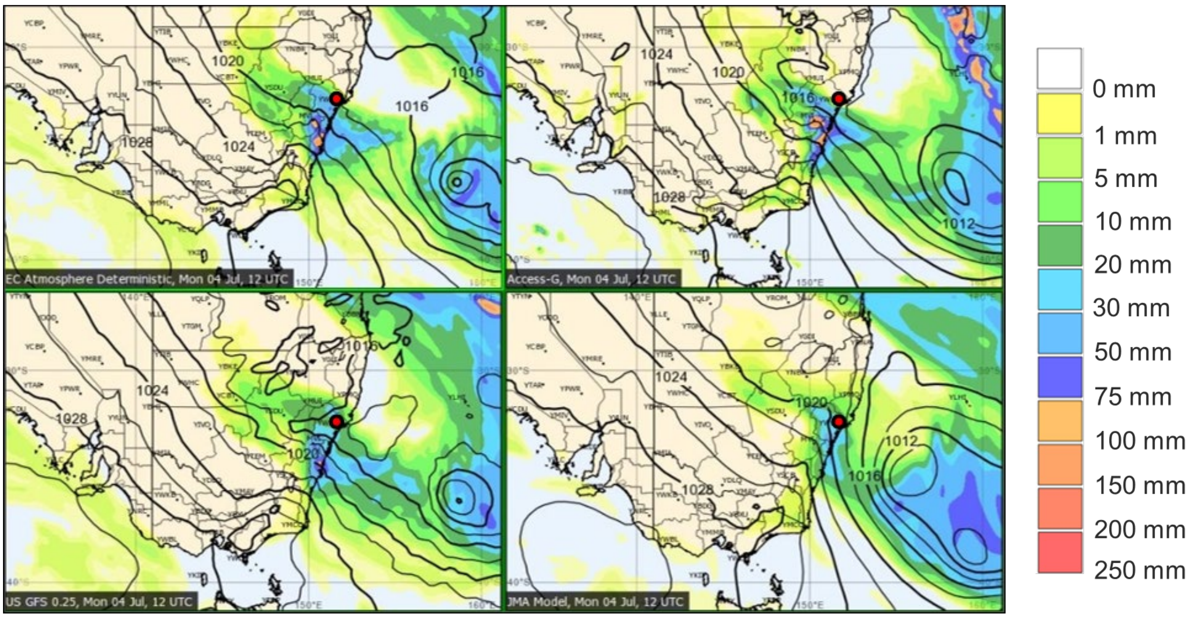
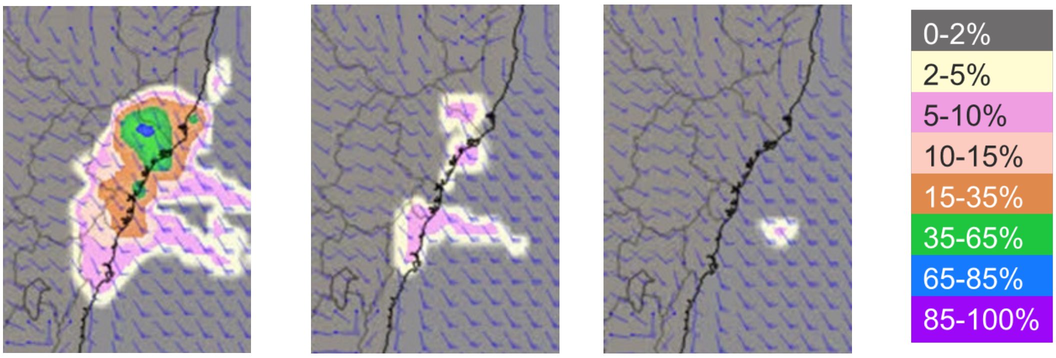


FIGURE 8 - 24HR RAINFALL FORECAST TO 10:00PM AEST 4 JULY 2022 (RUN ON 3 JULY 2022) FROM FOUR GLOBAL DETERMINISTIC MODELS. CLOCKWISE FROM TOP-LEFT; ECMWF, ACCESS-G, JMA, US GFS. THE LOCATION OF MAITLAND IS INDICATED BY THE RED MARKER.

The potential for extreme rainfall was also poorly indicated by the ensemble models. For example, only a very small fraction of EC ensemble members, shown in Figure 9, indicated a risk of moderate rainfall exceeding 50 millimetres on 5 July and none indicated a risk of over 100 millimetres.



% chance exceeding 25mm / 24 hour

% chance exceeding 50mm / 24 hour

% chance exceeding 100mm / 24 hour

FIGURE 9 – 24 HOUR RAINFALL FORECAST TO 10:00PM AEST 4 JULY 2022 (RUN ON 3 JULY 2022) FROM FOUR GLOBAL DETERMINISTIC MODELS. CLOCKWISE FROM TOP-LEFT; ECMWF, ACCESS-G, JMA, US GFS. THE LOCATION OF MAITLAND IS INDICATED BY THE RED MARKER.

Notable observations

Meteorological

During the broader rainfall event of July 2022, the central NSW coast experienced significant rainfall, with many areas recording their highest July rainfall on record or well above average falls, as shown in Figure 10.

As the rain gauge network in Wallis Creek is relatively sparse, the observations in the broader region were critical to monitor what was happening on the ground. These observations varied in severity. For example, on 4 July, nearby stations recorded rainfall ranging from approximately 40 to 150mm, while on 5 July, rainfall varied from around 20 to 160 millimetres. This corresponds to an Annual Exceedance Probability (AEP) of around 20-50 per cent, but some isolated locations experienced an AEP of around 10 per cent.

Significant rainfall was also observed at Maitland, where Belmore Bridge on the Hunter River recorded 99.5 millimetres in six hours up to 2:21pm on 3 July, exceeding the 10 per cent AEP for 6 hours of 88.3 millimetres. Maitland Airport Automatic Weather Station recorded 94.8 millimetres in six hours, surpassing the 10 per cent AEP of 82.6 millimetres.

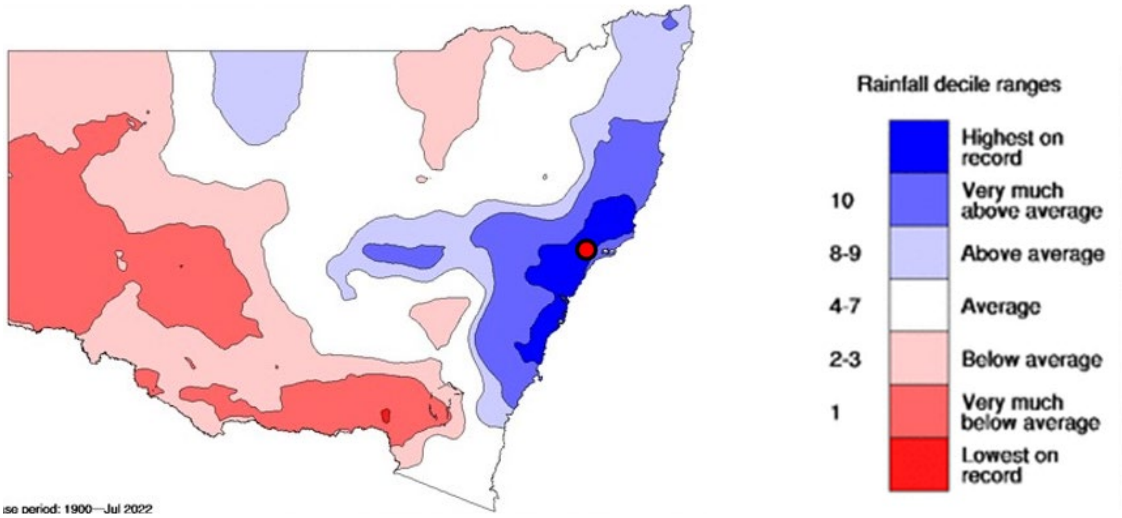


FIGURE 10 - RAINFALL DECILE RANGES FOR NSW FOR JULY 2022. THE LOCATION OF MAITLAND IS INDICATED BY THE RED MARKER. COURTESY HTTP://WWW.BOM.GOV.AU/CLIMATE/MAPS/RAINFALL.

Hydrological

During the event significant flooding affected much of eastern NSW, with numerous locations reaching major riverine flood levels and some even setting new records. The flooding in Wallis Creek was atypical due to the simultaneous flooding of the Hunter River, into which Wallis Creek discharges, refer to Figure 3.

The flow of water between these two courses is controlled by flood gates, located near their meeting point east of Maitland. When lowered, the gates are designed to prevent backflow from the Hunter River flooding the Maitland CBD. When the Hunter River water level is higher than the Wallis Creek water level, these gates close. Conversely, when the Wallis Creek water level is higher, they remain open.

During the July flood event, the flood gates were first lowered in response to the Bureau's initial Severe Weather Warning, as per the Hunter Valley Flood Scheme Flood Emergency Response Plan (Andrew McIntyre, personal communication, June 2025). As the Hunter River began to flood, the Wallis Creek flood gates closed, preventing the creek water from escaping into the Hunter River and resulting in a build-up of floodwater along the Wallis and Swampy Creek catchments around Maitland, exacerbating flood impacts in these areas. Wallis Creek was manually observed to peak at 7.188 metres on 10 July. The Hunter River at Belmore Bridge peaked at 10.41 metres on 8 July, just below the major flood threshold of 10.5 metres. The water level (river height) network within the Wallis Creek catchment was otherwise sparse, with some data unavailable and no rated gauge on Wallis Creek.

Communications/Summary of forecasts/Warnings

Between 28 June and 10 July, the Bureau of Meteorology conducted 107 Emergency Management Briefings for local, state and federal agency partners, including seven daily briefings to Resilience NSW. The risk of flash flooding was first communicated in late June, despite high uncertainty in model forecasts, described previously and shown in Figure 7. The 27 June briefing delivered by the embedded meteorologist at Wollongong SES Headquarters highlighted the risk and uncertainty, stating, ‘Significant weather system could impact the east of the state by the end of the weekend (current model uncertainty still very high)’. By 29 June, the risk of flooding was likely for southern/central parts of the coast, with the briefing noting, ‘flooding **likely** (flash flooding and riverine flooding)’ and mentioning the possibility of an east coast low forming. By 30 June, the communication emphasised the significance of riverine flooding: ‘Forecast rainfall from Friday [July 1] into next week has the potential to cause widespread riverine flooding.’ At this time the Flood Scenarios product, which provides additional detail for emergency management planning, indicated significant flooding risks, including moderate flooding at Maitland Belmore Bridge, although this forecast was later downgraded. On July 1, the likelihood of flash flooding from Hunter to Illawarra was stressed: ‘Flash flooding is therefore **likely** ... extending to between the Hunter to Illawarra Sunday [July 3] and Monday [July 4].’

The Bureau of Meteorology issued numerous public statements and products to alert the community to the flood threat, including eight press conferences held daily from 1 July to 8 July. The first flood watch for the region was issued on 30 June, highlighting the risk of flooding on the Hunter River. The first flood warning for Maitland (minor) was issued on 4 July and was progressively upgraded over the following days, reaching a likely major flooding level overnight on 7 July into 8 July. The first Severe Weather Warning to include the Hunter Valley and upper Wallis Creek catchments was issued on 2 July and extended to cover Maitland the following day, refer to Figure 11. This warning noted the potential for heavy rainfall and flash flooding:

‘HEAVY RAINFALL which **may** lead to FLASH FLOODING is forecast to continue in the Illawarra, Sydney Metropolitan, Blue Mountains, Hunter (including Central Coast) districts today as the East Coast Low approaches the coast ... Six-hourly rainfall totals between 70 to 120 millimetres are **possible**.’

The warning was accompanied by emergency statements advising the public to avoid floodwaters, seek refuge if trapped and stay vigilant, especially in fire-affected areas prone to rapid run-off and landslides:

** Don't drive, ride or walk through flood water.*
** Keep clear of creeks and storm drains.*
** If you are trapped by flash flooding, seek refuge in the highest available place and ring 000 if you need rescue.*
** Be aware that run-off from rainfall in fire affected areas may behave differently and be more rapid. It may also contain debris such as ash, soil, trees and rocks.*
** After bushfires, heavy rain and the loss of foliage can make the ground soft and heavy, leading to a greater chance of landslides.*
** Stay vigilant and monitor conditions. Note that the landscape may have changed following bushfires.*
** For emergency help in floods and storms, ring your local SES Unit on 132 500.*

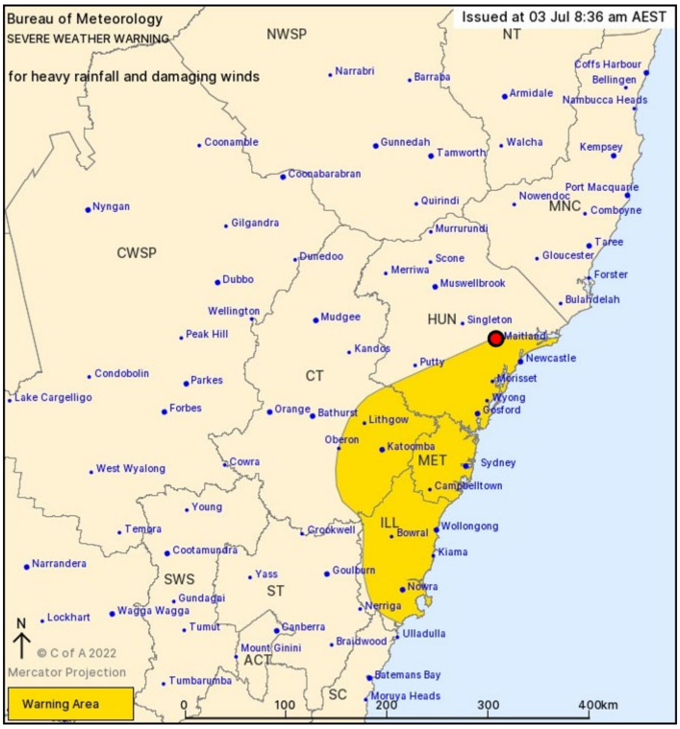


FIGURE 11 - THE FIRST SEVERE WEATHER WARNING TO COVER MAITLAND, ISSUED JULY 3 AT 8:36 AM AEST. THE LOCATION OF MAITLAND IS INDICATED BY THE RED MARKER.

During the event, the NSW SES also issued a range of public information. Between 3 July and 13 July, they released 38 flood warning bulletins for the Lower Hunter region, from Singleton to Newcastle. They also issued nine isolation warnings for the Hunter, Wallis Creek and Paterson rivers.

Additionally, there were numerous evacuation warnings and orders. Notably, an evacuation warning was issued for Central Maitland on Friday evening. At 9:20pm, due to structural concerns with a section of the levee system protecting the city, a geo-targeting text message was sent to residents in the Maitland LGA, instructing them to prepare for a possible evacuation. Residents were advised to stay alert, monitor the situation and prepare by lifting possessions, gathering essential items and sharing information with others. By 11:40pm, the Hunter NSW SES announced that the structural concerns had been resolved with temporary repairs and the threat had subsided.

'NSW SES is instructing all residents and property owners inside the Maitland levee to prepare for **possible** evacuation ... People in these [listed] areas need to be alert but not alarmed and continue to closely monitor the situation and be prepared.' (Coleman & Sharpe, 2022).

All warnings were disseminated through social media by the agencies and were further shared by their partner organisations, where appropriate.

Impacts

The flooding significantly impacted two main groups: the farmers on the floodplain and those who were isolated for several days (Maitland and District Historical Society, 2022). The main impact of the event unfolded within five days, although isolations and cleanup extended longer.

Around 2,138 homes and 5,871 residents across ten communities were isolated, with Gillieston Heights (population 4,796) remaining isolated for nine days (Maitland City Council, personal communication, June 2024). This was a particularly noteworthy isolation as before 2015, the relatively new town of Gillieston Heights had never been cut off from Maitland, which it largely depends on. The extended isolation, shown in Figure 12, disrupted access to essential services, supplies and medical care, significantly affecting the predominantly urban community.

FIGURE 12 - GILLIESTON HEIGHTS ISOLATED BY THE RISING WATERS OF WALLIS CREEK. PHOTO COURTESY EUGENE KOEN (MAITLAND AND DISTRICT HISTORICAL SOCIETY, 2022).

Agriculture was also severely affected, particularly beef, dairy, fodder and winter crops such as oats, ryegrass and clovers. Additionally, numerous fences were damaged or washed away, sheds and farm machinery sustained damage and hay was lost. Landholders who completed the Natural Disaster Agricultural Damage online survey reported estimated damages of $2,813,525 based on 17 reports from Maitland (Maitland City Council, personal communication, June 2024). Additionally, there was a variety of environmental damage, prompting cleanup efforts by the Environmental Protection Authority along flood shorelines and on land and the disposal of approximately 50 animal carcasses.

The flood caused extensive damage to public infrastructure, including roadways, the rail network, levees, bridges and restricted access to key sites like the Rally Ground and Maitland Park. Over 70 roads, including the crucial New England Highway, were closed, resulting in severe traffic disruptions across the region. Train services were halted for several days and for only the third time since their construction in the 1970s, the floodgates west of Maitland Railway Station had to be closed and sandbagged (Maitland and District Historical Society, 2022). In the Maitland LGA, 170 properties were damaged and two homes were destroyed.

Economically, the flood had a significant impact. During the peak flood period (7-8 July 2022), spending contracted by $2.5 million (34 per cent) compared to the previous Thursday and Friday (Maitland City Council, personal communication, June 2024). This was most pronounced in Central Maitland and an analysis over the following two weeks indicated economic impacts were ongoing. In contrast, spending in Gillieston Heights saw a slight increase, likely due to residents being stranded and having no choice but to make their purchases locally.

The relatively new community did not include resident civic infrastructure such as fire brigade, police or ambulance station or other medical facilities. The flooding and isolation led to significant social disruption with interruptions to employment, education, medical and social activities. The local primary school reported impacts to school attendance due to families evacuating and relocating due to floods. The local supermarket reportedly responded to coordinate community response and access to food while the broader emergency response was being mobilised.

Response

NSW SES, with the support of partner agencies, led the emergency response to riverine and flash flooding. Due to the scale of the July 2022 flood event and the need for multiple agencies, an Emergency Operations Centre (EOC) was activated on 6 July at the request of the Local Commander Police (LEOCON). It operated 24/7 before going remote on 11 July and standing down on 18 July. The EOC managed the Maitland and Port Stephens LGAs and quickly identified the need to establish an emergency evacuation centre, ultimately registering 51 individuals, with 38 accommodated.

To support isolated communities, the Salvation Army conducted food drops, while the SES assisted with grocery deliveries and the Local Land Services (LLS) delivered fodder to stranded animals. A Community Hub was opened in Gillieston Heights, the largest isolated population centre, to assist with the delivery of medication and support. The hub was staffed by SES, NSW Police, St John's Ambulance and a community champion. The EOC coordinated with local stores for the resupply of key items.

As several critical roadways were closed, traffic issues developed across the LGA. Transport for NSW managed signalling to support the traffic flow.

Sandbagging was also undertaken at a number of locations, including Horseshoe Bend, Pitnacree and Raymond Terrace, refer to Figure 13. In Maitland, sandbagging was undertaken at Maitland Showground and Maitland Railway Station with preparations for evacuating the CBD made on 8 July due to concerns over the levee breach. Several agencies, including the SES, prepared to undertake door knocks and evacuations on approximately 2,500 homes which was ultimately not required as the site was deemed safe.

FIGURE 13 - A POSSIBLE LEVEE BREACH AT MAITLAND SHOWGROUND (RING LEVEE) REQUIRED A SECTION TO BE SANDBAGGED. PHOTO COURTESY NSW SES (NSW SES, PERSONAL COMMUNICATION, JUNE 2024).

Value chain performance

The Wallis Creek flash flood event presented numerous challenges, which were reflected in the modest scores across the value chain, shown in Table 2. Overall, workshop participants assessed the value chain performance as fair, with an average score of 3 out of 5. The lowest score given was 2 (by three participants) and the highest score was 4 (by four participants). The propagation of uncertainties in the initial rainfall forecast had flow-on effects for most parts of the value chain, particularly in the hazard and impact forecasts. However, participants acknowledged the significant value of on-the-ground local knowledge in facilitating a reactive response.

Areas where the value chain performed well

The highest scoring elements of the value chain for the Wallis Creek case study concerned event observation and the communication and utilisation of warning information, each scoring roughly 3 out of 5. In terms of observations, it was noted that while there were insufficient rain and flood gauges in the region, most systems operated as they would under normal conditions. These sensor observations were generally regarded as average and local knowledge was considered crucial in responding to the event. There was a heavy reliance on on-the-ground observations to monitor flooding. For instance, a community member alerted authorities when they observed flooding at the showground emanating from an unusual direction. In terms of communication and utilisation of warning information, warnings were generally understood to have performed typically. Participants noted the extended lead time on the broader event, even if the forecasts lacked specificity. The warnings were also shared relatively successfully between agencies to disseminate the message.

Areas where the value chain could be improved

Workshop participants identified weather, hazard and impact forecasts as the lowest-scoring elements of the value chain for the Wallis Creek case study, each scoring 2-3 out of 5. Although models indicated a risk of flooding many days in advance, the high level of uncertainty in rainfall forecasts affected the entire value chain, especially hazard and impact prediction. The amount of rainfall was under-forecast, with models missing the extreme totals. Riverine flood forecasts for the Hunter River were generally assessed as performing well, given these limitations. However, there is no flash flood service for Wallis Creek and the complex interactions with the Hunter River made it extremely difficult to determine the level of flooding that would occur. Despite this, the broad risk of flash flooding was well identified for the area. The high magnitude of flooding that eventuated also presented significant challenges due to the lack of prior history for such extreme events. The isolation of Gillieston Heights appears to have come as a surprise to the community with the local member of parliament turning to social media to alert people to flooding and road closures. Participants noted the translation of warnings into individual actions was particularly challenging for residents of Gillieston Heights, where the population had increased significantly since the last big flood and local knowledge and hence risk awareness was low. While there was an extended lead time around the broader event, the timeliness of locally specific warnings was questioned. Warnings were generally reactive on the ground, with the rescinded evacuation warning for the Maitland central business district (CBD) identified as a notable example.

Sources of uncertainty

Several factors contributed to significant uncertainty in the Wallis Creek flash flood event. Firstly, there was a high level of uncertainty in rainfall forecasts, particularly for the Hunter Valley region. Although the broad potential for heavy rainfall over eastern NSW was well identified with reasonable lead time, there was high uncertainty about the amount of rain expected in the Hunter region, with predictions ranging from light rain to flood-producing levels. Despite this, even numerical weather prediction ensembles failed to capture the potential for the higher-end rainfall that eventuated.

When the rain began to fall, the sparse rain gauge network, especially over the Wallis Creek catchment, made it challenging to determine real-time conditions and predict the resulting flooding. Additionally, the sparse water level (river height) network, including the absence of a rated gauge on Wallis Creek, introduced further uncertainty regarding the waterway conditions. This issue was compounded by the unavailability of some existing data due to technical problems.

The nature of the flooding was also unusual. The closure of the Wallis Creek floodgates, caused by the simultaneous flooding of the Hunter River, meant that the creek flooded more than it would have if the Hunter River had not been in flood.

Conclusion

The flooding in the Wallis Creek catchment during 2022 was marked by significant uncertainty across all components of the value chain. High variability in predicted rainfall due to the east coast low made it difficult to provide accurate and timely forecasts which had a direct flow-on effect to the production of warnings and their communication. As the event unfolded, the relatively sparse network of rain and water level gauges hindered real-time monitoring and assessment, leading to difficulties in predicting the specific impacts on communities and infrastructure. Despite these challenges, local knowledge and on-the-ground observations played a crucial role in facilitating a reactive response.

There have been several significant changes and improvements amongst the SES and other participating agencies since the event that will result in future preparedness, warnings and response being considerably different. There have been administrative changes and updates to flood intelligence used by the SES for the region. Recently Maitland City Council embarked on an updated floodplain study that will inform capacity to predict, plan for, respond to and recover from flood events like the 2022 flooding described in this case study (Maitland City Council, 2025). Since 2022 NSW has adopted Australian Warning System for flooding, enabling more flexible and dynamic tools for flash flood events than those that were previously available.

Case study 2: Hobart, Tasmania

Event overview

During the evening of Thursday, 10 May 2018 and overnight into Friday, 11 May 2018, 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, significantly hampering 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.

Event timeline

The event timeline is shown in Figure 14, highlighting the initial talking points from the Bureau to relevant agencies on Tuesday, 8 May and the issuing of the initial flood watch for the eastern half of Tasmania on Wednesday, 9 May.

Heavy rain was observed during the evening of Thursday, 10 May and multiple significant impacts occurred as a result into the early hours of Friday May 11.

The Australian Government natural disaster declaration was made on Monday, 14 May.

Key Event Timeline: Hobart

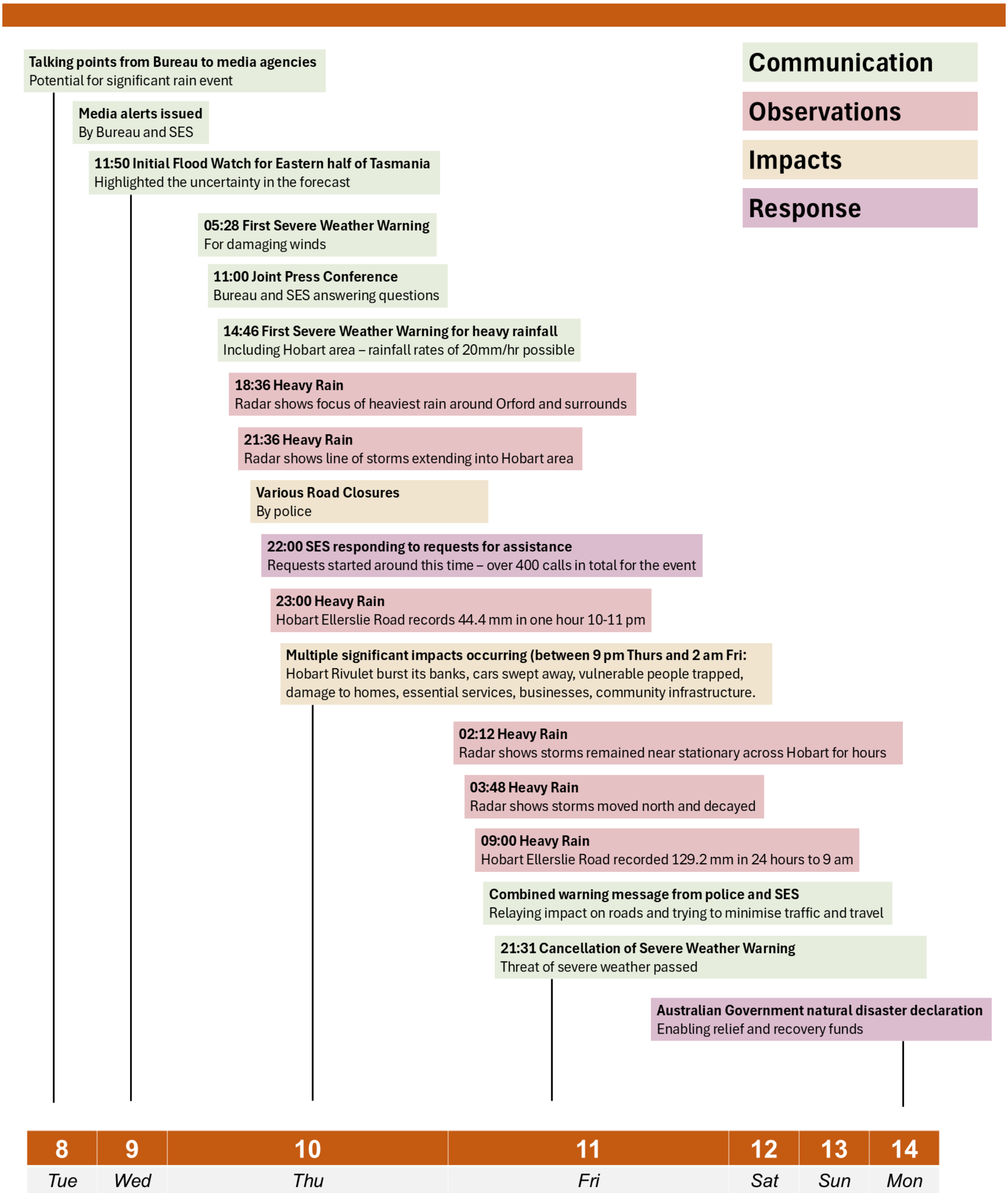


FIGURE 14 - KEY EVENT TIMELINE FOR THE HOBART EVENT FROM TUESDAY, 8 MAY TO MONDAY, 14 MAY 2018

Antecedent conditions

There had been a relatively prolonged dry period ahead of the event, with no significant rain since the preceding summer. The soil dryness index was high for the time of year (around 100 millimetres) and the ground was hard and dry. This resulted in the ground becoming hydrophobic and therefore more conducive to run-off and flash flooding. Figure 15 illustrates the relative soil moisture for Tasmania on 10 May 2018, showing that the values for Hobart and surrounds in southeast Tasmania were below average or very much below average at that time relative to the historical record.

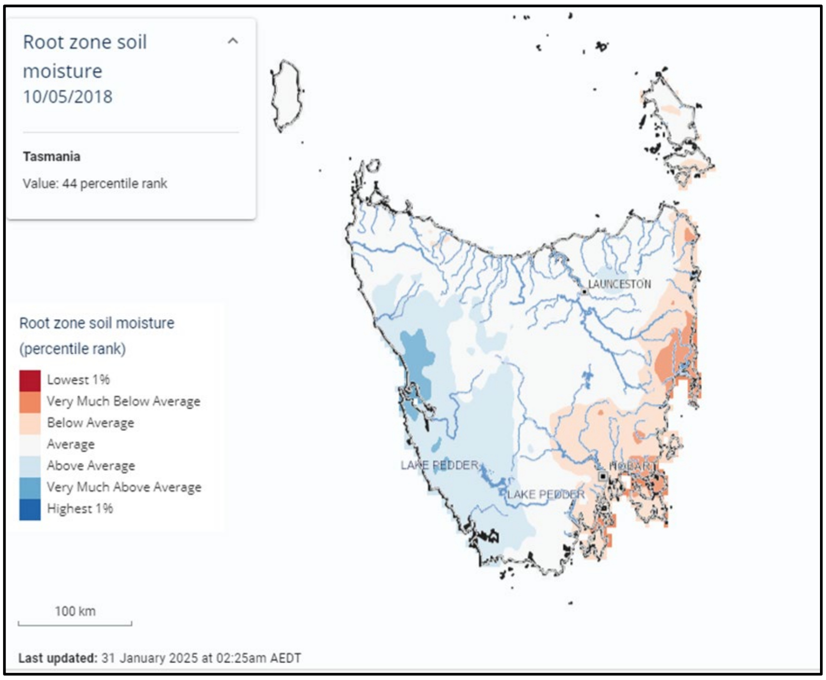


FIGURE 15 - ROOT ZONE SOIL MOISTURE (PERCENTILE RANK) FOR TASMANIA, MAY 10, 2018. AUSTRALIAN BUREAU OF METEOROLOGY (N.D.-A).

Synoptic overview

A cold front crossed Tasmania during Wednesday, 9 May 2018. Cold air in the wake of the front helped to generate a complex area of low pressure to the east of Tasmania during Thursday, 10 May. The low was 'cradled' by a ridge in such a way as to direct a narrow channel of moist, tropical air towards southeast Tasmania. The interaction of the cold, unstable air with the moist, tropical air triggered many storms, which formed into a coherent line with an east-to-west orientation over parts of Hobart and the southeast. The line of thunderstorms remained near stationary during the late evening and into the early hours of Friday, 11 May, bringing intense and localised rainfall, while the location of the low generated damaging southeasterly winds. The trough and line of thunderstorms began to decay during the early morning on Friday, 11 May as the low centre moved to the northeast. The heavy rain had significantly eased before dawn.

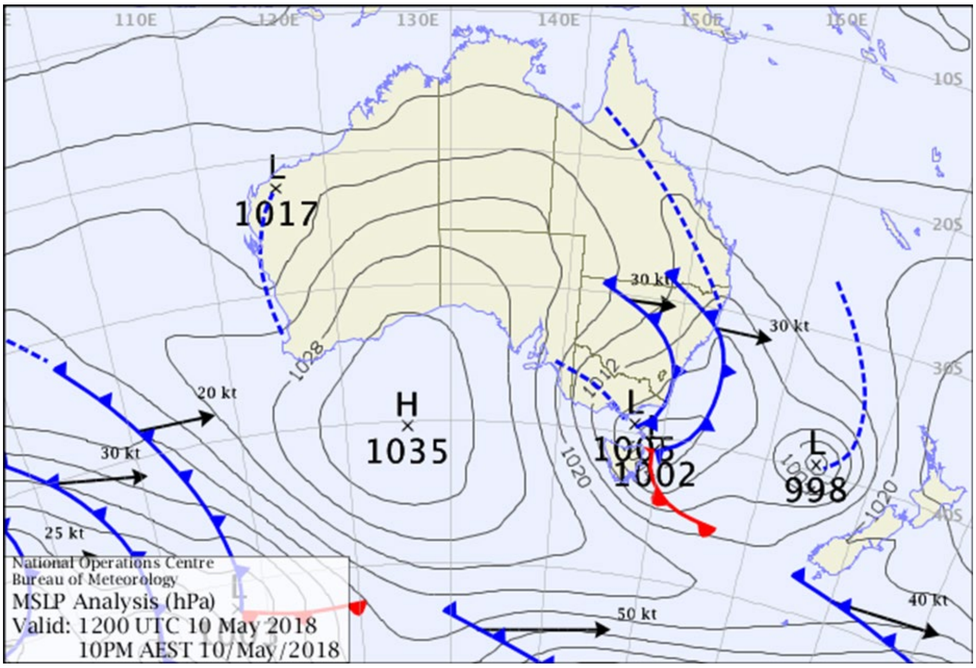


FIGURE 16 - MEAN SEA LEVEL PRESSURE (MSLP) THURSDAY, 10 MAY 2018 AT 10:00PM AEST, SHOWING THE LOW-PRESSURE SYSTEM CRADLED BY A RIDGE TO THE SOUTH.

Weather forecasts and event detection

Several days ahead there was an indication of a significant rain event occurring as a result of a complex low-pressure system. However, due to the nature of the low, there was significant model uncertainty with a wide area potentially affected. None of the model guidance picked the location and intensity of the heaviest rain ahead of the event.

Model variability continued up to and including the day of the event. Gridded NWP rainfall forecasts on Thursday morning were relatively low. The ACCESS-C high-resolution model showed relatively steady rain throughout and not the very intense short duration rainfall that occurred. The ECWMF model (with a coarser grid) predicted a 24-hour accumulation of around 60 millimetre for Hobart, around half of the final observed totals.

Following the event, the Bureau's regional reanalysis dataset was reviewed (Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia – Tasmania domain (BARRA-TA), Su et al., 2020). This enables an approximate reconstruction of the atmosphere in the past by taking all available observations and using a weather model to reanalyse the atmosphere, at a resolution of 1.5 kilometres.

BARRA-TA did not accurately model the exact location and intensity of the very heavy rainfall. The model physics was unable to resolve the highly convective and localised nature of the rain, even after the event with hindsight reanalysis using observations fed back in. This highlights the challenges involved in trying to predict convective and localised rainfall with NWP models. Figure 17 below shows the comparison of the observed versus the BARRA-TA modelled rainfall accumulations for Hobart.

More information about the BARRA dataset is available at (Australian Bureau of Meteorology n.d.-c)

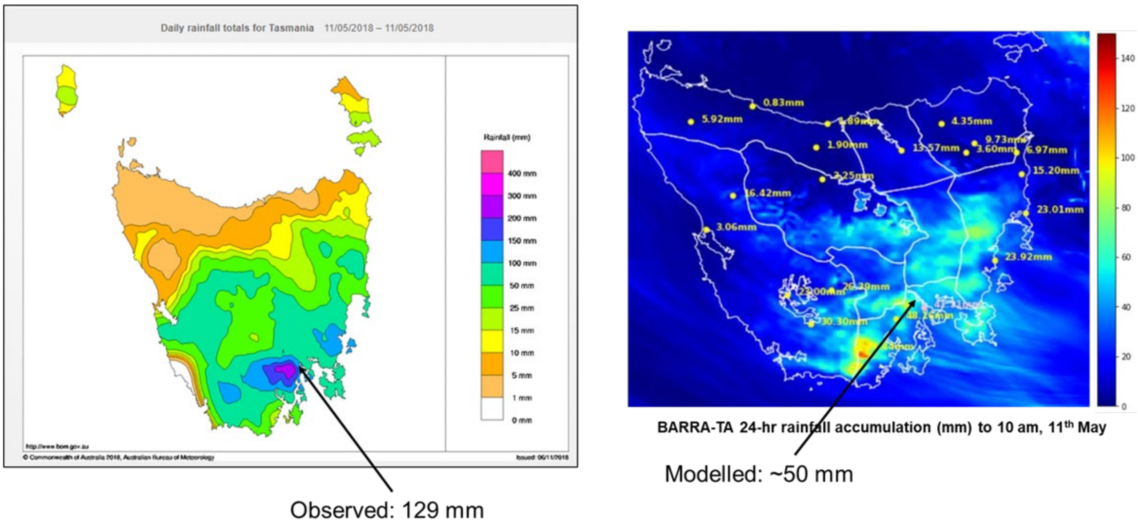


FIGURE 17 - OBSERVED VERSUS THE BARRA-TA MODELLED RAINFALL ACCUMULATIONS FOR HOBART

Notable observations

Radar imagery from the Mt Koonya radar (southeast Tasmania) captured the event evolution (refer to Figure 18). The initial focus of the heaviest rainfall was around Orford and surrounds, with the trough and line of storms developing near Maria Island and to the east (refer to image below at 18:36). By 21:36, a more coherent line of thunderstorms is visible to the south of Dunalley and extending into the Hobart area. This line of storms remained near stationary in the same area until the early hours on Friday, 11 May (refer to images at 21:36 and 2:12). The final image at 3:48 shows the line of thunderstorms has moved to the north and decayed.

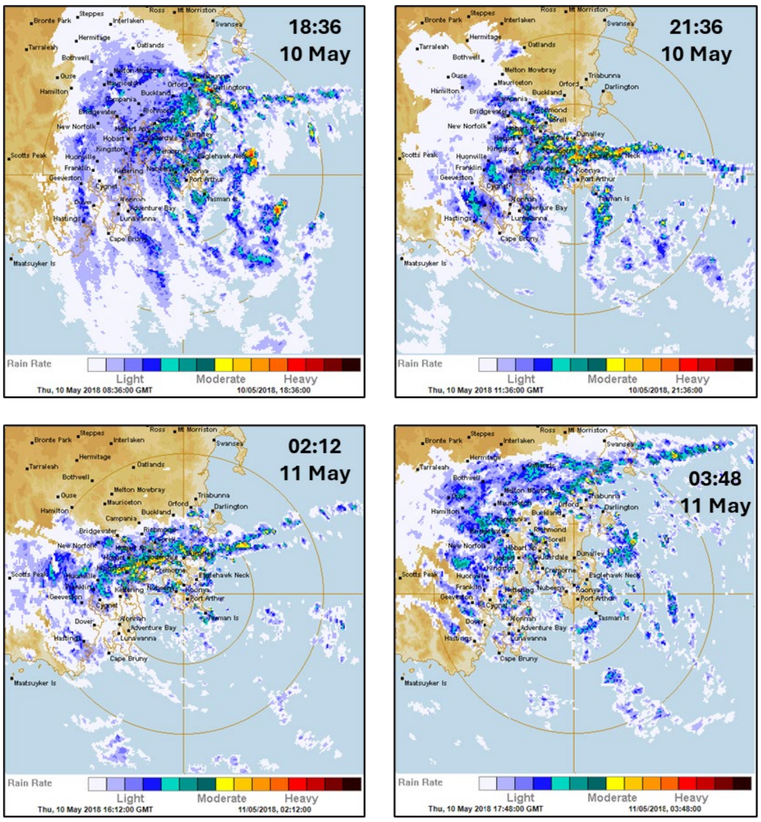


FIGURE 18 - MT KOOYNA RADAR IMAGES – THURSDAY MAY 10 AND FRIDAY MAY 11, 2018.

This was an extreme and very rare event. Figure 19 shows the daily rainfall totals for Tasmania for the 24 hours to 9:00am, 11 May, with much of this falling rapidly within a six to 12-hour period during the evening and overnight. The focus of the heaviest rain around Hobart is clearly visible from the map. Numerous gauges in this area recorded between 100-200 millimetres, with three gauges recording more than 200 millimetres. The intense rainfall was highly localised in nature, with Hobart (Ellerslie Road) recording 129.2 millimetres in the 24 hours to 9:00am, 11 May, whereas Hobart Airport recorded only 41 millimetres during the same time. Hobart (Ellerslie Road) recorded 44.4 millimetres in one hour (previous record was 28.9 millimetres).

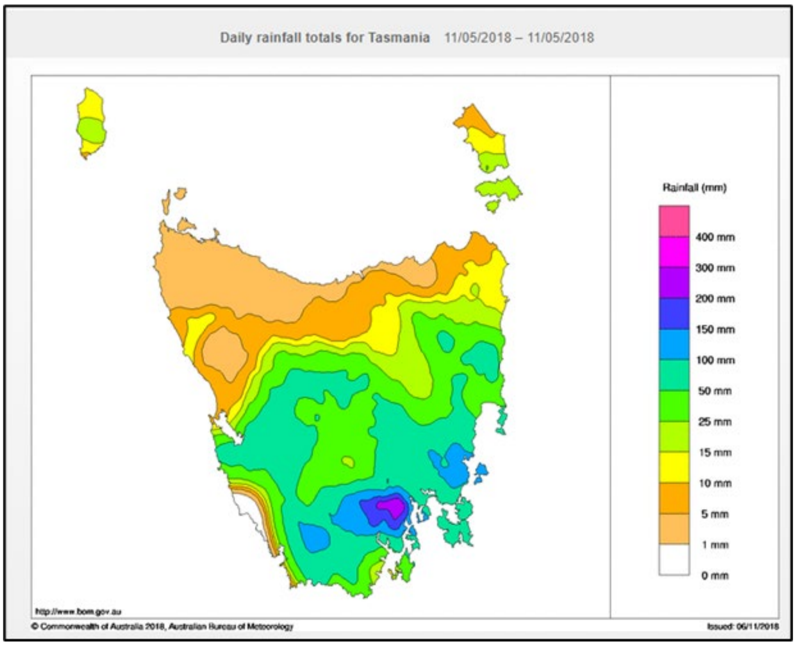


FIGURE 19 - RAINFALL TOTALS FOR THE 24 HOURS TO 9AM FRIDAY, 11 MAY 2018.

The observed storm envelope relative to AEP thresholds for Hobart (Ellerslie Road) is shown in Figure 20 below. In particular, the AEPs for rainfall durations of 30 minutes to six hours are exceptionally rare, being much less than the 1 per cent AEP. The storm envelopes for other surrounding gauges were consistent with those observed for Hobart.

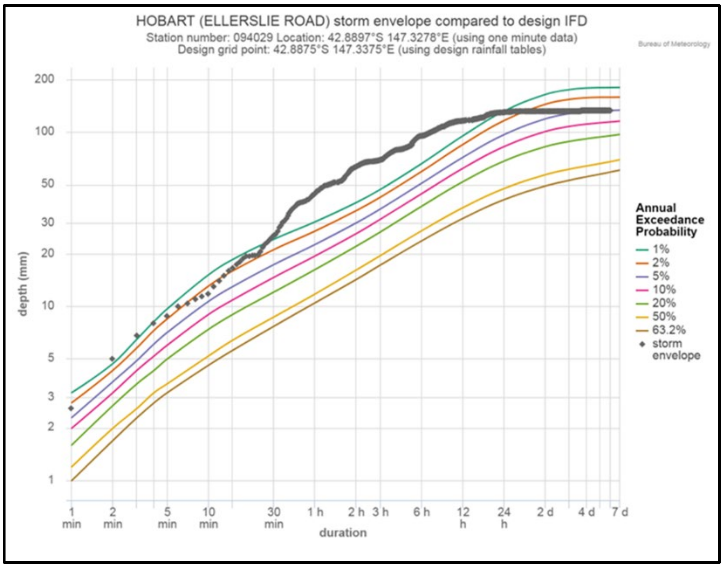


FIGURE 20 - RAINFALL TOTALS FOR THE 24 HOURS TO 9AM FRIDAY MAY 11, 2018.

Communications/Summary of forecasts/Warnings

Talking points were issued to media agencies by the Bureau several days ahead regarding the potential for heavy rain. On the morning of Tuesday, 8 May 2018, talking points highlighted the potential for a significant rain event across eastern and southern Tasmania on Thursday, Friday and Saturday, with the possibility of flash flooding or riverine flooding occurring.

There was also direct communication between the Bureau and emergency management agencies, providing verbal advice in addition to the routine forecasts and warnings. SES held a video meeting with the emergency coordinators from several councils and Tas Networks.

Media alerts were issued on Wednesday, 9 May by both the Bureau and Tasmania SES followed by a joint press conference on the morning of Thursday, 10 May. An additional press conference was held in the evening by the Bureau, a few hours before the event.

A summary of the public facing flood watches and severe weather warnings issued by the Bureau is listed below. Several road weather alerts and minor flood warnings were also issued during this period.

- The first warning to be issued was an Initial flood watch for the eastern half of Tasmania on Wednesday, 9 May at 11:50 am. This flood watch highlighted the uncertainty involved in the forecast and was subsequently updated on Thursday and Friday mornings.

> 'Friday is likely to see the highest rainfall totals, with widespread 50-100 mm forecast across eastern and central parts of the State. Higher rainfall totals up to 120 mm are possible in elevated areas.
>
> Due to the nature of the complex low there is uncertainty in the forecast rainfall. These amounts may change in the coming days as the position of the low becomes more certain.
>
> River rises are expected in response to the forecast rainfall. Flooding may develop in some catchments from Friday onwards, with the severity depending on the rainfall totals. Further catchment specific warnings will be issued if and when required.
>
> Strong and dangerous flows are expected in small creeks and low-lying areas in locations that receive heavy rainfall.'

- The first severe weather warning issued was at 5:28am on Thursday, 10 May and focused on the threat of damaging winds. Heavy rainfall and flash flooding was considered less of a risk at that stage.
- The first severe weather warning to mention heavy rainfall was issued at 2:46pm on Thursday, 10 May (refer to Figure 21) and stated:

> 'HEAVY RAIN which may lead to FLASH FLOODING is possible for east and southeastern coasts and adjacent hills late Thursday evening and early Friday morning. This includes the Hobart area. Rainfall rates around 20mm within an hour are possible. The heavy rainfall is dependent on the development of thunderstorms and as such, is not expected to be widespread but more isolated to where storms form.'

- Eight further severe weather warnings were issued during Thursday evening and through Friday, before the final cancellation warning at 9:31pm on Friday, 11 May.

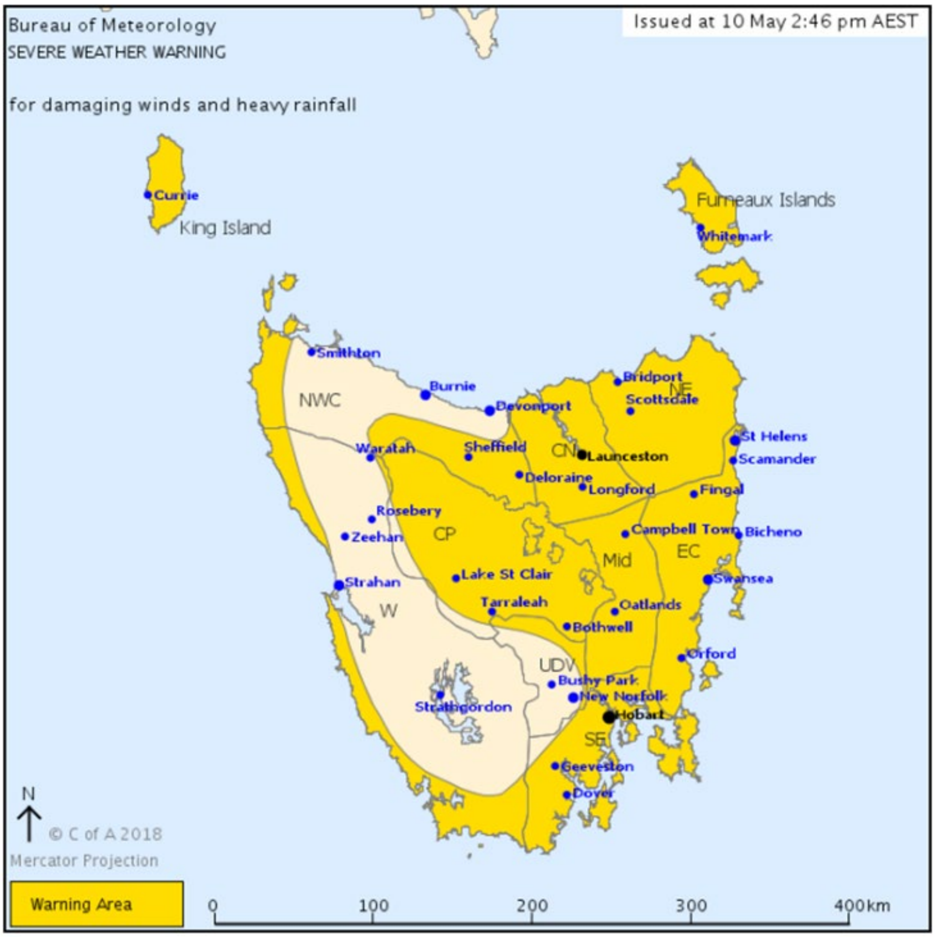


FIGURE 21 - THE FIRST SEVERE WEATHER WARNING TO MENTION HEAVY RAINFALL, ISSUED AT 2:46 PM ON THURSDAY, 10 MAY.

There were no additional warnings issued by the SES on Thursday evening. There were some road closures by the police, but the next emergency management warning was not issued until the morning of Friday, 11 May – and this was a combined message from the police and SES about the impact on roads and a caution to minimise traffic and travel.

Impacts

In August 2018, the Insurance Council of Australia (ICA) declared the southern Tasmania extreme weather event to be the largest natural hazard to impact Australia that year. Estimated known costs of the event exceed $135 million.

The worst affected areas were the southern suburbs of Hobart and the elevated areas directly inland. The key impacts occurred between 9:00pm on Thursday evening and 2:00am on Friday morning as the heaviest rain focused on Hobart.

The Hobart Rivulet burst its banks, overtopping at Collins Street and several cars were swept away through the CBD. There was no loss of life or injury. However, there was extensive damage to homes, essential services, businesses and local government and community infrastructure and disruption to many community activities and events. Multiple elderly and disabled people were trapped in their homes and required rescuing.

Tas Networks was significantly impacted and more than 13,000 homes lost electricity. More than 30 schools were closed due to flooding and loss of power.

- **Economic impacts** – included stock losses and extensive damage to business premises and damage to crops, fencing and land in the Derwent and Huon Valley. There was also significant damage to the University of Tasmania's Sandy Bay campus, with several buildings and some student accommodation flooded.
- **Social impacts** – many people were displaced from their homes and had to seek temporary accommodation while their homes were being repaired. Many people suffered substantial property losses and based on insurance data, around 5,000–8,000 households in greater Hobart were directly affected.
- **Environmental impacts** – discharge of untreated sewage into the Derwent River and the pollution of waterways from chemicals, fuels, waste, debris and litter.

Response

Multiple agencies including the SES, Police, Fire Service, local councils and Tas Networks were involved in the response. The SES received over 400 calls for assistance during the event, with the Tasmania Fire Service responding to an additional 110 requests for help. The City of Hobart council received 8 times its usual number of calls for the 24 hours between Thursday evening and Friday evening.

Temporary evacuation centres were established in Hobart and Kingston for affected community members, with many others seeking shelter with friends and family.

Value chain performance

The Hobart flash flood event was an exceptional and rare event. There were a number of challenges, reflected in the value chain scores (refer to Table 2). The overall warning value chain scored just 2.3 out of 5 (with seven participants scoring). The lowest score given for any element was 1 (13 times) and the highest score was 5 (four times).

Overall, the warning chain performed poorly, with the forecasts not being accurate enough and the subsequent response being largely reactive due to limited warning of the event severity ahead of impacts occurring.

Areas where value chain performed well

The highest scoring element was for the event observation (at 4.1 out of 5), which in this context refers to the available rain gauge data and extent of radar coverage. There is a relatively dense network of rain gauges and water level gauges and a high quality of radar imagery in the Hobart area and surrounds.

The next highest score (at 3.0 out of 5) was for the warning communication. This reflected the reasonable amount of communication and warning of the potential for a significant rain event prior to the event. However, the extreme nature of the event and its sudden development over Hobart was not well predicted, meaning that there was limited to no time available for providing specific targeted warnings to the community ahead of impacts occurring.

Areas where the value chain could be improved

The weakest points along the value chain were the hazard forecasting and impact prediction (both scoring 1.6 out of 5), closely followed by use of warnings (2.0 out of 5) and weather forecasting (2.1 out of 5).

There is no specific forecast for flash flood, rather the Bureau forecasts heavy rain that *may lead* to flash flooding and the weather forecasting guidance was unable to pinpoint the heaviest rain amounts and locations. There was also limited hazard and impact intelligence available at the time to estimate when and where the impact would occur. Warnings were issued with minimal or no lead time which meant that the response could only be reactive.

Potential areas for improvement discussed at the workshop included:

- This event was picked up on the radar and rain gauges as it happened, with limited model guidance beforehand. Newer models of ACCESS are available now, plus ensemble guidance and would be talked through during live briefings in terms of most likely and outlier scenarios. The community also now has access to the 'future' radar pictures/nowcasting.
- There is a strong desire to receive detailed briefings to understand the forecast uncertainty. Emergency management agencies value the personalised decision support and being able to ask questions to clarify possible scenarios.
- Linking ensemble guidance (per cent chance of a certain rainfall intensity and duration) to impacts as part of an action plan for response – to allow pre-positioning of resources and faster response, for example for closing susceptible roads quickly.
- Undertake scenario analysis as part of planning and response exercises – for example what would happen at different times/days of the week in terms of disruption, traffic impacts, risks to life – qualitative assessment and targeted response.
- There are more frequent and detailed conversations between the Bureau and SES now and the regional emergency management and briefing structure has changed since the event. Council has also changed their work practices to ensure culverts etc., are clear ahead of time and on the day of the event enable staff to be in response mode with the Incident Management Team (IMT) available.
- Understanding of the impacted areas. Maps of flash flood hotspots are available now (depth and velocity hazards) but weren't at the time of the event.
- Road closures are unlikely before an event, as there is a reluctance to close key roads 'just-in-case'. However, there could be signs prepared and ready to roll out, particularly linked to intense rainfall.
- The introduction of the TasALERT website and app has enabled a much greater emergency alerting capability, for faster dissemination of messages to the community.

Sources of uncertainty

There were several sources of uncertainty during the Hobart flash flood event, the key ones being:

- There was a high level of uncertainty in the rainfall forecasts (both totals and areas of impact) due to the complexity of the weather system. It was not well predicted by the guidance, with flash flooding initially considered a lower probability than damaging winds.
- Community knowledge of flood risk and the potential for severe weather impacts was limited. Relevant factors include lack of recognition of overland flow paths as flood areas, infrequent flooding (the last event of this magnitude was in 1960) and limited heavy rain events in Hobart, the second driest capital city in Australia.

Conclusion

Low probability, high-impact events such as the Hobart May 2018 flash flood event highlight the importance of decision support, ongoing engagement and appropriate risk communication throughout the warning value chain to ensure optimum outcomes for the community.

Since this event there have been significant improvements across the Bureau, SES and other participating agencies in preparedness, warnings and response. These changes include organisational, structural and procedural aspects, introduction of the Australian Warning System and TasALERT, flash flood hazard mapping to identify problem hotspots and updated forecast models including use of ensembles. Reanalysis of the event with the new ensemble model technology is being undertaken to better understand how these would have improved the forecast.

Case study 3: Adelaide, South Australia

Event overview

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 per cent AEP for heavy rainfall; 2 per cent 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 SES 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.

Event timeline

The event timeline is shown in Figure 22, highlighting the initial briefing from the Bureau to the SES on Thursday, 23 November and the subsequent follow-up briefings over the weekend.

Severe Thunderstorm Warnings for Adelaide were issued from the early hours of Tuesday, 28 November and the Metro South Incident Management Team was activated at 7:30am in response to observations of heavy rain and multiple impacts.

By 4:00pm on Tuesday, 28 November, weather conditions had improved and floodwaters receded.

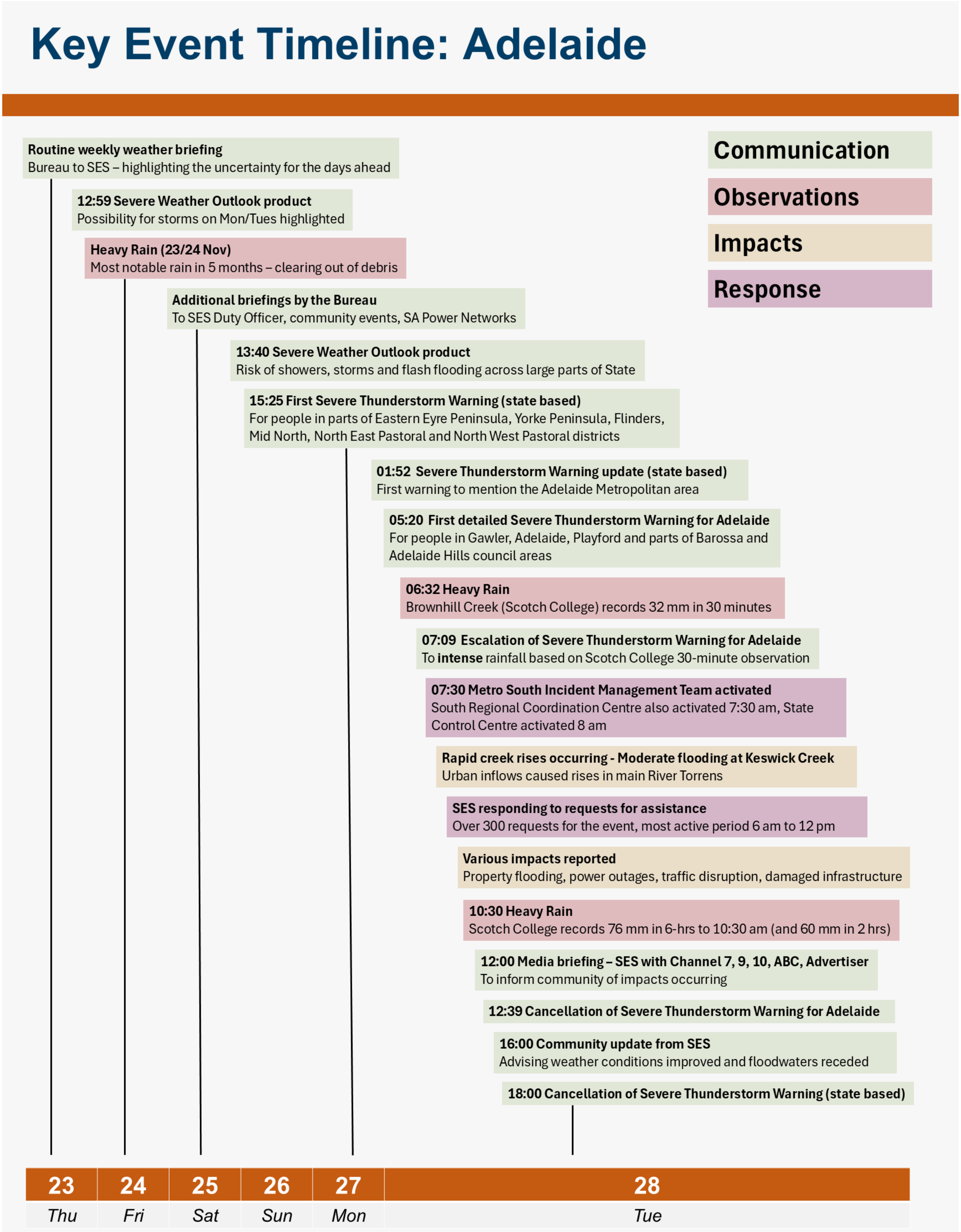


FIGURE 22 - KEY EVENT TIMELINE FOR THE ADELAIDE EVENT FROM THURSDAY NOVEMBER 23 TO TUESDAY NOVEMBER 28, 2023

Antecedent conditions

Late winter and spring 2023 had been very dry, leading to a focus on bushfire risk rather than storms and wet weather. The most significant rainfall for five months occurred on the Thursday/Friday prior to the event (23-24 November) and flushed some debris from the catchment.

Figure 23 illustrates the relative soil moisture for Adelaide and surrounds on 23 November 2023, showing that the values were very much below average or in the lowest 1 per cent at that time relative to the historical record.

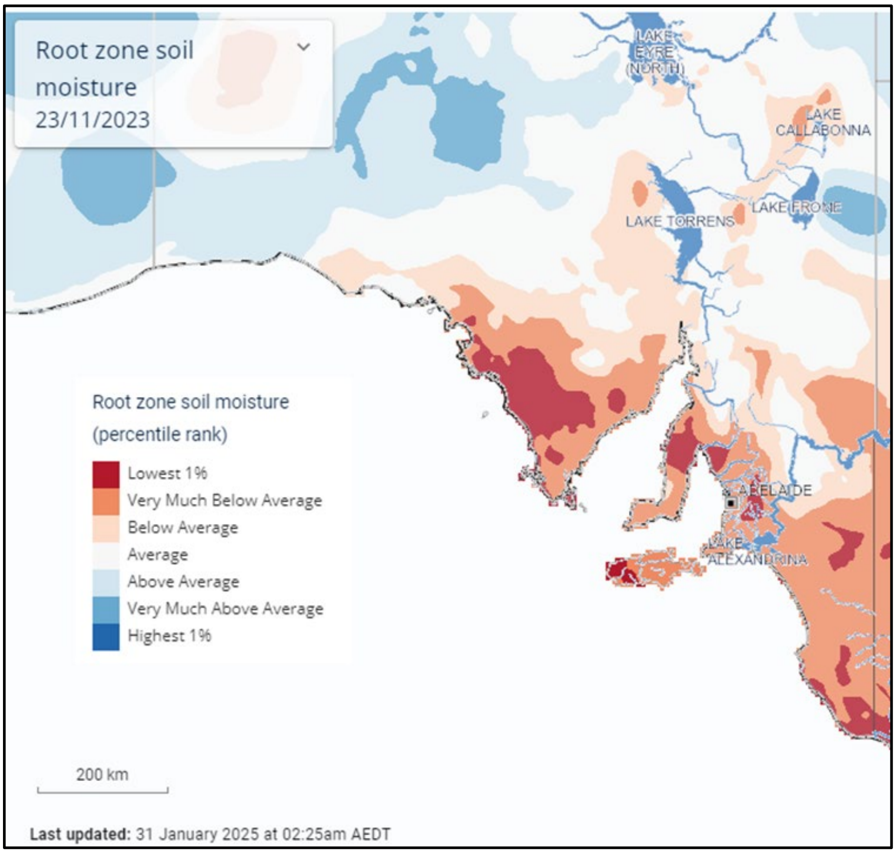


FIGURE 23 - ROOT ZONE SOIL MOISTURE (PERCENTILE RANK) FOR SOUTH AUSTRALIA, NOVEMBER 23, 2023. AUSTRALIAN BUREAU OF METEOROLOGY (N.D.-A).

Synoptic overview

A low-pressure system about the northeast of South Australia combined with a complex trough system moved south across central and eastern parts of the state during the morning of Tuesday, 28 November. This complex system interacted with an upper low-pressure trough as it moved south.

A high-pressure system was situated well south of the Bight and was moving slowly eastwards whilst maintaining a southeasterly airstream about the southeast of South Australia.

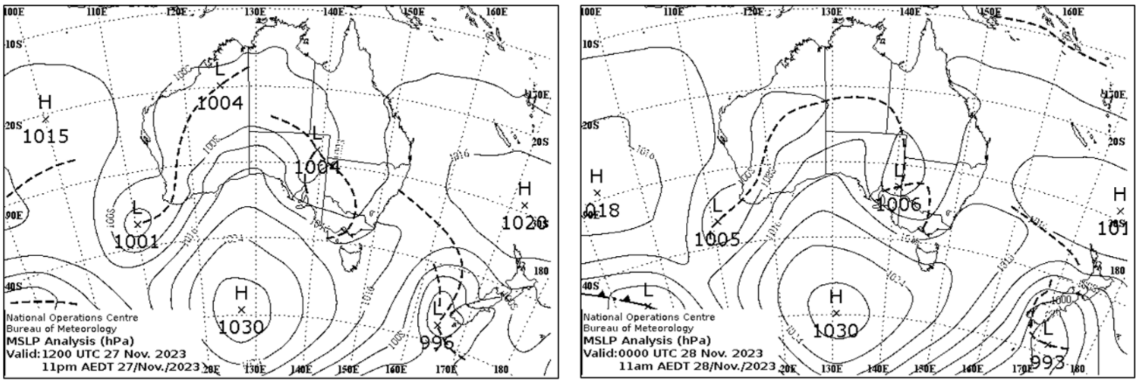


FIGURE 24 - MEAN SEA LEVEL PRESSURE (MSLP) ANALYSIS CHARTS FROM THE EVENING OF MONDAY, 27 NOVEMBER (10:30PM ACDT) AND THE MORNING OF TUESDAY, 28 NOVEMBER (10:30AM ACDT).

Weather forecasts and event detection

The complexity of the weather system, being a cut-off low, meant that there was significant uncertainty in the rainfall totals and locations, particularly a few days ahead. Around four to five days out, the official Bureau forecast was heavily model-driven, using the ECMWF and ACCESS deterministic and ensemble models and a consensus forecast approach.

During the routine weekly weather briefing between the Bureau and the SA SES on the Thursday prior to the event (23 November), the model uncertainty was highlighted. The initial model guidance did not indicate the Adelaide area (refer to Figure 25); the EC model showed virtually no rainfall for South Australia and while ACCESS was picking up the low and rainfall totals, its focus was about 500 kilometres north of Adelaide.

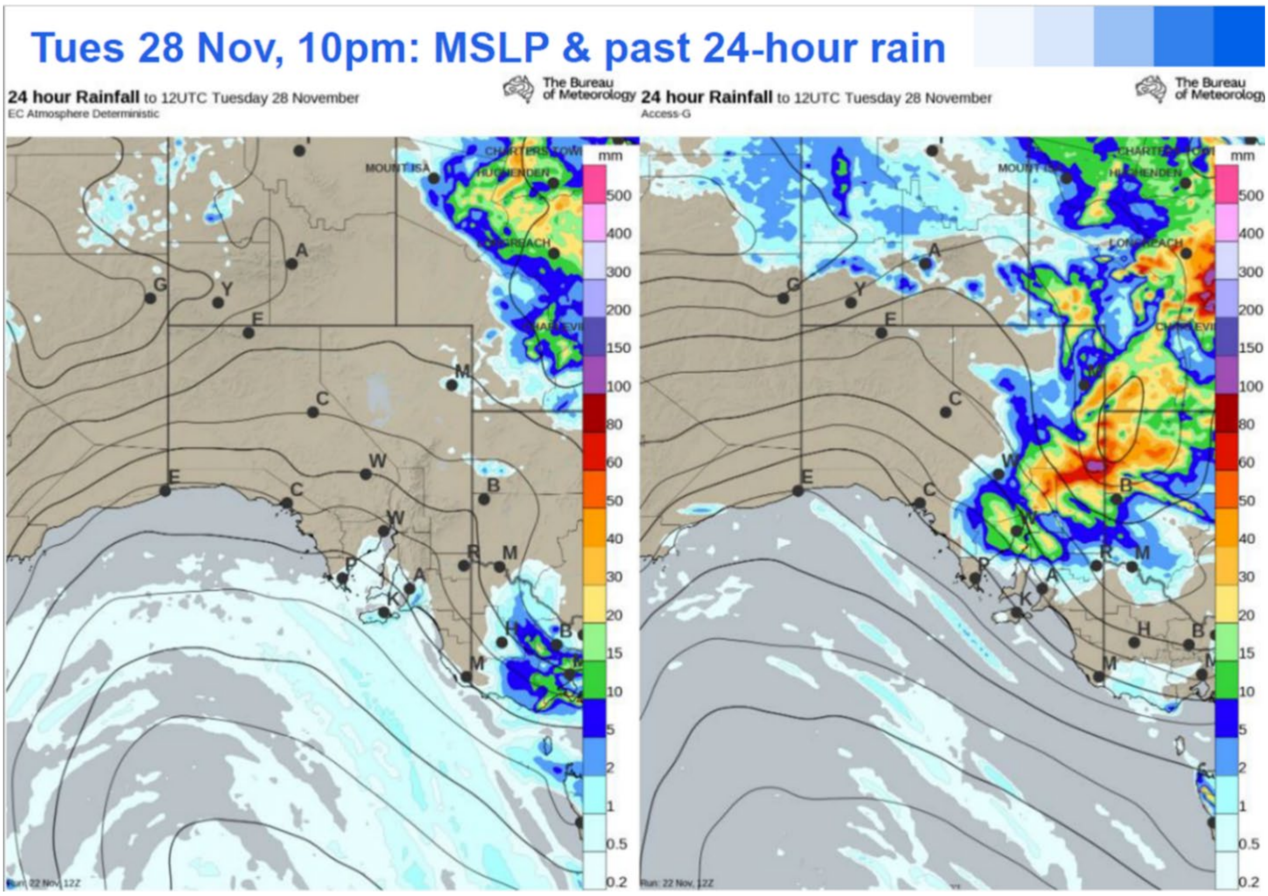


FIGURE 25 - MODEL GUIDANCE (ECMWF ON THE LEFT AND ACCESS-G ON THE RIGHT) FOR TUESDAY, 28 NOVEMBER, AS BRIEFED TO THE SES ON TUESDAY, 23 NOVEMBER.

The weekly briefing is supplemented by a Severe Weather Outlook (SWO) product issued three times a week by the embedded meteorologist for the SES. This product provides guidance on the timing and severity of severe weather hazards over the coming 5 days.

On Friday, 24 November, the focus was on the short-term weather for that day, with thunderstorms and heavy rainfall forecast. The possibility of storms for the following Monday and Tuesday was highlighted, but with low certainty on rainfall amounts or flash flood risks.

'A second trough and low now appears likely to result in further showers and possible severe thunderstorms across large parts of the state later Monday and Tuesday. Again, localised heavy rainfall is expected to be the main risk, however, there is high uncertainty on totals and areas more likely to be impacted at this stage.'

The SWO issued on Monday, 27 November highlighted the risk of showers, storms and flash flooding across large parts of the state, but still as 'possible' rather than 'likely' due to continuing uncertainty.

'A trough and upper low-pressure system will trigger showers and thunderstorms across large areas of the state from this afternoon until later Tuesday. Local heavy falls leading to a flash flood risk is the main hazard with storms, although a severe wind gust risk can't be ruled out, particularly over the Flinders and NEP today. Heavier rain/storms will be patchy, however, broad totals of around 10-30 mm are expected, with local higher falls to around 60 mm possible. Refer to shading in the table for expected timing of the severe potential.'

The public-facing weather forecast for the Adelaide metropolitan area started to highlight the chance of storms and heavy rainfall for Tuesday, 28 November from the Friday prior and maintained this through the Saturday, Sunday and Monday forecasts – refer to Table 3.

Table 3 – Heavy rainfall and storm messaging in Adelaide public facing weather forecast

Lead-in day	Adelaide Forecast (PM issue) for Tuesday, 28 November
Thursday 23/11 (5 days)	Slight chance of a shower. Chance of any rain: 20%
Friday 24/11 (4 days)	High chance of showers, most likely in the morning and afternoon. The chance of a thunderstorm. Heavy falls possible about the northern suburbs. Possible rainfall: 0 to 20 mm. Chance of any rain: 80%
Saturday 25/11 (3 days)	Very high chance of showers, most likely in the morning and afternoon. The chance of a thunderstorm. Heavy falls possible. Possible rainfall: 2 to 25 mm. Chance of any rain: 90%
Sunday 26/11 (2 days)	Very high chance of showers, most likely in the morning and early afternoon. Showers tending to rain at times in the south in the morning. The chance of a thunderstorm. Heavy falls possible. Possible rainfall: 3 to 20 mm. Chance of any rain: 90%
Monday 27/11 (1 day)	Very high chance of showers, most likely in the morning and early afternoon. The chance of a thunderstorm, with possible heavy falls in the morning. Possible rainfall: 8 to 20 mm Chance of any rain: 90%

Notable observations

The heaviest rainfall developed overnight and during the early hours of the morning with storms moving from the north-east and across the Adelaide metropolitan area. Rainfall accumulations for the six hours to 10:30am ACDT showed the highest total at Scotch College gauge of 76 millimetres and several other rain gauges with greater than 50 millimetres. Scotch College recorded 59.8 millimetres in two hours (and 19.2 millimetres in 15 minutes). Rainfall thresholds for these six-hour totals equate to less than 1 per cent AEP for Scotch College and 2-5 per cent AEP for several other gauges. The radar images from the day confirmed that the heaviest rainfall was in and around that area.

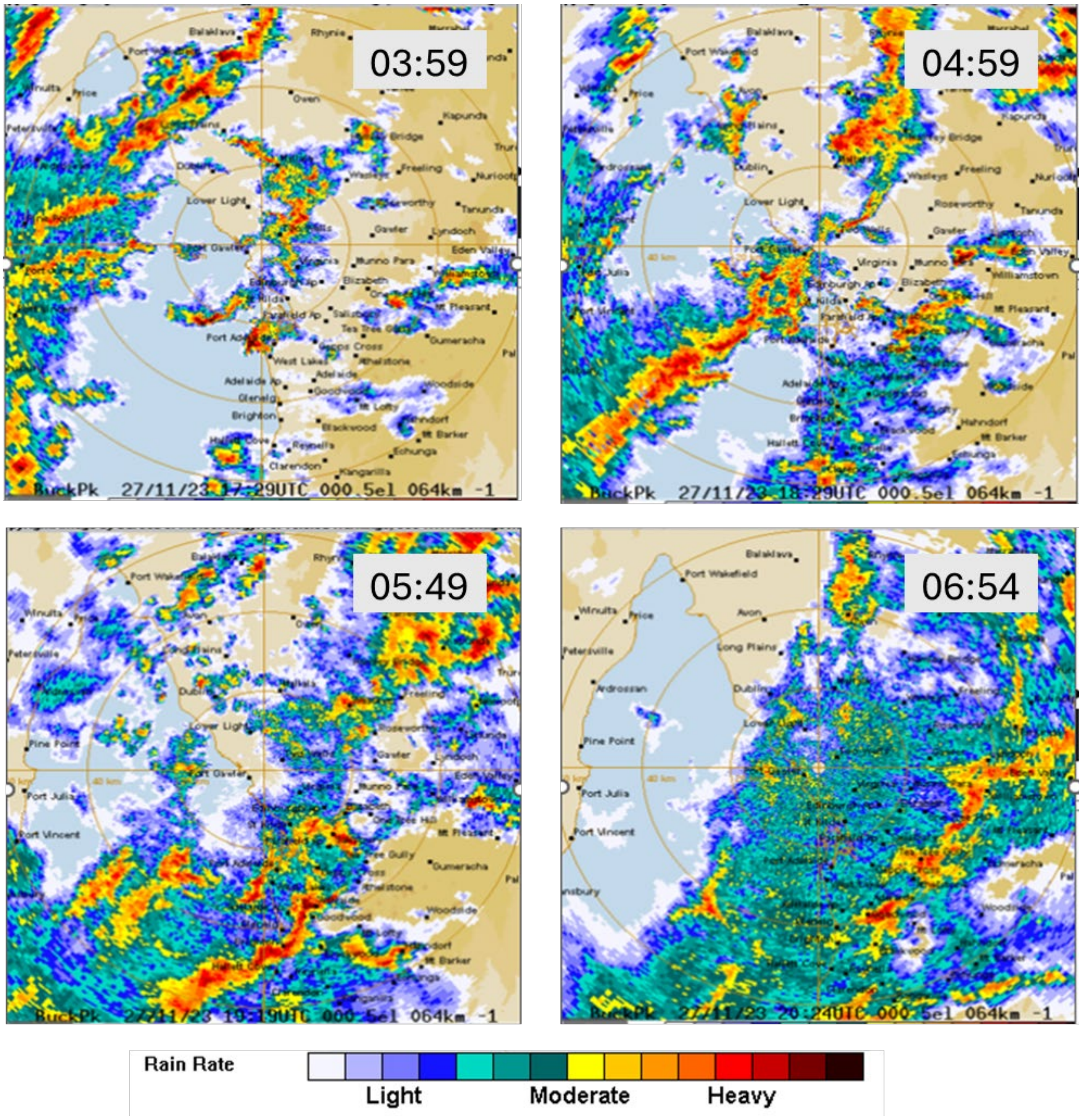


FIGURE 26 - BUCKLAND PARK RADAR IMAGES – TUESDAY, 28 NOVEMBER 2023 (TIMES IN ACDT)

Patawalonga Lake, which is in the Adelaide coastal suburb of Glenelg, plays a vital role in stormwater management for the Brownhill and Keswick Creek catchments, by diverting urban stormwater into the Gulf of St Vincent via the Barcoo Outlet. Without effective pre-event management, such as lowering the lake level and favourable tide conditions to support direct outflow to sea via the Barcoo Outlet, there is a high risk of backflow through local drainage systems and inundation of nearby properties and local roads.

During high-intensity storm events, such as the 28 November flash flood, the lake's limited capacity can be quickly overwhelmed. On the morning of 28 November, the rainfall resulted in rapid rises in local creeks. At the Keswick Creek gauge, river levels rose by around 2.5 metres in a couple of hours and exceeded the moderate flood level. Urban inflows caused rises in the main Torrens River, which runs through the city of Adelaide. Fortunately, the Patawalonga Lake level had been lowered prior to the event, enabling the lake to collect excess stormwater from the Keswick and Brownhill Creeks. Additionally, low tide levels at the time allowed a larger volume of stormwater to be discharged directly to the sea via the Barcoo Outlet rather than exacerbating urban area flooding.

Communications/Summary of forecasts/Warnings

In the days prior to the event the Bureau provided additional briefings to the SES State Duty Officer and specialist briefings for the Adelaide 500 car race event, the Adelaide Oval roof climb and SA Power Networks.

Once the event unfolded on the morning of Tuesday, 28 November, there were several additional media enquiries and requests for radio crosses from 6:00am onwards, plus several reports of impacts across social media platforms.

A severe weather warning was not issued ahead of time due to a lack of certainty about the location and the severity of the hazard. This meant that the lead time available for the public to prepare was limited.

Warnings issued by the Bureau for this event included:

- five state-based severe thunderstorm warnings during Monday afternoon and evening. The update at 1:52am on Tuesday included reference to the Adelaide Metropolitan area
- at 5:20am a detailed cell-based severe thunderstorm warning for Adelaide for heavy rainfall (refer to Figure 27). This warning advised:

> 'The Bureau of Meteorology warns that, at 5:20 am, severe thunderstorms were detected on the weather radar near Tarlee and Hamley Bridge. These thunderstorms are moving towards the south. They are forecast to affect Elizabeth, Gawler and Angle Vale by 5:50 am and Adelaide City, Salisbury and Tea Tree Gully by 6:20 am.
>
> Heavy rainfall that may lead to flash flooding is likely.'

- this warning was subsequently updated at 5:59am and 6:43am, before being escalated to intense rainfall at 7:09am based on the latest observation from Brownhill Creek (Scotch College) of 32 millimetres being recorded in 30 minutes
- in total, there were 16 severe thunderstorm warnings and 10 detailed cell-based severe thunderstorm warnings for Adelaide issued for the event.

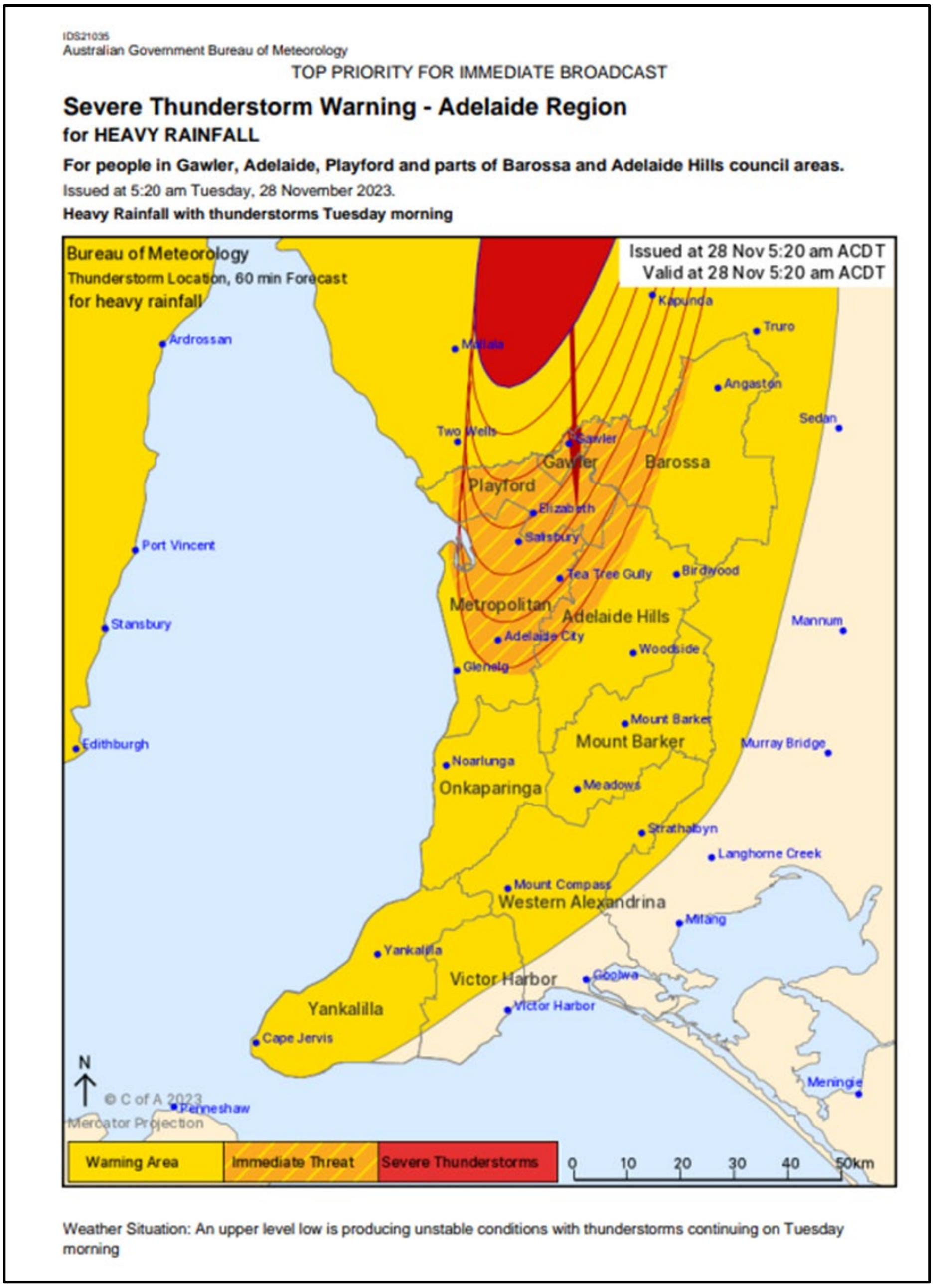


FIGURE 27 - DETAILED CELL-BASED SEVERE THUNDERSTORM WARNING FOR ADELAIDE ISSUED AT 05:20 AM, TUESDAY NOVEMBER 28.

The Bureau issued warnings several hours prior to the onset of flash flooding but their timing during the night was not optimal in terms of reach to the community.

The SA SES did not issue any warnings or public updates ahead of the event due to the uncertainties in the weather forecasts and concern about warning fatigue. They did provide generic social media posts about clearing gutters and the like, undertake active monitoring of social media channels and amplify other agencies messaging and Bureau warnings.

There was also a media briefing on Tuesday, 28 November at 12:00 pm and several media interviews throughout the day to inform the community of the impacts of the flash flooding. At 4:00pm on Tuesday, the SES issued a community update advising that weather conditions had improved and floodwaters receded but that the community should continue to take care if in the area.

SES warnings need location specificity, severity and sufficient confidence to be issued. For Emergency Alert level, there will be direct push notifications to mobile phones related to a polygon area, but not for Advice or

Watch and Act. The lack of forecast detail constrained the capacity of SES to provide detailed warnings ahead of the impact.

Impacts

The thunderstorms and flash flooding experienced on Tuesday, 28 November led to several significant impacts. These were compounded by the timing of the event during the morning peak hour traffic. A quadrant of the city was flooded and isolated and there were extensive traffic delays.

Key impacts included:

- damage to private residences, schools, hospitals and businesses from water entering through ceilings and across flooded roads
- Millswood, Hawthorn and Wayville areas reported flooding during the early morning (refer to Figure 28)
- numerous power outages, with more than 14,000 customers losing power
- the Riverbank Christmas display was damaged, with the Moby Dick sculpture being washed downstream along the Torrens River (this last occurred in 2005)
- transport disruptions including road flooding, traffic light outages and closure of the airport
- reports of injuries and people being trapped in cars.

FIGURE 28 - PHOTO OF BROWNHILL CREEK IN MILLSWOOD (TAKEN AROUND 7AM ON TUESDAY NOVEMBER 28, 2023) – PROVIDED COURTESY OF BROWN HILL KESWICK CREEK STORMWATER PROJECT. THIS HOUSE DIDN'T FLOOD BUT OTHERS FURTHER DOWNSTREAM DID.

Response

The Metro South Incident Management Team, South Regional Coordination Centre and State Control Centre were all activated.

The SA SES was actively involved in responding to incidents. There were over 300 requests for assistance during the event. The Metropolitan Fire Service, Country Fire Service and SA Power Networks were also involved in the response.

Timing of the event during the night made the response to warnings less effective. With more certainty in the forecast, there would have been a larger pre-deployment of resources for response and full activation overnight rather than on-call rosters. The first triggers of impact were requests for assistance from the community rather than flood monitoring alerts from rain or river gauges.

Value chain performance

The Adelaide flash flood event presented several challenges, with the value chain scores (see Table 2) showing significant room for improvement. The overall warning value chain scored 2.9 out of 5 (with 13 participants scoring). The lowest score given for any element was 1 (5 times) and the highest score was 5 (4 times).

Uncertainties in the rainfall forecasts for this event resulted in a largely reactive response and limited effectiveness of warnings due to their timing overnight.

Areas where the value chain performed well

The highest scoring element was around the event observation (at 4.0 out of 5), which in this context refers to the available rain gauge data and extent of radar coverage. With the event being focused on the Adelaide metropolitan area, there is a relatively dense network of rain gauges and water level gauges and a high quality of radar imagery.

The next highest score (at 3.2 out of 5) was around the weather forecasts – acknowledging that at a broad level the conditions for heavy rainfall were forecast several days out, but the convective nature of the rainfall meant it was difficult to accurately pinpoint the highest totals and areas affected with sufficient lead time during the event.

Areas where the value chain could be improved

The three weakest areas were the hazard forecasting (2.5), impact prediction (2.3) and use of warnings (2.5). This reflects the fact that there is no forecast for flash flood, rather the Bureau forecasts heavy rain that *may lead* to flash flooding. There is also limited hazard and impact intelligence available to understand who will be impacted and when. Warnings in this event were not well used, reflective of the timing of issuance during the early hours of the morning. The response to the hazard was reactive

Workshop participants identified potential areas for improvement to include:

- improved weather briefing for local councils
- improved understanding of the local conditions and the complexity of the Adelaide Hills and its effect on the weather

- increased specificity in forecast products for flash and riverine flood
- improved processes and procedures around on-call support and activations
- better availability of lead time information to enable more proactive warning by SES. This includes earlier advice even if at low probability, using percentage terms (e.g. might be ~10 per cent, 50-50 ~50 per cent, probable ~80 per cent +)
- simplify language in warnings and include maps
- increase community education about flood and flash flood risk
- improved hazard and impact intelligence
- increase support for the development of flash flood forecasting systems. Consider updating the resources on the Bureau's Flash Flood Advisory Resource, FLARE (Australian Bureau of Meteorology n.d.-b).

Sources of uncertainty

The main sources of uncertainty during the Adelaide flash flood event were as follows:

- There was a high level of uncertainty in the rainfall forecasts (both totals and areas of impact) due to the complexity of the weather system and the unusual pattern from the northeast rather than the more common pattern of moving across from the west.
- Significant variation in model guidance in the lead up, with initial guidance not highlighting the Adelaide area as being at risk.
- Limited understanding of warning terms – 'heavy' vs 'intense' rainfall, 'likely' vs 'possible' – across agencies and the community.
- Public understanding of the potential for, and impacts of, flash flooding is low.

Conclusion

The Adelaide area is susceptible to flash flooding and is often impacted during heavy rainfall, at thresholds below those used by the Bureau for issuing severe weather warnings. Earlier heads-up communications during daylight hours would assist, even if there is uncertainty and a low probability of occurrence.

The event in November 2023 was complex due to the unusual weather pattern, rapid development of storms and urban flash flooding in a highly populated area that occurred during the morning rush hour. There needs to be an uplift in public knowledge and awareness of flash flooding, including the causes, risks, warning terminology and actions to take to stay safe.

There are several local improvements taking place in Adelaide to alleviate flash flooding. These include collaborative undertakings by councils, such as the Brown Hill Keswick Creek stormwater project, to develop a comprehensive stormwater management plan for the area. In addition, the Department for Environment and Water is developing a pilot flash flood forecasting system for the Dry Creek and Brown Hill Keswick Creeks that could be used to inform SES flash flood warnings.

Cross-case discussion

In this section, a cross-case analysis is presented, beginning with a general discussion comparing the events. This is followed by an analysis of the influence of uncertainty factors on the operation of the value chain, first by considering the typical sources of uncertainty and then how uncertainty is communicated.

Value chain scoring

The value chain scoring for each case study, as shown in Table 2, reveals several clear patterns. Most components of the chain receive modest scores across all case studies. The overall scores are relatively consistent (3.1, 2.9, 2.3). 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 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 more reactive.

Sources of uncertainty

Uncertainty is endemic across the flash flood 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. There is specific guidance on conversion of rainfall to run-off for urban areas which makes it more achievable than for non-urbanised catchments. 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 value chain.

Antecedent conditions and soil moisture significantly impact the landscape response in flash flood events. These can be difficult to assess and create uncertainty about landscape response to heavy rainfall although these may be less uncertain in urban catchments which are dominated by impervious surfaces.

Data assimilation uncertainties also exist due to gaps in the observation network. Accurate portrayal of the initial state of the atmosphere is important because it influences the numerical models prediction outputs.

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 about rainfall at a location.

Radar can be a good alternative when rain gauge data is limited. Coverage is concentrated around urban areas and airports which can mean it is not a viable alternative in rural areas with sparse gauge networks.

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 element of uncertainty.

Weather forecasts

Numerical weather prediction (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 rainfall scenarios in 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 location could vary 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.

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 as described in Section 2. Instead, rainfall forecasts and warnings are often used 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 climatological rainfall thresholds (defined by AEP), for rainfall that is 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 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. Although these factors may be less relevant in urbanised catchments.

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 described in Section 2 show that responsibility is shared across the three jurisdictions: Commonwealth, state, territory and local governments. 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 value chain for flood.

Using a value chain perspective, the complexity of flows of communication can be highlighted and include both agency-to-agency and agency-to-public 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.

Although the Bureau severe weather warnings and severe thunderstorm warnings are an important tool during flash flood events, the effectiveness of the current style and language warrants consideration to ensure that they can communicate the risk and uncertainty appropriately. Warnings are also frequently issued with minimal lead time and during inconvenient hours, which can hinder the public's ability to 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 Australian Warning System has been introduced and implemented and is proving a useful mechanism for delivering responsive, location specific warnings to communities. However, the nature of the flash flood hazard and the uncertainty around the rainfall forecast means that situations will continue in which flash flooding occurs and warnings can only be issued reactively.

Response and decision

Forecast uncertainty and rapid development typically results in reactive response to flash flood, by both agencies and the public. This underscores the importance of increasing public awareness of flash flood potential and its hazardous nature, to ensure that people take the appropriate action to avoid danger. For example, keeping up to date with the latest conditions and avoiding unnecessary travel. In the Adelaide case study, which occurred during the morning rush hour, cars became trapped in floodwater and the number of cars on the road exacerbated flooding of houses as water was pushed from the roads.

Emergency management agencies have clearly defined and well-practised processes and procedures in place for responding to events to keep the community safe. 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.

However, the level of preparedness for the events and severity of flooding that occurred was limited by the uncertainty in the weather, hazard and impact forecasts. Although all cases included some indication of heavy rainfall in the days ahead, there was significant complexity and uncertainty in predicting the resulting localised impacts. With more certainty in the forecast, there could have been a larger pre-deployment 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 could help in pre-positioning of resources and faster response, for example for closing susceptible roads quickly. Ensemble guidance (per cent 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

This report outlines the various ways uncertainty affects the value chain during flash flood events.

Uncertainty is a well-recognised and inherent aspect of flash flooding, but its effective communication is challenging. The case studies demonstrated that the tools available to provide the community with information about the potential risk of flash flooding were limited. The primary tool for communicating 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.

Both warnings similarly communicate these risks. A typical warning passage reads: 'HEAVY RAINFALL which **may** lead to FLASH FLOODING is **possible**.'

This passage attempts to communicate two distinct types of uncertainty:

1. The uncertainty in the rainfall forecast, which is often quantified using ensemble predictions and described here as 'possible'.
2. The uncertainty in the flash flooding, which is more difficult to quantify due to local factors that cannot be assessed on a broad scale and is instead loosely linked to the risk of heavy rainfall.

The phrasing is cumbersome in its expression of likelihood, making it difficult for people to discern the actual level of risk. The warnings do not define terms like 'possible', 'likely', or 'expected', leaving room for inconsistent interpretations by those issuing, receiving and acting on the warnings. Similar issues affect messaging by emergency services messaging often includes uncertainty terminology and is affected by similar issues. The development and use of agreed definitions would help to ensure clarity of messaging.

There are quite simple graphics in both products. The severe weather warning employs a single 'level' to represent threat, which means there is no visual differentiation of areas with heightened risk. This means that all locations are classified under the same threat level, which limits the efficacy of visual communication. Public understanding and response are increased with the application of tiered warnings which can conveying critical information, such as the severity of a hazard and its likelihood.

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. Australian Warning System warnings now issued by states and territories can be used to fill this gap and can provide locally responsive communication to the public than was the case in the past.

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 the uncertainty surrounding various potential outcomes. While these briefings are highly valued, there remains room for improvement in the consistency and clarity of 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.

Strategies to improve the communication of uncertainty

Several service gaps were identified during the case studies, with many of these related to the communication of uncertainty. There are a range of opportunities to improve the communication of uncertainty across the warning value chain. These are presented in the table below.

Table 4 – Gaps and strategies to improve the communication of uncertainty.

Gap	Strategy
Qualitative language to convey risk and lack of cues to facilitate understanding.	Use of best practice strategies in risk communication. • The use of clear contextual information. For example, communications could specify that flash flooding may occur in areas more prone to the hazard, such as locations near drains or low-lying areas. • Numerical probabilities accompanying uncertainty terminology. For example, adding further detail to messages such as 'Possible (20% chance)'
Limited or confusing graphics/visuals, including a single 'level' to represent threat.	Enhanced use of graphics. • Graphics incorporate warning levels to visually indicate locations at higher risk.
Inconsistent use and understanding of uncertainty and rainfall terminology.	Shared terminology • Simple language. • Standardise terminology used in warnings and briefings to ensure clarity. • Definition of terms such as 'possible' and 'expected'.
Lack of understanding of thresholds of concern and required certainty/lead time.	Co-designed decision support • Collaborative development of decision support tools, warning thresholds and response triggers would make them more user-relevant and improve application in decision-making process. • Provide earlier advice using percentage terms, even if at low probability, to enable more proactive local warnings and response. • Link ensemble guidance (per cent chance of a certain rainfall intensity and duration) to impacts as part of an action plan for response. • Ensure briefings and decision support tools are available to all agencies along the value chain.
Limited public understanding of flash flooding	Public education and awareness • Raise public awareness about the causes and consequences of flash floods. • Improve public understanding of flash flood definitions, risk factors and appropriate responses, especially in high-risk or newly

Gap	Strategy
	urbanised areas to enhance community resilience and reduce response delays.

Other areas for improvement in the flash flood value chain

The case studies identified several areas across the flash flood value chain where improvements could be made. The broad themes were identified through the three case studies. These themes would benefit from being tested across the whole value chain for specific services to confirm their relevance and value generation in the particular case.

- **Observation coverage** - Increased and more targeted observation coverage across the country, particularly in terms of rainfall and water level gauges, would assist communities and emergency management agencies by providing additional and locally relevant real-time information. Current coverage remains sparse in some areas and especially in more remote locations, limiting the ability to monitor and respond effectively to flash flood events.
- **Predictive tools** – Further developments in predictive tools are needed to enhance forecasting accuracy and reliability and translate weather forecast information into usable hazard and impact predictions that can inform warnings and response. Greater forecast specificity for rainfall, including capturing of extreme rainfalls, coupled with local flash flood forecasting systems and improved impact intelligence (such as flash flood mapping) would be advantageous.
- **Roles and responsibilities** - Shared understanding of roles and responsibilities in flash flood management, including related processes and procedures, should be strengthened. The current arrangements are complex and require greater clarity to ensure coordinated and effective response. Bringing key stakeholders together regularly to refresh knowledge and undertake scenario analysis and response exercises would be of value.
- **Decision support information** - Enhanced decision support information, including access to local forecasters, is highly valued. To be most effective, thresholds of concern should be linked to known impacts and provided to forecasters and forecast systems to ensure briefings and warnings are fit-for-purpose.
- **Dissemination of warnings** - The speed of disseminating locally specific warnings to the community should be improved. The adoption of direct triggers, linked to known thresholds and impacts, should be considered to enhance timely communication and response during flash flood events.
- **Support for the development of flash flood forecasting systems** – Advisory support for agencies looking to set up their own systems would be beneficial. This could potentially include the establishment of a community of practice and an update to the resources on the Bureau's Flash Flood Advisory Resource, FLARE.

References

Australian Bureau of Meteorology n.d.-a, Australian Water Outlook, Australian Government, viewed 29 May 2025, <https://awo.bom.gov.au>.

Australian Bureau of Meteorology n.d.-b, Flash Flood Advisory Resource, Australian Government, viewed 29 May 2025, <http://www.bom.gov.au/australia/flood/flashfloodadvisoryresource/>.

Australian Bureau of Meteorology n.d.-c, *High-resolution Regional Reanalysis for Australia (BARRA)*, Australian Government, viewed 29 May 2025, <http://www.bom.gov.au/research/projects/reanalysis/>.

Australian Government 2022, Natural disaster declarations extended, Australian Government, viewed 29 May 2025, <https://minister.homeaffairs.gov.au/MurrayWatt/Pages/natural-disaster-declarations-extended.aspx>.

Australian Warning System n.d., Australian Warning System: A national approach to emergency information and warnings, viewed 29 May 2025, <https://australianwarningsystem.com.au>.

Coleman, C & Sharpe, D 2022, NSW SES sends geo-targeting SMS flood alerts advising of rapidly rising flood waters across the Hunter, viewed 29 May 2025, <https://www.maitlandmercury.com.au/story/7807807/nsw-ses-sends-geo-targeting-sms-flood-alerts-advising-of-rapidly-rising-flood-waters-across-the-hunter/>.

Council of Australian Governments 2018, Intergovernmental Agreement on the Provision of Bureau of Meteorology Hazard Services to the States and Territories, viewed 29 May 2025, <https://federation.gov.au/sites/default/files/about/agreements/intergovernmental-agreement-provision-bureau-meteorology_0.pdf#page=11&zoom=100,0,0>.

Dowdy, AJ, Pepler, A, Di Luca, A, Cavicchia, L, Mills, G, Evans, JP, Louis, S, McInnes, KL & Walsh, K 2019, Review of Australian east coast low pressure systems and associated extremes, Climate Dynamics, vol. 53, pp. 4887–4910.

Ebert, B, Perrels, A, Mooney, C, Hoffmann, D, Tupper, A, Mills, B, Pástor-Paz, J, Liang, X, Msemo, H, Da Costa, J & Lazo, J 2024, Value chain approaches to describe, improve, value and co-design early warning systems.

Ebert, EE, Hoffmann, D & Mooney, C 2024-a, Warning Value Chain Questionnaire and Guide, Zenodo, viewed 29 May 2025, <https://doi.org/10.5281/zenodo.13966993>.

Golding, B, Ebert, B, Hoffmann, D & Potter, S 2023, Preparing for the unprecedented, Advances in Science and Research, vol. 20, pp. 85–90, viewed 29 May 2025, <https://doi.org/10.5194/asr-20-85-2023>.

Maitland and District Historical Society 2022, Bulletin of Maitland and District Historical Society Inc., Volume 29, Number 3, August 2022, viewed 29 May 2025, <https://www.maitlandhistorical.org/resources/Bulletin%20Vol%2029%2C%20No%203%20-%20August%202022.pdf>.

Maitland City Council 2025, Maitland Council embarks on updated floodplain study, viewed 29 May 2025, <https://www.maitland.nsw.gov.au/news/maitland-council-embarks-on-updated-floodplain-study>.

Neal, R & Titley, H 2024, A detailed warning value chain assessment for Storm Eunice, Zenodo, viewed 29 May 2025, <https://doi.org/10.5281/zenodo.12697561>.

Šakić Trogrlić, R, van den Homberg, M, Budimir, M, McQuistan, C, Sneddon, A & Golding, B 2022, Early Warning Systems and Their Role in Disaster Risk Reduction, in B Golding (ed.), Towards the "Perfect" Weather Warning, Springer, pp. 11–46, viewed 29 May 2025, <https://link.springer.com/chapter/10.1007/978-3-030-98989-7_2>.

Seed, A, Leahy, C, Duthie, E & Chumchean, S 2008, Rainfields: The Australian Bureau of Meteorology system for quantitative precipitation estimation and its use in hydrological modelling, in Proceedings of Water Down Under, pp. 661–670.

Su, CH, Eizenberg, N, Jakob, D, Fox-Hughes, P, Steinle, P, White, CJ & Franklin, C 2020, BARRA v1.0: Kilometre-scale downscaling of an Australian regional atmospheric reanalysis over four midlatitude domains, Geoscientific Model Development Discussions, vol. 2020, pp. 1–34.

Titley, HA, Cloke, HL, Stephens, EM, Pappenberger, F & Zsoter, E 2024, Using ensembles to analyze predictability links in the tropical cyclone flood forecast chain, Journal of Hydrometeorology, vol. 25, pp. 191–206, viewed 29 May 2025, <https://doi.org/10.1175/JHM-D-23-0022.1>.

Zanchetta, ADL & Coulibaly, P 2020, Recent Advances in Real-Time Pluvial Flash Flood Forecasting, Water, vol. 12, no. 2, p. 570, viewed 29 May 2025, <https://doi.org/10.3390/w12020570>.