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Warning cultures in practice: Shadow systems in local flood risk governance

Jeff Da Costa [a,*], Hannah L. Cloke [a,b], Jessica Neumann [a], Nathan Salvidge [a]

[a] Department Geography and Environmental Science, University of Reading, RG6 6AB Reading, United Kingdom
[b] Department of Meteorology, University of Reading, RG6 6ET Reading, United Kingdom

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ABSTRACT

Early warning reduces flood risk when forecasts are interpreted and converted into timely local action. In Luxembourg, a nationally centralised system, with no intermediate tier, places the next line of decision making immediately with municipalities. This paper examines how a structured shadow system emerges at the local scale to bridge gaps between national alerts and operational needs. Evidence is drawn from a focus group with municipal officials in a flood-affected community, including a flood-scenario exercise simulating an evolving rainfall event to examine decision-making under uncertainty. Thematic analysis shows that national flood alerts are generic, repetitive, and weakly linked to municipal thresholds for initiating preparedness measures. Ambiguous terminology, colour codes, and broad spatial and temporal framing limit their operational usefulness for local response. Frequent low-level alerts contribute to warning fatigue and erode trust. Officials construct meaning through institutional knowledge, lived experience, peer exchange, and heuristics. These locally embedded practices highlight the importance of scale, showing how municipal knowledge both localises and at times overrides national messages. The configuration strengthens local responsiveness but concentrates interpretive responsibility at municipal level without formal support, which can increase variability across jurisdictions. The analysis points to a need for impact-based, temporally precise, municipality-scale products with clear triggers and guidance co-developed with local officials and potentially residents, so that centrally issued forecasts can be converted into anticipatory action at the local level.

1. Introduction

1.1. Early warning systems

Early Warning Systems (EWS) are a core component of disaster risk reduction, providing lead time to reduce flood losses and save lives [1,2]. Although forecasting accuracy is essential, the effectiveness of a warning also depends on how information is communicated, how responsibilities are organised and whether users are able to respond effectively [3,4,5,6]. In Luxembourg, warnings are issued by Meteolux, the national weather service and complemented by the national flood service AGE (Water Management Administration) and LU-Alert, a mobile platform that disseminates emergency notifications to the public. The same centrally issued forecasts and warnings are made publicly available to all users, including municipalities, who must interpret them according to their own mandates, capacities and operational contexts. When roles are unclear or procedures are fragmented, even accurate forecasts may not lead to early action. Users are more likely to respond when they understand the message, trust the source and know what to do. Delays, overly technical language, or poor alignment between warnings and user responsibilities can reduce the likelihood of action [7,8,9,10].

Design choices in warning systems affect both institutional and individual responses. At the municipal level, local authorities must interpret national alerts, coordinate with emergency services and implement protective measures. How risk is defined and communicated nationally shapes local preparedness, coordination and operational decision-making. Municipal actors must interpret, adapt and contextualise centrally issued information before it becomes operationally useful. The effectiveness of warning systems depends on how users interpret, adapt and apply information within their institutional and geographic context. In many cases, these interpretive practices form shadow systems that link centrally issued alerts with the realities of local preparedness and response.

International guidance encourages a shift from hazard-based warnings, which focus on physical thresholds, toward systems that

* Corresponding author.
E-mail addresses: j.dacosta@pgr.reading.ac.uk (J. Da Costa), h.l.cloke@reading.ac.uk (H.L. Cloke), j.l.neumann@reading.ac.uk (J. Neumann), nathan.salvidge@reading.ac.uk (N. Salvidge).

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communicate the likely impacts of an event and the actions that should be taken. These approaches incorporate probabilistic forecasts and aim to describe what a hazard is expected to cause, rather than what it is [11,12,13]. The World Meteorological Organization identifies impact-based, actionable and user-oriented services as core components of effective multi-hazard early warning systems [6].

Luxembourg's system remains primarily based on physical hazard thresholds, using colour-coded alerts defined by physical criteria such as rainfall totals or river levels. While colour codes can be useful for communicating urgency, their meaning depends on clear and consistent interpretation. In Luxembourg, colours reflect hazard magnitude rather than probability or impact, which limits their decision-making value. By contrast, some systems, such as those used by the UK Met Office and the Environment Agency, apply a risk matrix to determine alert levels, combining severity and probability to support decision-making [14]. These integrated approaches tend to better support decision-making because they link forecasts to specific response options. However, even in these probabilistic and impact-based systems users may not always understand what the colours represent. Studies show that people often interpret colours as indicators of probability, even when they are intended to reflect severity or threshold exceedance [15]. Inconsistencies between system design and user interpretation can reduce the effectiveness of warnings. When users interpret warning colours or messages differently from their intended meaning, the result is inconsistent action and declining confidence in the warning system.

1.2. Municipal responsibilities

In Luxembourg, civil protection operates at both national and municipal levels. Luxembourg does not have an intermediate administrative tier, which positions municipalities as the direct link between national authorities and local populations [16].

The Law of 27 March 2018 on civil security established the *Corps Grand Ducal d'Incendie et de Secours* (CGDIS), a national agency under the Ministry of Home Affairs. It centralised operational fire and rescue services, consolidating previously dispersed brigades and emergency units (CGDIS [17]). CGDIS is responsible for emergency response, including flood interventions that exceed the capacity of a municipality.

Municipalities, meanwhile, retain statutory responsibilities for flood prevention, preparedness and recovery. They are expected to maintain protective infrastructure, plan and budget for equipment, provide information to residents and organise post-event clean-up and support. Municipalities are legally obliged to implement flood protection on their territory, but the law does not specify how or to what extent these measures must be carried out (CGDIS [17]).

As CGDIS operates at the national level, municipalities serve as the interface between national warnings and local response. Their legal responsibilities are broad but lack detailed prescriptions, so interpretation and discretion play a key role. Operational liability lies with CGDIS, while preventive responsibilities remain with municipalities. Municipalities are expected to take proactive measures before an event, while CGDIS intervenes during or after, either upon request or when impacts exceed local capacity. This arrangement creates uncertainty around the timing of action and the handover between local and national actors. This governance structure places a substantive interpretive weight on municipalities, who must translate national warnings into context-specific actions.

1.3. The July 2021 floods in Luxembourg

In July 2021, intense rainfall caused severe flooding across Western Europe, including Luxembourg, where more than 6500 properties were affected and damages exceeded €145 million [18,19]. Impacts were geographically widespread, with municipalities across the country experiencing varying degrees of disruption. This was the first major flood event since the 2018 reform that established CGDIS as the national authority for emergency response. It highlighted the practical challenges that municipalities may face in interpreting and acting on forecasts and warnings, particularly under conditions of uncertainty and limited lead time [20].

Warnings were issued one to two days before the peak rainfall, but local authorities reported that clear, actionable information was only available hours before the event [21]. The event also revealed how municipal decisions depended on judgement, local knowledge and ad-hoc interpretation rather than on structured guidance.

In Luxembourg, significant interpretative responsibility is placed directly on municipalities, shaping how officials make judgments under uncertainty. Municipal staff operate between national forecasts and local action, translating centrally issued warnings into operational decisions within their own constraints. The analysis examines municipal decision-making, focusing on how warnings are interpreted, adapted and acted upon and where institutional or procedural gaps continue to limit anticipatory response.

1.4. Institutional context and analytical focus

The July 2021 floods affected several Western European countries that experienced similar meteorological conditions but operated under different systems for issuing and interpreting weather and flood warnings. In Germany and Belgium, warnings moved through decentralised structures involving national, regional or provincial and municipal authorities [22]. In Luxembourg, warnings were issued by national agencies and interpreted directly by municipalities, with no intermediate administrative tier. These institutional configurations highlight why undocumented interpretive practices may develop where official guidance is limited.

These structural differences can be explained using a value chain approach, which views Early Warning Systems as integrated processes linking forecasting with communication and decision-making [20,23,24,25]. The value chain traces the flow of warning information from forecast producers to end users, emphasising the role of institutional actors in shaping and changing the value of information at each stage. Each link in the chain involves interpretation, coordination and decision-making that determine how, when and by whom action is taken [5].

In decentralised systems, the warning chain typically involves multiple levels of government. Subnational authorities often adapt centrally issued forecasts and warnings and coordinate with local actors. This structure can improve the localisation and relevance of warnings but may also introduce delays or inconsistencies if responsibilities are unclear or fragmented [26].

In centralised systems, fewer actors are involved in the chain. This may reduce the time between forecast and response and simplify communication. However, when local authorities are expected to interpret national warnings without structured support or operational guidance, they may lack the capacity or clarity needed to act effectively [27].

Luxembourg's system is more commonly found in small or island states, where institutional frameworks tend to link national and local levels directly [28,29]. Within Western Europe, a region largely characterised by decentralised governance structures, Luxembourg's configuration is unusual. Its small size and absence of an intermediate make it a particularly revealing case for examining how forecasts are translated into local action and how institutional design influences the practical use of warning information. Comparisons across countries of flood risk management arrangements suggest that capacities to deal with floods and the distribution of responsibilities vary significantly between contexts, which reinforces the need to examine how warning information is interpreted and used within specific national and local governance settings [30]. Recent work further highlights that these contextual differences extend to the procedural and social dimensions of local flood governance, where inclusive and situated practices shape

how risk information becomes actionable [31].

Since 2021, the national forecast and warning framework has been reorganised to combine meteorological and hydrological government plans under a single structure [32]. Meteolux produces meteorological forecasts and the Water Management Authority (AGE) produces river forecasts. These forecasts are shared with CGDIS and the High Commission for National Protection (HCPN) and are made available to the public via *inondations.lu* and *meteolux.lu*. When thresholds are exceeded, the corresponding colour-coded warning is issued and upon request from the HCPN, a national crisis team can be activated by the Prime Minister if broader coordination is required.

The introduction of the LU-Alert platform in October 2024 created a unified national channel for official warning and information messages. The system enables public authorities to issue geo-targeted alerts via cell broadcast and location-based SMS [32]. At the same time, the previous flood-specific terminology (vigilance, pre-alert, alert) was replaced with awareness levels (yellow, orange, red and violet), applied across meteorological and hydrological systems (Table 1). The violet level was added as a new category for imminent danger and is reserved for extreme or rapidly developing events but has not yet been used operationally. The other levels represent increasing degrees of potential or confirmed impact and are linked to standard public guidance.

These arrangements were formalised in the Government Crisis Management Plan for Extreme Weather and Flooding approved in January 2025 [33]. The plan sets out the roles of the forecasting, emergency and coordination bodies and standardises the use of the four awareness levels; yellow (be aware), orange (be careful), red (utmost vigilance) and violet (imminent danger) for all weather- and flood-related hazards. In practice, the visual and informational presentation of alerts currently remains inconsistent. Warnings appear differently across inondations.lu, meteolux.lu and LU-Alert and some platforms do not display the full information contained in the official plan (Appendix A). Table 2 summarises the national awareness levels, rainfall and flood thresholds and the associated behavioural guidance, adapted from the Governmental plan for hydrometeorological hazards [33]. These classifications provide the reference framework for the issue and interpretation of forecasts and warnings in Luxembourg. The analysis examines how this institutional configuration leads to the formation of shadow systems in which local officials interpret and adapt national warnings to make them operationally more meaningful.

Fig. 1 National warning structure for extreme weather and flood hazards in Luxembourg (Adapted from the Governmental Plan for Hydrometeorological Risk, [33]). (A) Common vigilance and warning levels defined jointly by Meteolux and the Water Management. The progressive scenario (yellow, orange, red) represents increasing levels of potential risk and public vigilance. The imminent scenario (violet) corresponds to an acute danger requiring immediate action, to be declared only in exceptional cases of extreme and rapidly evolving phenomena (e.g. tornado). The violet stage has been defined in policy but not yet applied operationally. (B)Rain hazard; quantitative thresholds ($\geq$ 31–45 l/m^2 in 6 h / 41–60 l/m^2 in 12 h / 51–80 l/m^2 in 24 h) and corresponding possible consequences and behavioural advice for orange and red warning levels issued by Meteolux (C) Flood hazard – hydrological alert thresholds (exceeding pre-alert or alert levels) and related consequences and behavioural advice for orange and red vigilance stages coordinated by the Service de prévision des crues (Flood Prevention Service).

1.5. Interpreting warnings at the local level

Flood preparedness at the municipal level depends on how authorities interpret and act on national warning information, which is often too general for local needs [34,35]. Municipal actors rely on local knowledge, past experience and undocumented practices. They monitor landmarks, assess drainage and draw on prior events to guide decisions [36]. Ensemble forecasts are rarely used without contextual interpretation and officials often supplement national data with citizen observations and internal reporting to improve situational awareness [37,38]. These practices highlight the need for warning products designed in collaboration with local stakeholders to support operational decision-making alongside technical precision [39].

The language of warnings directly shapes response decisions [15]. Terms such as “moderate” or “high risk” and colour-coded alerts often lack clear operational meaning. At lower alert levels (yellow or orange), this can create ambiguity, while severe alerts such as red warnings are more consistently acted upon, particularly when accompanied by explicit guidance on protective actions [40,41,42]. When warnings are vague or lack clear timing and instructions, both officials and the public may delay their response. The absence of escalation indicators or guidance on when to act can cause hesitation, especially during fast-evolving events [43].

Variability in successive weather forecasts, often described as forecast jumpiness, can diminish user trust and interfere with effective decision-making [44,45]. When forecasts shift in timing or magnitude across consecutive updates, even if overall accuracy remains intact, users may perceive the information as unreliable and become less likely to act on it. This reduction in trust is particularly pronounced when changes occur without explanation or contextualisation. Inconsistencies between forecast models and the warning messages issued by authorities can also undermine public confidence, leading to reduced compliance with safety recommendations and lower perceptions of forecast quality [46].

Repeated warnings without observable impacts can reduce effectiveness [47]. When local authorities receive multiple low-level alerts, that are not followed by visible flooding or significant disruption, they may become desensitised and pay less attention to subsequent messages [48]. This process, referred to as alert fatigue, has been shown to erode trust in warning systems. Uncertainty in warnings, if not clearly communicated, can further weaken credibility and delay protective action. Studies show that decision-makers struggle to act on forecasts when the presentation of uncertainty is too technical or disconnected from their operational thresholds [7,49].

Table 1
National warning structure for extreme weather and flood hazards in Luxembourg (Adapted from the Governmental Plan for Hydrometeorological Risk, (Le Gouverenment du Grand Duche de Luxembourg, 2025)).(A) Common vigilance and warning levels defined jointly by Meteolux and the Water Management. The progressive scenario (yellow, orange, red) represents increasing levels of potential risk and public vigilance. The imminent scenario (violet) corresponds to an acute danger requiring immediate action, to be declared only in exceptional cases of extreme and rapidly evolving phenomena (e.g. tornado). The violet stage has been defined in policy but not yet applied operationally. (B)Rain hazard; quantitative thresholds ($\geq$ 31–45 l/m^2 in 6 h / 41–60 l/m^2 in 12 h / 51–80 l/m^2 in 24 h) and corresponding possible consequences and behavioural advice for orange and red warning levels issued by Meteolux (C) Flood hazard – hydrological alert thresholds (exceeding pre-alert or alert levels) and related consequences and behavioural advice for orange and red vigilance stages coordinated by the Service de prévision des crues (Flood Prevention Service).

A	Warning Levels	
Progressive Scenario	Yellow	**Be aware (low risk / potential danger)**
	Orange	**Be careful (medium risk / danger)**
	Red	**Utmost vigilance (high risk / significant danger)**
Imminent Scenario	Violet	**Imminent danger / Immediate action**

B	Hazard			
Rain	**Orange**	31-45 l/m² in 6 hours or 41-60 l/m² in 12 hours or 51-80 l/m² in 24 hours	**Red**	(> 45 l/m² in 6 hours or > 60 l/m² in 12 hours or > 80 l/m² in 24 hours)
	Possible Consequences		**Possible Consequences**	
	• Heavy rainfall that may cause/trigger flooding, which may affect the economic life of certain sectors of activity. • Possible flooding with fast currents and slope runoff in the areas indicated on the heavy rain hazard maps. • Local overflow of streams and ditches. • Risk of overflow of sewerage networks. • Difficult road traffic conditions.		• Very heavy rainfall that can cause/trigger flooding, which can affect people's economic life and activities for several days. • Severe flooding, as well as strong slope runoff with fast current, even in areas that are rarely flooded. • Locally rapidly rising water levels in otherwise calm streams. • Extremely difficult road conditions. • Risk of overflow of sewerage networks. • Risk of damage to the electricity grid.	
	Behavioural Advice		**Behavioural Advice**	
	• Continuously follow the weather forecasts on the www.Meteolux.lu website. • Consult the heavy rain hazard maps on map.geoportail.lu to find out if your location could be affected. • Charge your phone and, if available, a "power bank" to use the mobile phone in an emergency even without to be able to recharge power access. • Avoid shore areas and under all flooded paths (beware of aquaplaning). **In vulnerable areas:** • Starting from the lowest room to the top bring your goods that are damaged in safety and monitor the rise of the water. • Close windows, shutters and shutters of floors that may be flooded and secure the house or outside with sandbags, boards or mobile guards. Make sure that the water drain grates are free and, if necessary, check whether your backwater flap works. • Prioritize the removal of environmentally hazardous substances from the flood hazard area. Take in the rooms that are most likely to be flooded electrical appliances from the power grid and turn off the heating. • Before you travel, find out about any difficulties on the roads. Be aware of any detours and roadblocks.		• Make sure that you have implemented the recommendations of the orange warning level. • Stay indoors if possible and continuously follow the weather forecasts on the www.Meteolux.lu website. • Avoid any unnecessary stay in the affected areas. If you absolutely have to go somewhere, be extremely careful and inform your relatives of your departure and destination. • Be aware of any detours and road closures. • Avoid shore areas and flooded paths under all circumstances (beware of aquaplaning). • If the power is out or turned off, use battery-operated devices such as your smartphone, a battery-operated radio or a car radio. **In vulnerable areas:** • In flood-prone areas and even in areas where flooding rarely occurs: Take all necessary precautions as early as possible to protect your goods from the rising water. • Stay away from unprotected openings. Do not enter rooms at risk of flooding (basements, garages, beware of electric shocks). • In the event of an emergency, flip the circuit breaker of the power supply for the entire house. Have a flashlight and a supply of drinking water ready. • Stay calm and act deliberately: Saving people takes precedence over the preservation of material assets. Facilitate the work of the emergency services who propose an evacuation to you and heed their advice so as not to endanger your life or that of the emergency services.	

C	Hazard			
Flood	**Orange**	Danger, exceeding the pre-warning level, risk of local flooding	**Red**	Great danger, exceeding the alert level, risk of widespread flooding
	Possible Consequences		**Possible Consequences**	
	• Local flooding that could affect individual sectors of the economy • Possible flooding in the usual floodplains • Difficult road traffic conditions		• Widespread flooding that can affect people's economic life and activities for several days • Large-scale flooding, including in areas that are rarely flooded • Extremely difficult road traffic conditions • Risk of overflow of sewerage networks • Risk of damage to the electricity grid.	
	Behavioural Advice		**Behavioural Advice**	
	• Track the current flood warnings on www.inondations.lu and the weather warnings on www.Meteolux.lu or on the radio or television. • Check the Flood hazard maps on the website geoportail.lu , topic water, whether your area could be affected. • Charge your phone and, if available, a "power bank" to use the mobile phone in an emergency even without to be able to recharge power access. **In flood-prone areas:** • Turn off the electricity in all rooms that are connected by flood endangered. Turn off your heating and interrupt the gas or oil supply. Make sure that your oil tank is adequately secured. • Pack all important personal documents and documents and bring them together to a location outside the danger zone. Keep a sleeping bag, rubber boots and a flashlight ready. Think about your Medication. • Store environmentally hazardous substances outside of the flood hazard area. • Get your car out of the danger zone (only, if there is still enough time for it). • Read the flood protection and Evacuation plan of your building (if any) attentively.		• Make sure that you have implemented the recommendations of the orange warning level. • If possible, stay indoors and follow the current flood warnings on www.inondations.lu and the weather warnings on www.Meteolux.lu or on the radio or television. • Avoid any unnecessary stay in the affected areas. If you absolutely have to go somewhere, be extremely careful and inform your relatives of your departure and destination. Be aware of any roadblocks and detours. **In flood-prone areas:** • Avoid flooded paths and bank areas at all costs. • If the power is out or turned off, use battery-operated devices such as your smartphone, a battery-operated radio or a car radio. • Do not enter rooms at risk of flooding (basements, garages, beware of electric shocks). • Facilitate the work of the emergency services who propose an evacuation to you and heed their advice so as not to endanger your life or that of the emergency services. • Stay calm and act deliberately. Saving people takes precedence over the preservation of material assets. Please note that the fire brigade does not pump out flooded rooms during the flood • Pumping out during flooding could cause different pressure conditions and damage the walls.	

Table 2
Composition of the focus group. Ten officials participated, representing key municipal departments with responsibility for preparedness, communication, technical services and response. Code assignment for transcript.

Department	Role	Code
Mayor's Office	Mayor	BM1
Aldermen"s College	Alderman	1CE
Aldermen"s College	Alderman	2CE
Municipal Administration	Representative	RC1
Communication Department	Representative	SC1
Communication Department	Representative	SC2
Technical Services	Representative	ST1
Security Services	Representative	SS1
Sustainable Development	Representative	SD1
Municipal Administration / First Responder	Representative	RC2

Beyond the content of warnings, their source and credibility also influence how they are received and acted upon [50]. Trust in the source of information strongly shapes local response. Municipal staff and residents often trust local sources such as city officials or local media more than national meteorological agencies, especially when the latter are perceived as distant or unresponsive [51]. To assess risk, local officials commonly cross-check official bulletins, media updates, citizen observations and mobile apps to balance perceived threat with the feasibility of response [52,53].

Preparedness at the local level is shaped by how warnings are interpreted, trusted and contextualised [54]. Clear communication, institutional trust and flexibility for local judgement are key to ensuring effective warning response. Interpretation itself represents an act of responsibility, as local authorities must translate generalised information into context-specific action under uncertainty. This interpretive responsibility extends beyond reading warnings to deciding when and how to act, often with limited guidance or support from higher levels of governance. Recent work emphasises the role of geographical imaginaries and local context in disaster governance, showing that risk information becomes meaningful only when embedded in locally relevant social and geographic contexts [55].

Despite substantial research on warning system design, forecast communication and public response [3,56,57,58,2], existing frameworks for flood risk governance and early warning largely conceptualise the warning chain in terms of structures embedded within established decision-making processes. Much less attention has been given to the interpretive work carried out by municipal officials who sit between national forecast providers and local populations [54,20,36], particularly in settings where local authorities are directly responsible for preparedness and recovery. This gap limits understanding of how warnings are made operationally meaningful at the municipal level and how these interpretive practices interact with specific governance configurations that shape responsibilities, authority and decision-making [23,24,25].

This paper addresses that gap by conceptualising municipal interpretive practices as shadow systems that link national weather and flood warnings with local preparedness and response in Luxembourg. Methodologically, the paper combines a value chain perspective with a scenario-based focus group to analyse how municipal officials interpret, adapt and act on national warnings under conditions of uncertainty. Applied contributions include clarifying how these shadow systems both support and strain the existing warning framework and identifying where warning products and governance arrangements could better align with municipal needs. This analysis examines how municipal officials interpret national weather and flood warnings in practice and how these interpretive strategies shape the operational value of warning information within Luxembourg's governance context.

2. Methods

2.1. Research design

We used a qualitative focus group to investigate how municipal officials in Luxembourg interpret and act on hydrometeorological warnings. Focus groups help explore collective practices by surfacing shared interpretations and how they emerge through discussion (Krueger & Casey, [59]). We needed officials directly and indirectly responsible for preparedness and response. The smaller group setting enabled in-depth discussion of thresholds and decision logic. We combined scenario-based tasks, written reflection and open discussion so participants could use different modes, compensating for variation in comfort with speaking. Qualitative methods allow access to experiences and perceptions that structured surveys cannot.

The session included a scenario-based simulation in which participants were presented with realistic, time-structured weather and river-level information over three "days". The simulation served as a situational judgement task, allowing comparison between how they had acted during past floods and how they would respond under an evolving scenario. Situational judgement tasks and role-play simulations are established approaches for eliciting tacit decision criteria and exploring judgement under uncertainty in hydrometeorological and disaster governance research [60,61,36,62]. Highlighting these processes was important for our analysis because it revealed thresholds for action and demonstrated how local knowledge could inform improvements to flood preparedness. The focus group session combined five structured activities designed to better understand the participants' interpretations of forecasts and warnings. First, an association exercise captured immediate reactions to the term "warning" using individual sticky notes, followed by brief plenary discussion. Second, a handout exercise asked each participant to write what the colour levels (green, yellow, orange, red) meant to them for Meteolux (weather) and AGE (floods) before comparing entries (see Tables 4–6). Third, participants mapped their preferred information sources for weather and flood forecasts, producing a Municipal Forecast and Warning Ecosystem diagram (Fig. 1) that included official, commercial, independent, media and heuristic nodes. Fourth, they reflected on their experiences during the July 2021 floods, noting what information had been available, how it was used and what was missing. Fifth, a staged scenario simulation presented officials with typical Meteolux rainfall warnings and AGE flood bulletins over three "days," combining real products with adapted details. Each "day" was followed by group discussion of how they would interpret the information, what actions they would consider and how they would communicate with residents and partners. Across activities, individual reflection preceded moderated discussion. Situational judgement tasks and role-play simulations are established methods in disaster and hydrometeorological research for exploring decision criteria and action under uncertainty [36]. At the time of the focus group, held on 4 March 2025, the Water Management Authority (AGE) had updated its flood-warning terminology approximately ten weeks earlier, on 20 December 2024, in connection with the launch of the LU-Alert system. Participants were unaware of this change until shown example bulletins. Results report only the observed effects of the new vocabulary on their operational reading.

2.2. Setting and participants

The focus group was held in March 2025 in a Luxembourg municipality significant flooding in July 2021. The anonymised municipality is mid-sized and represents a typical municipal configuration as described in Section 1.2. Ten officials took part, representing the mayor's office, aldermen's college, municipal administration, communication, technical services, security, sustainable development and first response. Their positions meant they were directly and indirectly responsible for interpreting warnings, monitoring conditions, or coordinating measures.

Table 3
Thematic framework developed from the focus group transcript. Categories and subcategories reflect how municipal officials described public responses to warnings, interpretation of forecasts, understanding of terminology and information dynamics. Only the four categories most directly related to the research aim are presented.

Category	Subcategory
1. Public Response to Warnings	a. Warning overload and fatigue b. Disinterest and alert annoyance c. Disengagement from warnings d. Erosion of trust in alerts
2. Forecast Interpretation and Local Context	a. Challenges in forecast interpretation b. Perceived forecast uncertainty c. Understanding forecast thresholds d. Need for local forecast context
3. Warning Terminology and Message	a. Unclear warning terminology b. Interpretations of Warning Levels c. Repetitive or vague messaging d. Lack of actionable communication
4. Information Dynamics and Verification	a. Catastrophising and risk amplification b. Spread of misinformation c. Trust in information sources d. Multi-source verification

Participants' identities were anonymised and each role was assigned a code used in the presentation of results and transcripts (Table 3).

A purposive sampling strategy was employed. Recruitment began through the mayor's office, which compiled an initial list of relevant officials circulated via email. Follow-up exchanges ensured that different roles were represented so that the group reflected the range of responsibilities relevant to flood preparedness. This was a targeted selection, complemented by snowballing within the municipality to identify additional relevant officials. The presence of senior figures, such as mayors, may have influenced discussion, though alternating written tasks with moderated rounds ensured that all participants contributed before open discussion. Participation took place during working hours and was considered part of professional duties. No financial incentives were provided.

2.3. Procedure and materials

The focus group session lasted approximately 4.5 h. It was moderated by the lead researcher, who also designed the activities and supported by a research assistant who took notes and facilitated logistical aspects such as timekeeping, recording and material distribution. Participants were reminded of ground rules at the outset. That there were no right or wrong answers, contributions would be anonymised and all participants would have equal opportunity to speak. To manage dynamics, the moderator alternated open discussion with structured rounds of questioning, ensuring that both more vocal and quieter individuals were heard. Particular attention was given to power dynamics, with structured turns and questions designed to prevent dominant voices from steering the discussion, while leaving space for all participants to contribute. Participants were also given the option to note responses in writing if they preferred not to speak at length.

Throughout the session, participants were provided with printed handouts. These handouts contained short written questions for each activity, such as *"What words do you associate with 'warning'?"*; *"How do you interpret the different alert levels?"*; *"What sources of weather information do you prefer and why?"*; and *"Did you feel you had the information you needed during the 2021 floods?"* Participants wrote short notes in the handouts before each discussion. These responses were not formally coded but were preserved as. Their main purpose was to stimulate memory, ensure that each participant engaged with the exercise and provide a record of individual reflections that could be drawn on in group discussion. The session closed with open reflections on current warning systems and feedback on recent reforms.

2.4. Data collection and ethics

Ethical approval for the study was granted by the University of Reading School of Archaeology, Geography and Environmental Science Research Ethics Committee (Ref. 2024). All participants received information sheets in advance, in their preferred language (Luxembourgish, German, French) and provided written consent before the session began. The information sheets explained the aims of the study, that participation was voluntary, that the session would be audio-recorded and that anonymised data could be used in publications, conference presentations and other research outputs. Consent covered participation during working hours, audio recording, anonymised quotation and academic outputs. The consent form also specified that participants could withdraw their data until 15 April 2025, after which removal would no longer be possible because of the progress of the research. To preserve confidentiality, no comments were attributed to individuals and quotations were anonymised by role codes without identifying the municipality.

The session was conducted in Luxembourgish, with code-switching into French and German, reflecting typical practice in local administration. All materials were provided in German, French and Luxembourgish. The session was audio-recorded and supplemented by detailed notes in Luxembourgish taken by the research assistant. The lead researcher translated and fully transcribed the recording into English. Notes taken during the session were used to check for accuracy.

2.5. Analytical approach

The English transcript was analysed thematically, following Braun and Clarke's [63] framework. Coding was conducted line by line in Excel by the lead researcher. Initial codes were generated inductively from the data, then grouped into subcategories and refined into broader categories. Analysis focused on identifying how participants described their interpretation of warnings, their use of terminology and thresholds, their trust in different information sources and the role of local heuristics. Written notes from handouts were preserved as context but were not formally coded. The comparison of retrospective accounts of 2021 and real-time scenario discussions allowed triangulation between past experience with hypothetical decision-making. This was important because past experiences continue to shape how officials interpret present situations and anticipate future ones. This comparison revealed consistencies and shifts in decision-making logic between lived and hypothetical scenarios, strengthening internal triangulation.

Quotations reported in this paper were translated into English while maintaining meaning and tone. The coding process generated a structured framework of categories and subcategories that captured recurring themes in how participants described forecast interpretation, warning terminology, trust in information and the broader institutional context. We refined the framework until it provided a coherent basis for reporting, focusing on the categories most directly related to how municipal actors interpret and act on warnings (Table 3).

3. Results

The findings reveal a gap between how national warnings are designed and how municipal actors interpret and adapt them in practice to make them operationally useful. Officials filtered and reframed warnings using local knowledge, peer verification and lived heuristics. They reworked alerts through undocumented practices, practical judgement and experience-based monitoring.

3.1. Public response to warnings

Warnings carried a wide range of meanings for municipal officials, from emotive associations such as *"danger"* and *"fear"* to concrete references such as *"flood," "apps,"* and *"112"*.

3.1.1. Warning fatigue and annoyance

Participants emphasised the volume and tone of warnings, which they said produced fatigue, irritation and eventually disengagement. RC2 remarked:

"There are too many warnings. Once there is an actual emergency, nobody takes them seriously. It rains for a day…yellow warning. There is a lightning flash…red warning. One cannot take it seriously anymore."

BM1 gave a similar example, highlighting repeated false alarms:

"We received wind warnings for gusts up to 100 km/h, ten times already! And it has never been the case.".

Annoyance was also linked to the practicalities of communicating with residents. CH1 noted that frequent alerts created unrealistic expectations, saying they could not continually advise people to clear their basements for example. Similarly, other said the frequency of notifications led them to ignore or even disable the LU-Alert mobile app. SC1 described:

"Indeed, it can really get on your nerves… It annoyed me so much that I deleted it from my phone. Downright!"

Humour was also used to underline frustration. BM1 suggested that a warning could be titled *"Moutarde après dîner"* (mustard after dinner), a French idiom meaning "too late to be useful". Participants used this to emphasise that alerts sometimes arrived after key decisions had already been taken.

3.1.2. Disengagement and trust Erosion

Most said that they no longer paid close attention to official warnings (LU-Alert, Meteolux) and instead prioritised sources they found more useful for municipal decision-making. They explained that they ignored certain alerts altogether, particularly those they considered obvious or generic. Some described warnings as equivalent to ordinary forecasts rather than urgent communications. SC1 commented:

"I also think that the word 'warning' is not appropriate for a situation like that, it is more like a weather forecast. I take an umbrella with me… because at the moment warnings like that are very frequent from Meteolux."

Others summarised the limited operational effect of alerts on local action, with ST1 stating that they did not change municipal decisions. They relied on alternative sources such as Regenradar, MeteoFrance, wetter.de, MeteoBoulaide and water-level apps like *Meine Pegel*, as well as non-codified channels through local fire and rescue. Some questioned the credibility and clarity of official bulletins, particularly Meteolux outputs relayed through LU-Alert. CH1 remarked:

"Meteolux is irrelevant, we could have said this ourselves."

During the scenario exercise, BM1 and RC1 both dismissed the bulletins as unhelpful or repetitive, noting that successive alerts offered little actionable information and were issued too frequently to support decision-making. Participants said that repeated alerts, especially at lower warning levels, made it harder to see which situations actually required action. When the wording of alerts did not reflect what they observed on the ground, they relied instead on their own judgement and experience.

3.2. Forecast interpretation and local context

Participants focused on how rainfall forecasts and colour-coded alerts were interpreted in practice. Across activities, four issues emerged: difficulty with rainfall values, perceived forecast inconsistency, confusion over thresholds and lack of geographical context.

3.2.1. Challenges in forecast interpretation

When reacting to Meteolux rainfall bulletins, several explained that values in litres per square metre did not help them decide what to do. Officials said the units were technically clear but not easily related to rivers, catchments, or municipal measures. BM1 illustrated this gap by noting that moderate rainfall totals such as 15–20 l/m^2 could already raise river levels by about one metre within a day, which they felt did not match the official warning colour category. Participants said they could not easily translate such values into expected river levels and instead relied on local knowledge, such as travel times between river gauges and settlements. BM1 explained:

"From (upstream municipality A) to (municipality) it takes about seven hours and then from (upstream municipality B) to here another two. But that information you will not find in any app."

The mayor added that official forecasts systematically ignored urban discharges into the river, which from experience could raise levels sharply within hours. This absence was described as a major blind spot in national guidance. SS1 summarised this frustration, saying:

"We have to calculate the weather ourselves … we sit here with the phone, watch the clouds move."

This was described as necessary improvisation in the absence of what they considered actionable official guidance. Such adjustments formed part of their routine monitoring, linking national information with locally observed conditions and past experience.

3.2.2. Perceived forecast uncertainty

Frequent changes in rainfall forecasts were described as a key source of uncertainty. They explained that it was unclear whether the figures referred to full-day totals or to separate periods and that repeated updates with similar values could in reality represent much higher cumulative rainfall. This inconsistency reduced confidence in the forecasts and made them harder to apply in practice.

"Forecasts change like that?" (BM1).

Forecast variability created hesitation about when and how to act. To compensate, they routinely compared information from multiple sources. Meteolux forecasts were regarded as useful but too broad for local purposes, while LU-Alert updates were considered irregular in timing and content. Foreign platforms such as Météo-France and wetter.de were often preferred because they were seen as more precise for Luxembourg. By contrast, forecasts from the German Weather Service were mentioned less frequently and described as less relevant, as they felt they rarely shaped rainfall patterns in Luxembourg. Uncertainty was described in terms of frequent changes that created hesitation about when and how to act.

3.2.3. Understanding alert levels

Colour-coded alert levels were another focus of discussion, particularly the ambiguity of the interpretation of the yellow alert level. Most said that although the colour sequence was familiar, there was little guidance on how to translate it into concrete action. Several officials explained that the levels appeared as fixed categories without clear operational thresholds, leaving uncertainty about when resources should be deployed. Some described the lower levels as offering almost no actionable information and said that red alerts often arrived only once flooding was already visible. 1CE noted that the practical value of any alert lay in whether it clearly indicated when to start protective measures, adding:

"Ultimately, isn't it so that people want to know when to put sandbags in front of their garages, that is what counts."

They wanted warnings to state clearly when resources should be mobilised. They explained that colour-coded alert levels were treated as fixed values but carried little operational meaning unless directly linked to specific protective actions.

3.2.4. Need for local forecast context

Forecasts need to be framed at the municipal scale rather than at national level. They explained that official bulletins often covered large areas, such as entire river basins or the country divided into north and south, while their own responsibilities concerned individual municipalities. Several officials noted that this broad spatial framing limited the relevance of the information for local preparedness. They also said that some of the terminology used in warnings did not correspond to observed conditions, as flooding could occur locally before official alert thresholds were reached for warning issuance. BM1 said that local

impacts were already visible before they were reflected in the official warnings:

"For us the word 'minor flooding' has already an influence…we already have flooding and the river has not burst its banks yet."

Participants further emphasised the importance of timing, explaining that they needed to know when information became operationally relevant for preparedness. RC2 asked at what point forecasts become actionable for local response:

"The question is rather, at what point is the information useful to do something in advance?"

To compensate for the lack of municipal detail, officials relied on their own heuristics, estimating river-travel times, consulting www.inondations.lu (Official flood portal) and using apps such as *Regenradar* to monitor rainfall in real time. They said that national forecasts were too coarse to guide specific actions and therefore based their interpretation on local rivers, streets and timing.

3.3. Warning terminology and message

Participants' discussions about warning terminology highlighted the gap between official definitions and their own operational interpretations and a preference for process-oriented phrasing that they considered clearer and more flexible. Entries from the handout exercise are summarised in Tables 4–6.

3.3.1. Unclear warning terminology

The wording of official bulletins was discussed and several expressions were deemed too vague to support operational decisions. They explained that phrases such as "moderate rain" or "awareness level" were difficult to interpret, especially when accompanied by numerical rainfall values that lacked context. BM1 said that the language used in these descriptions did not match the meaning implied by the colour codes:

"I find the wording inappropriate: 'moderate rain, 15–20 l/m^2'. It does not fit with the colour."

Participants also questioned newer terminology that replaced process-oriented terms with broader danger-based categories. They explained that expressions such as "medium danger" or "important danger" provided less practical guidance than earlier labels like "pre-alert" or "minor flooding." SS1 noted that the older terminology allowed more flexibility in communication:

"A pre-alert can be withdrawn, but the word danger … you cannot withdraw it. It is unfolding."

They continued to rely on familiar, process-based terms because these conveyed stages of escalation and could be adjusted as conditions evolved. The new vocabulary, by contrast, was perceived as static and less adaptable to local response needs. This change was seen as reducing clarity in preparedness communication. A summary of how participants interpreted these terminology changes is presented in Table 4.

3.3.2. Interpretations of warning levels

Participants said that the colour-coded alert system was presented as a straightforward way to communicate warning levels, but in practice its meaning was inconsistent and difficult to apply. Handout entries indicated that officials often equated yellow with a normal or monitoring phase, orange with the first stage requiring action and red with a late stage when flooding was already under way. Several noted that this interpretation differed from the official definitions, which classify yellow as potential danger and orange as danger (Table 5). BM1 said that this difference reflected how the colours were used in practice:

"The yellow level is art for art's sake. Orange informs on potential warning and red is danger."

Yellow was described as carrying little or no operational weight, orange as the point at which preparedness activities began and red as coinciding with flooding already in progress. SD1 summarised this interpretation in simple terms:

"Yellow means it could, orange means it is there and can get worse."

Others said that red alerts were generally issued only once impacts were visible and one participant noted that red was perceived as exceeding the formal scale of seriousness. Participants said that the meaning of each colour also extended to its expected impacts. They explained that yellow alerts were issued so frequently that they carried little practical effect, serving mainly as a reminder to monitor conditions. Orange was consistently associated with the first signs of flooding and the need to prepare local measures, while red was seen as corresponding to severe flooding already in progress rather than advance notice. Officials added that, in practice, the colour system was interpreted through experience and local observation. Differences between official terminology and participant interpretations, together with the associated expected impacts, are summarised in Tables 5 and 6.

3.3.3. Repetitive or vague messaging

Official bulletins were often repetitive, generic and lacked operational detail. Several noted that the messages appeared to be automatically generated, with little variation in wording across events. BM1 said that the content frequently sounded identical from one situation to the next, giving the impression that it was produced automatically. It was also mentioned that the temporal layout added to the confusion. They explained that rainfall amounts were usually listed for morning, afternoon and evening without clarifying whether these figures were cumulative totals or separate periods. ST1 said that this structure was too general to be of practical use for planning at the municipal level. 1CE said:

"Nobody remembers this."

Table 4
Flood warnings: terminology update by the Water Management Administration (AGE), January 2025. Left column shows legacy terminology (pre-2025), centre column shows the updated labels introduced in 2025 and right column summarises how participants perceived the change in meaning.

Warning Level	**Old terminology** (AGE pre-2025)	**New terminology** (AGE 2025)	**Perceived change in meaning** (participants)
Green	Normal phase	Normal phase	• Unchanged: accepted as baseline
Yellow	Vigilance phase	Yellow Awareness Level	• Reframed as *"potential danger"* but still vague
Orange	Pre-alert phase (risk of minor flooding)	Orange Awareness Level (medium danger)	• Major change: *"minor flooding"* replaced by *"danger"*; • less precise and less reversible. • *"danger cannot be withdrawn"*
Red	Alert phase (major flooding)	Red Awareness Level (important danger; major impacts)	• Shift toward generic danger language • Lost specificity about flood stages

Table 5
Official vs participant interpretations of warning terminology.

Warning level	Rainfall warnings Official terminology	Rainfall warnings Participant interpretations (representative)	Flood warnings Official terminology before 2025	Flood warnings Participant interpretations (representative)
Green	**No danger**	Pre-filled as *"no danger"*; not discussed	**Normal phase** / No danger	Pre-filled as *"no danger"*; not discussed
Yellow	**Potential danger**	*"Slight risk," "watch out," "pre-alert,"* but also *"normal" / "no danger"*	**Vigilance phase** / Potential risk	*"Pre-alert," "possible danger,"* but often *"nothing" / "normal"*
Orange	**Danger**	*"Torrential rain," "danger," "be prepared"*; first actionable stage	**Pre-alert phase** / Minor flooding	*"Preparedness," "first floods," "risk established"*
Red	**Extreme danger**	*"Highest alert," "real danger," "land under"*; seen as late	**Alert phase** / Major flooding	*"Major floods," "imminent flood risk," "red alert"*; impacts already unfolding

Table 6
Official vs participant interpretations of expected impacts at each warning level.

Warning Level	Official Rainfall Warnings: expected impacts	Rainfall warnings ***Participant-perceived impacts*** (representative)	Flood warnings ***Official expected impacts***	Flood warnings ***Participant-perceived impacts*** (representative)
Green	No impacts	Accepted baseline; not discussed	No impacts	Accepted baseline; not discussed
Yellow	Minor disruption possible; awareness advised	*"Almost no impact," "little rain," "normal"; monitoring only*	Vigilance phase; possible minor flooding	*"No impact for population," "river rises slightly," "levels monitored"*
Orange	Significant disruption; possible local flooding, sewer overflow, difficult driving	*"Torrential rain," "danger likely," "road closures"*; impacts for population and services; preparedness	Pre-alert exceeded; minor flooding likely	*"Levels rise significantly," "first floods," "local flooding"*; preparedness starts
Red	Severe disruption; widespread flooding possible	*"Flooding," "roads closed," "highest danger," "stay at home"*	Alert phase; generalised flooding expected	*"Large floods," "significant damages," "country-wide flooding"*; impacts already unfolding

Such repetition made bulletins difficult to recall and contributed to the perception that they were generated from templates, which undermined their credibility. Officials said that when information is presented in the same format each time, without reference to local consequences or clear transitions between alert levels, it risks being disregarded. They added that messages repeated too often tended to lose urgency and were ignored unless clearly linked to local risks. Several also observed that this automated format reflected a broader shift toward standardised outputs but one that reduced the operational value of the information in municipal settings.

3.3.4. *Lack of actionable communication*

Participants' strongest concern was the lack of clear, actionable guidance in official bulletins. Several said that the messages described current conditions but did not specify what protective measures should be taken or when these should begin. This created uncertainty about how and when to act. BM1 said that bulletins should have contained direct statements when flooding was inevitable, such as:

"The flood is coming."

The importance of receiving timely information that clearly indicated when action should start was emphasised as being of particular importance. They explained that, in the absence of a decisive message by midday 14 July 2021, local activation was delayed. BM1 noted that the continuing uncertainty left communities waiting for confirmation rather than preparing immediately:

"Everybody is still full of hope."

The lack of guidance on the transition between orange and red warning levels was identified as a key gap. Officials said that residents respond to specific and concrete cues, for example, whether and when to deploy sandbags. As noted earlier in Section 3.2.3, 1CE explained that people mainly look for such signals to know when protective actions should begin, a point echoed by several participants. Officials said that once the term *"sandbags"* is used, residents immediately recognise the need for u action.

Municipal representatives also described the need to adapt vague national bulletins into clearer, multilingual messages for local audiences. RC2 said that important information was routinely published in the three official languages of the country and in English to ensure accessibility. This translation and reformulation work created additional work for municipalities, requiring them to turn generic alerts into locally relevant and actionable messages.

Officials said that, without clear criteria indicating when to act, they relied on their own judgement. Across the group, warnings were described as informative but not directive, obliging municipalities to interpret and reframe them to make the messages operationally meaningful.

3.4. *Information dynamics and verification*

Participants mapped their information environment as a Municipal Forecast and Warning Ecosystem (Fig. 1). Fig. 1 caption notes these classes explicitly, with green lines denoting the official chain. These connections formed a hybrid system in which officials routinely cross-checked multiple inputs. They explained how they navigated this environment, noting shifts in tone, the role of social media, varying levels of trust in sources and their verification practices.

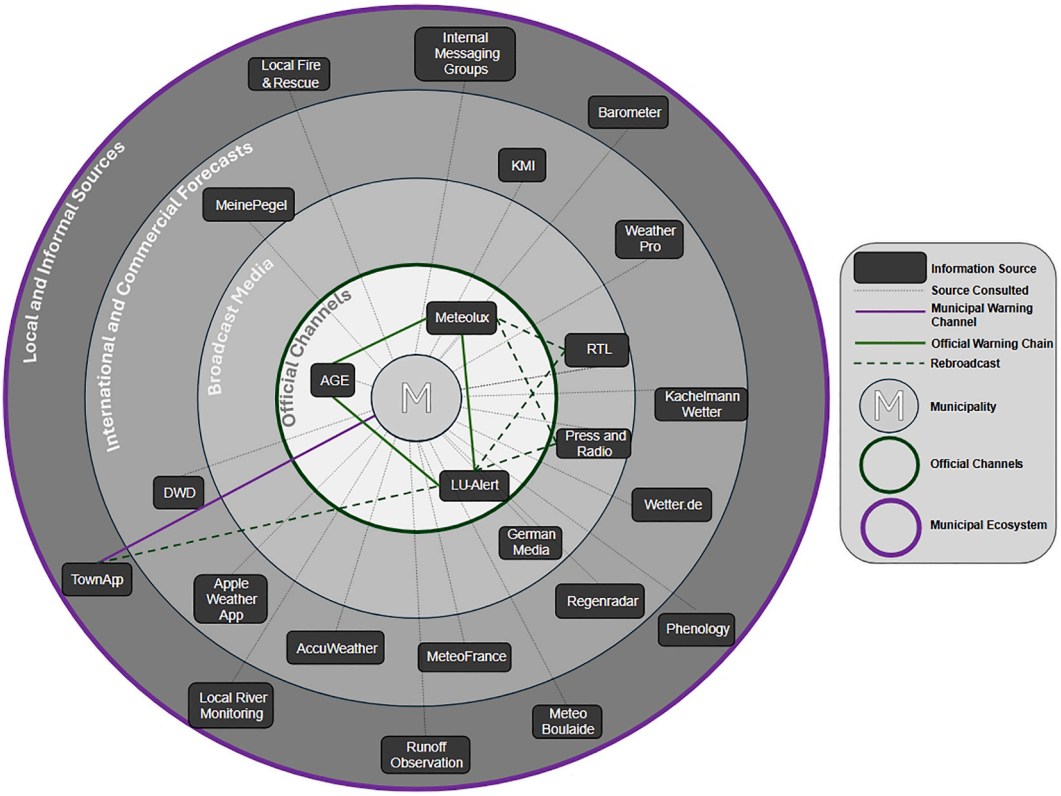

Fig. 1. Municipal Forecast and Warning Ecosystem. At the centre are municipal officials, who monitor a wide spectrum of sources (grey dashed lines). The official warning chain (green lines) connects Meteolux, AGE/Inondations.lu, LU-Alert and municipal apps. Municipal practice extends further, linking to local operational channels (e.g. Fire & Rescue, internal messaging) and trusted external providers (e.g. MeteoFrance, Regenradar, MeteoBoulaide). Broadcast media (RTL, press/radio) rebroadcast both Meteolux alerts and alternative forecasts, illustrating the hybrid system of official, local and external sources on which municipal officials rely. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4.1. *Catastrophising and risk amplification*

Participants said that the tone of official alerts had become increasingly dramatic, often using strong terms for conditions they considered routine. Some linked this to what they described as a shift from underreaction during past events to overreaction in more recent communication. BM1 said that the tone of messages had changed noticeably, referring to the aftermath of the 2021 flood disaster:

"There were people under criticism for not having reacted properly. Now they overreact… nobody knows where they're at anymore."

The repeated use of words such as *"danger"* reduced the distinction between ordinary and genuinely severe situations. They said that this made it harder to identify which warnings required action and which could be monitored without response. 1CE said that such messaging created a sense of continuous alarm that was difficult to sustain:

"There is way too much catastrophism…you don't exactly live well under constant threat."

The frequency and intensity of alerts created background noise and reduced the perceived urgency of later messages. They explained that, over time, they had developed their own undocumented filters to judge when conditions were serious enough to warrant action. These filtering practices formed part of how they navigated the wider municipal forecast and warning ecosystem shown in Fig. 1.

3.4.2. *Spread of misinformation*

Participants described social media as a rapid but unverified source of situational information that required careful filtering. During the simulation exercise, LR1 gave an example of how quickly such reports appear online:

"People can say what they want on social media."

Officials said that these posts were monitored but not used as a direct basis for action. In the same exercise, RC2 explained that such information was reviewed alongside official data sources but was not treated as authoritative:

"We keep an eye on it, but we do not react to it."

Local observations shared on social media sometimes informed municipal awareness when verified. RC1 explained that when a post tagged the municipality and appeared relevant, they took a screenshot and forwarded it to the internal messaging group to keep colleagues informed. Others said that such posts occasionally complemented hydrological data or confirmed early signs of flooding. Social media was seen as both a challenge and a resource. While it could contain unverified or exaggerated statements, it also provided early cues and local feedback. Officials distinguished trusted intermediaries such as Meteo-Boulaide, which began on Facebook before developing a dedicated app, from unverified citizen posts that required confirmation through other sources. Social media served multiple roles within the municipal information environment. It functioned as a monitoring tool, a source of public signals and occasionally a means of verification. These overlapping uses added to the complexity of forecasting and preparedness, showing how official, local and undocumented information intersect in practice.

3.4.3. *Trust in information sources*

Trust in different forecast and warning information providers was uneven. They contrasted official sources such as Meteolux with international, commercial and local services, often favouring the latter for the speed and detail of their rainfall and storm updates. Several mentioned that MeteoFrance was valued for its regional precision and for showing where rain systems originated, helping them anticipate whether incoming fronts would reach their municipality. Regenradar

was described as highly accurate, with one participant recalling that its short-term forecasts during July 2021 predicted rainfall almost to the minute.

The independent forecaster known as MeteoBoulaide, who manages a dedicated app and Facebook page, was frequently cited for his local focus and accessible communication. The trust in MeteoBoulaide came from his precision and from his communication tone, which they described as calm, factual and adapted to the local context. They also appreciated his annotated graphics and his willingness to respond directly to questions online. This personal and conversational style was contrasted with the automated phrasing of national bulletins. SC1 said:

"He has his own app … he is so precise and good, I like to support him."

Officials also referred to global weather applications such as WeatherPro, AccuWeather, Apple Weather, wetter.de and wetteronline, which they used for hourly updates and short-term monitoring. Hydrological tools such as MeinePegel were used to follow river gauges across borders. Participants valued MeinePegel for its near real-time data and for showing upstream stations outside Luxembourg, noting that rivers do not stop at national boundaries. These platforms formed what was.

described as a patchwork information system in which Meteolux occupied the centre, surrounded by links to wetter.de, MeteoBoulaide, RTL, DWD, MeteoFrance, inondations.lu and local heuristics. Each source served a specific operational function, from tracking rainfall movement to confirming river levels. For some, trust also rested in local leadership. SC1 said that they relied on the mayor's direct calls as a signal to act:

"We trust the mayor a lot, who calls us and tells us, it is time."

Officials said they would not hesitate to issue a municipal warning earlier than the national one if local thresholds were exceeded. They explained that trust in both people and platforms was built on clarity, reliability and a communication style that matched their operational routines. Choosing sources that spoke their professional language helped them make better-informed local decisions. Several also noted that this reliance on individual experience and leadership could become a vulnerability. No formal mechanism existed to record or transfer such experiential knowledge, raising questions about how institutional memory and decision-making capacity are maintained over time.

3.4.4. Multi-source verification

No single information source could be relied on in isolation. They said that they routinely compared and cross-checked data from official, commercial, local and heuristic sources before forming a judgement. ST1 explained that they used different platforms depending on the situation, saying that RTL was sufficient for ordinary days but that they consulted inondations.lu to monitor water levels when warnings were active. SC1 added that wetter.de was viewed as a professional reference and that MeteoBoulaide served as an additional local input. RC1 noted that Meteolux warnings were automatically transferred to the municipality's mobile application, which allowed them to be shared directly with residents. Several emphasised that this cross-checking was not optional but essential for adapting national forecasts to municipal geography. They said that they relied on local rules of thumb for river travel times and discharge, which they considered more informative than abstract numerical thresholds. Officials described combining national alerts, foreign forecasts, independent apps and local observations to build a composite view of evolving risk. Social-media posts, river-gauge readings, barometer data and local experience were all incorporated into this verification process. Verification across multiple channels was described as a routine professional practice. They said that while Meteolux remained the reference point, its messages were always interpreted in relation to other sources. These practices illustrated the interpretive work required at the municipal level to make forecasts actionable.

4. Warning cultures in practice

Officials consistently described warnings not as ready-made instructions but as raw inputs that had to be reworked before they became operationally meaningful. This process of adaptation grounded in knowledge, habit and local geography shaped how alerts became meaningful in practice.

4.1. Shadow systems

Municipal officials did not treat warnings as finished products. They acted as interpreters who had to make alerts meaningful before they could be used. This work was constant, not occasional and it gave rise to what we refer to here as a *shadow system*. We use the term *shadow system* to describe the undocumented, adaptive practices through which municipal officials interpret and act on national warnings. The concept is borrowed from organisational studies, where it refers to user-created systems that emerge to fill gaps in formal structures [64]. We use it to describe how local actors construct meaning, trust and action beyond the boundaries of the official warning system. Each new bulletin, colour code, or rainfall value had to be filtered through what officials already knew about local rivers, travel times, previous events and practical thresholds. They cross-checked information across multiple sources, including MeteoFrance, wetter.de, Regenradar, independent apps like MeteoBoulaide and their own visual or physical cues such as plant behaviour, barometers, or river gauges. This created a parallel layer of monitoring and interpretation that surrounded the official system. Officials reformulated bulletins, translated warnings into multiple languages, adapted messages for residents and added operational meaning through examples and timing. These practices formed a shadow system. It was not undocumented in the sense of being improvised or unreliable. Rather, it was structured and habitual, grounded in routines of trust and shared knowledge, though not formally codified, it allowed warnings to be localised, tested and sometimes overridden [20,39,16]. From an analytical standpoint, this reflects a basic principle in interpretive policy analysis, where rules and tools only work when they are made meaningful in practice (Hajer & Wagenaar, [65]; Yanow, [66]). Officials had to construct their meaning in context. A rainfall figure or colour level carried no automatic implication. Its significance had to be worked out, often under pressure and in reference to the particular geography. Interpretation was how the system functioned. While all warnings require interpretation, in Luxembourg this interpretive work formed a parallel and routine system of monitoring and translation that effectively shadowed the official chain. Similar patterns are documented across Europe, where local authorities construct parallel monitoring systems to adapt national alerts to local needs [54,39,16]. These dynamics reflect the role of geographical imaginaries, where disaster knowledge and action are shaped less by categories of risk than by situated understandings embedded in place [55]. Framing these practices as shadow systems highlights how municipal officials combined institutional knowledge, lived experience and heuristics into actionable warning cultures. The results indicate that the practical usefulness of warnings in the municipal context is shaped largely by undocumented routines that staff develop to interpret and apply official information. These facilitate day-to-day operational decisions but remain mostly undocumented, which means they also depend on the continuity of personnel. This pattern reflects a form of institutional memory vulnerability, where knowledge embedded in individual experience and practice is lost through staff turnover or organisational churn rather than formal handover processes. Similar dynamics of institutional amnesia, driven by reliance on agential knowledge and limited mechanisms for knowledge retention, have been identified in disaster governance and public administration research [67].

4.2. Warning fatigue

Participants described a system in which warnings were too frequent to be trusted and too dramatic to be useful. Yellow and orange alerts were received so often that they were treated as background noise, no longer carrying the weight of actionable guidance. Several said that repeated alerts for ordinary weather eroded their credibility and even caused annoyance, leading some to delete official apps or ignore lower-level messages altogether. At the same time, they noted a post-2021 shift in tone, where words like danger were used more readily, even when conditions felt routine. This blurred the boundary between attention and saturation. The result was a communication landscape where warnings did not stand out, because they were too persistent to retain urgency. These findings align with broader research on warning fatigue, which show that repeated alerts without clear escalation can cause disengagement and reduce public responsiveness [7,47]. In this study, warning fatigue refers specifically to institutional disengagement among municipal officials, rather than to public behaviour, which may follow different dynamics. Similar effects have been documented in the UK, where the frequent issue of yellow weather warnings has been associated with reduced salience and inattention [49,53]. Participants describe this as a structural weakness in the system, one that weakened institutional trust and pushed them to rely on their own judgement. Several described warnings as predictable or even boring, while others treated them as forecasts rather than incentives for early action. Once the language of alerts becomes too familiar, it stops serving as a signal and becomes part of the informational background. Officials compensated by filtering alerts through local knowledge or waiting for personal heuristics to confirm their relevance. Amplified language did not help them act sooner. It pushed them toward self-reliance, creating distance between national messaging and municipal practice. Comparable findings from European flood events show that when institutional alerts are mistrusted or perceived as repetitive, local actors increasingly fall back on their own networks and improvisation [54,20]. In Luxembourg, this tendency has been reinforced by the experience of the 2021 flood disaster, which tested municipal capacity and raised concerns that undocumented compensations may not scale under more frequent extremes [18,21].

4.3. Terminology and trust

Participants repeatedly highlighted how the language used in official warnings did not connect with the decisions they needed to make. Terms like *"moderate rain"* or *"awareness level"* were seen as too abstract to trigger specific actions. The reform of flood warning terminology in 2025, which replaced process-based categories like *"pre-alert"* with generalised labels such as *"danger"*, further widened this gap. None of the officials were aware of the reform prior to the focus group, indicating that end-user consultation was minimal at best. Without involving the actors responsible for applying these terms, reforms risk reducing rather than improving clarity. Officials explained that *"danger"* suggested an irreversible situation already unfolding, whereas *"pre-alert"* allowed for reversible preparedness. These shifts reduced flexibility and weakened the ability to communicate escalating risk in a way that aligned with how municipalities actually prepare. Colour codes were similarly reinterpreted through local experience. Yellow was seen as routine, orange as the first actionable level and red as a late-stage signal often reached after impacts had begun. This reinterpretation process can be described as trust asymmetry, where proximity, specificity and responsiveness shape how warnings are trusted [54,12]. Participants consistently contrasted Meteolux's repetitive language with the more tailored and explanatory outputs of providers like *MeteoBoulaide*, whose annotated graphics, use of Luxembourgish language and careful tone were described as more useful for communication and decision-making. Trust migrated toward sources that were perceived as responsive and contextual, even when they lacked formal authority. Similar findings are documented in studies of decentralised flood response, where institutional distance can erode trust in centrally issued alerts [41,11].

4.4. Local context and action thresholds

A consistent finding across the focus group was that national warnings did not align with the spatial or temporal scale of municipal responsibilities. Bulletins were often issued for the entire country or broad time frames, while municipal officials were accountable for highly localised impacts. Participants explained that even phrases like *"minor flooding"* did not match on-the-ground conditions, since local flooding could occur before official thresholds were triggered. The language and metrics used in national products were perceived as too general to inform decisions such as when to deploy resources or inform the public. To bridge this gap, officials relied on local knowledge, such as estimating river travel times between known points, consulting inondations.lu for local gauges, or using third party weather apps to monitor rainfall in real time. These practices show how national forecast values had to be situated within local hydrological knowledge and terrain in order to support action. Similar dynamics have been observed in other European contexts, where municipalities adapt national systems to suit their geography and exposure [39,13]. Participants described how they maintained internal thresholds based on river levels or rainfall accumulation which could trigger municipal action independently of official alerts. Although this has not yet resulted in issuing earlier warnings than national providers, participants made it clear that they would not hesitate to do so if needed. This reflects a broader challenge for warning system design, where standardised thresholds may support coordination at national level, but often require local adaptation to become actionable. The discussion also revealed that much of this local calibration is not formally recorded. Trust in local judgement particularly in the hydrological expertise of the mayor was seen as a strength, but also a potential vulnerability in the event of personnel changes. Local knowledge of rivers, catchments and past events functioned as a living archive, but one that remained largely undocumented. These findings underline that warning systems are embedded in institutional memory, territorial knowledge and human relationships. Without alignment between scale, content and operational needs, warnings are not people-centred and remain descriptive. Participants also highlighted that navigating uncertainty was part of their practice, particularly when official warnings used ambiguous terminology or provided wide temporal windows. In these situations, local heuristics and undocumented thresholds functioned as pragmatic tools for resolving ambiguity, even though they depended heavily on individual experience. This reliance on personal judgement was viewed as effective in the moment but raised concerns about continuity should key staff or elected officials change.

These findings show that weather and flood forecasts remain uncertain and difficult to use in municipal decision-making. Ensemble approaches aim to describe this uncertainty, but participants described persistent difficulties in translating probabilistic forecasts that are presented as state of the art into clear decisions about when and how to act. Current forecast development places strong emphasis on higher spatial resolution, additional physical processes and, increasingly, data-driven and artificial-intelligence-based models [68]. The discussion here shows that comparable attention is required for how uncertain forecast information is interpreted, communicated and connected to concrete courses of action at the municipal level [69,70].

4.5. System design

These practices of local filtering and interpretation, while often effective, also point to broader structural issues in the national warning

system. The findings suggest that the effectiveness of early warning is not determined by technology alone but by how institutional structures and communication protocols shape the use of information. Municipal officials routinely compensated for the absence of locally specific guidance by constructing their own interpretive systems. This interpretive work was central to how warnings were made operational. In theory, centralisation through agencies like Meteolux and the CGDIS was designed to improve coordination and standardisation. In practice, however, participants described national products as too generic, too frequent, or too delayed to serve municipal decision-making. This resulted in a decentralised system where each municipality built its own situational awareness using tools that were trusted, familiar, or responsive. While this enhanced local responsiveness, it also introduced risks. Variation in local interpretation can lead to inconsistent action across jurisdictions, particularly during high-impact or fast-moving events. Comparable challenges have been reported in other European contexts, where decentralised interpretation created uneven protection and fragmented responses [20]. The lack of regionally embedded intermediaries meant that municipalities acted with a high degree of autonomy, interpreting national alerts without additional guidance or support. No participant described any regional or intermediate coordination structures that could help mediate between national forecasts and local needs. This absence reinforced the binary structure of the system, where responsibility passed directly from national agencies to individual municipalities without intermediate support. In Germany and Belgium, the warning chain includes regional authorities that adapt and relay information between national and local levels [71,22]. Trust asymmetries further reinforced this decentralisation. Participants consistently placed greater confidence in sources that offered clarity, specificity, or a history of responsiveness, whether foreign providers, local forecasters, or individual leaders such as the mayor. These dynamics reflect a wider governance challenge in disaster risk management. The effectiveness of national systems depends on alignment with the institutional structures through which decisions are made [72]. In Luxembourg, this alignment remains partial. Warning systems can function, but only because municipal actors actively rework and supplement them. The risk is that this reliance on undocumented adaptation masks deeper structural issues, leaving local capacity dependent on individual initiative and memory. As weather events grow more frequent and severe, these undocumented compensations may no longer be sufficient. Recent attribution studies show that human-induced climate change has already increased the likelihood and intensity of extreme rainfall events such as those of the July 2021 floods in Western Europe [73]. The IPCC Sixth Assessment Report also concludes with high confidence that heavy precipitation and pluvial flooding have become more frequent in Central and Western Europe due to anthropogenic warming [74]. These findings suggest that Luxembourg's flood risk governance will increasingly be tested by extremes whose probability has shifted. Future climate resilience will require systems designed to support meaningful, context-aware action at the municipal level. In practical terms, the results point to the need for co-developed warning products and procedures that are designed with municipal users. Collaborative processes could include structured exchanges between national agencies and municipal services, iterative testing of formats in different languages and joint scenario exercises that link awareness levels to concrete municipal actions. Co-development supports the people-centred, impact-based approaches advocated in international guidance [2,5].

Limitations to this study should be acknowledged. The analysis is based on a municipality and findings cannot be generalised to all municipalities in Luxembourg or to other national contexts. Data are retrospective and self-reported rather than drawn from real-time observation of operational decision-making and they do not include perspectives from residents or businesses. These constraints may have led some dynamics to be under-represented or over-emphasised. At the same time, the depth of discussion provides a detailed window into how shadow systems function in practice. Future research could extend this work by comparing multiple municipalities, incorporating public perspectives and combining qualitative analysis with operational data on warning use and response.

5. Conclusion

Municipal officials in Luxembourg play an essential interpretive role in translating national weather and flood warnings into local action. Local actors actively construct meaning through a mix of institutional knowledge, lived experience, peer exchange and undocumented heuristics. This interpretive ecosystem what we refer to as a *shadow system*, compensates for perceived shortcomings in the national warning framework, including unclear terminology, overly general thresholds and a lack of actionable guidance. The findings reveal that frequent, vague, or exaggerated alerts contribute to *warning fatigue*, eroding trust and prompting disengagement from official sources. The municipality increasingly relies on their own internal indicators and trusted external sources, such as independent apps and local knowledge, to validate forecasts and determine when to act. These adaptive and interpretative practices are both a strength and a vulnerability. They reflect the resilience and institutional memory embedded in municipal governance. However, they also expose structural weaknesses in the design and communication of centralised warning systems. The absence of intermediary institutions forces municipalities into a position where they must assume interpretive and operational responsibility without formal support, often leading to fragmented or inconsistent responses. Moreover, changes to terminology and alert systems, such as the 2025 reform of flood warnings, risk further misalignment if not co-developed with end users. The study calls attention to the limits of purely technical or top-down solutions in disaster risk governance. Early Warning Systems need a communication that is precise, trust-building, people-centred and operationally aligned with the needs of local decision-makers. As climate-related hazards intensify and warning systems become more central to risk governance, it is important to design them for understanding, trust and action on the ground. Shadow systems are a component of how early warning operates in practice in Luxembourg. Their presence demonstrates both the adaptive capacity of municipal actors and the structural gaps that require reform at the national level. Strengthening the relationship between national warning providers and local authorities will be essential for improving anticipatory action and reducing reliance on undocumented or person-dependent knowledge. In doing so, this study contributes directly to the aims of Sustainable Development Goal (SDG) 11 on resilient cities and SDG 13 on climate action, by strengthening the capacity of local authorities to anticipate, absorb and recover from flood events [75].

Moving forward, the findings underline the value of examining early warning systems infrastructures but as governance arrangements shaped by interpretation, discretion and trust. The analytical approach developed in this paper is transferable to other small states and multi-level governance contexts where local actors are required to operationalise national warnings under uncertainty and it offers a framework for identifying similar forecast-to-action gaps elsewhere.

Future research could focus on ensuring that national warnings provide spatial and temporal detail meaningful for municipal responsibilities and on communicating uncertainty in ways that allow local decision-makers to assess confidence, plausible developments and conditions for escalation. In addition, future work could explore how these interpretive practices relate to formal uncertainty-modelling and expert-judgement frameworks used in more engineered or digitalised risk-management contexts. Participants also emphasised the importance of documenting local procedures more systematically so that experience and judgement are not lost when personnel change. Closer collaboration

between national services and municipalities would help ensure that warning language, thresholds and formats reflect both technical constraints and the realities of local operations. The findings show that designing warnings with local use in mind, supported by clarity, consistency and collaboration, is central to strengthening the link between national and municipal action and enabling more timely decisions during future hydrometeorological events.

CRediT authorship contribution statement

Jeff Da Costa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hannah L. Cloke:** Writing – review & editing, Supervision. **Jessica Neumann:** Writing – review & editing, Supervision. **Nathan Salvidge:** Writing – review & editing, Supervision.

Declaration of competing interest

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

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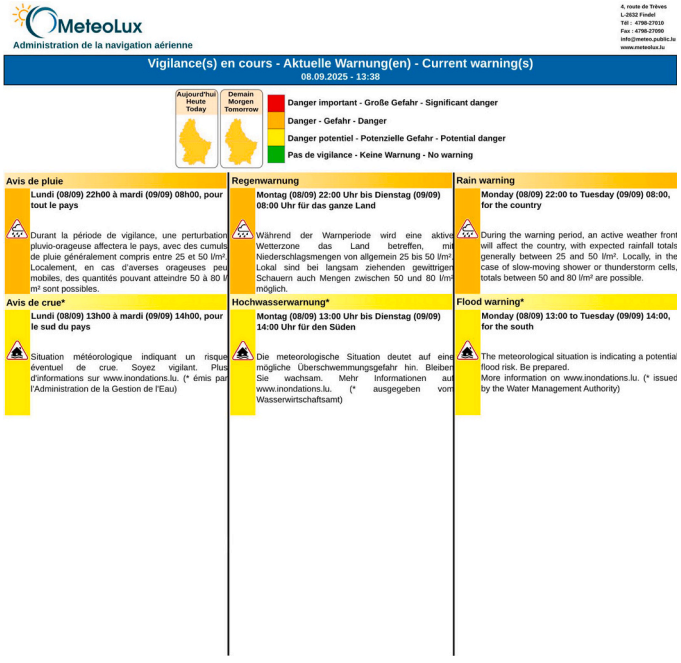
Appendix A. Examples of warning presentation across platforms

This appendix presents screenshots of official warnings and alerts disseminated during a hydrometeorological event in Luxembourg on 8 September 2025. An orange rainfall warning was issued for the entire country, valid from 22:00 on 8 September to 08:00 on 9 September 2025. A yellow flood warning was issued at 13:00 the same day, later upgraded to orange and subsequently accompanied by a red flood warning late that night. An LU-Alert SMS was sent at approximately 18:18 (CET) on 8 September 2025. The message did not specify a warning level or contain an active hyperlink. The event was covered in real time on Meteolux, Inondations.lu, Meteoalarm.org, LU-Alert and Infocrise.lu, which confirmed the alert level and timing in an official press release (available at https://infocrise.public.lu/en/). These screenshots are reproduced solely to illustrate differences in visual presentation, terminology and detail across official platforms, as referenced in the main text (Section 1.4). No interpretation or technical evaluation is provided.

A.1. Official warning bulletin (Meteolux, 8 September 2025, 13:38)

Official Meteolux weather and flood warning bulletin issued on 8 September 2025 at 13:38 CET. The bulletin displays a national awareness map and trilingual text indicating rainfall and flood warnings for Luxembourg.



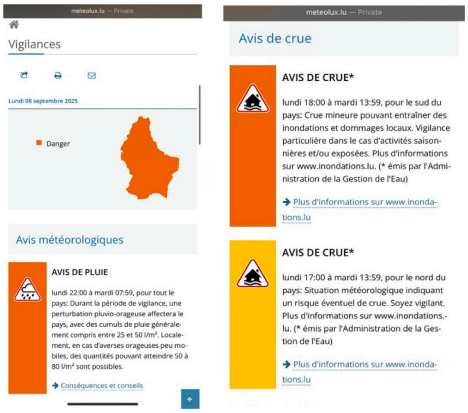
A.2. Meteolux website homepage (screenshot 08.09.2025 at 14:12)

Homepage showing the orange rainfall warning (country outline in orange) and a link to further information with rainfall and flood icons. The yellow flood warning for the south is visible but visually secondary to the orange rainfall warning.

A.3. Meteolux website warning information (screenshots 08.09.2025 at 20:55)

Warnings in place as published on the www.Meteolux.lu website, with orange rainfall warning in place. The page lists rainfall thresholds associated with each level and provides links to impact descriptions and safety advice (available in French and German) here:
https://www.Meteolux.lu/fr/vigilances/dangers-meteorologiques/

The flood warnings are listefbelow the rainfall warning. The earlier yellow flood warning was upgraded to orange at 18:00. The orange flood warning is described as being a risk for minor flooding. For more information on the flood warnings there is a link to the www.inondations.lu website (Water Management Administration)



A.4. Water management authority flood bulletins (screenshots 08.09.2025 at 17:30 and 23:00)

Screenshots of flood bulletins issued by the Water Management Administration via inondations.lu (available in German only). The bulletins distinguish northern and southern catchment areas and treat the Moselle separately due to channel regulation. Each bulletin includes a situational evaluation (not shown here).

Administration
de la gestion de l'eau
Grand-Duché de Luxembourg

Hochwasserlagebericht für Luxemburg

Montag, 8. September 2025

23:00

01. Lagebericht

Süden: Wachsamkeitsstufe rot

Der Süden Luxemburgs befindet sich in der Wachsamkeitsstufe rot für Hochwasser vom 08.09.2025 23:00 bis 09.09.2025 18:00.

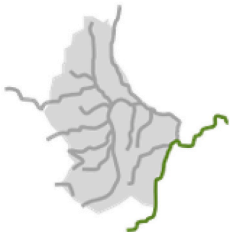
Die Wachsamkeitsstufe kann in Abhängigkeit von der weiteren Entwicklung der Situation angepasst oder verlängert werden.

Norden: Wachsamkeitsstufe orange

Der Norden Luxemburgs befindet sich in der Wachsamkeitsstufe orange für Hochwasser vom 08.09.2025 23:00 bis 09.09.2025 18:00.

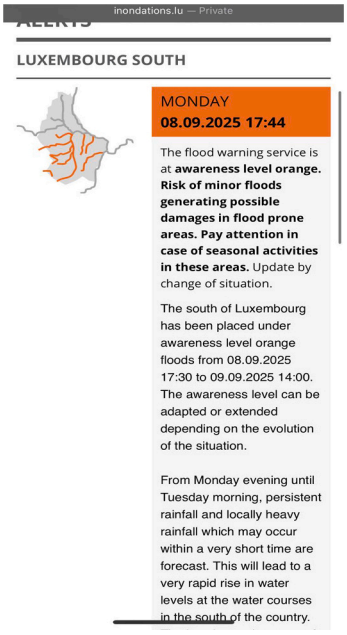
Die Wachsamkeitsstufe kann in Abhängigkeit von der weiteren Entwicklung der Situation angepasst oder verlängert werden.

Mosel: Information/Aktuell kein Risiko für Hochwasser



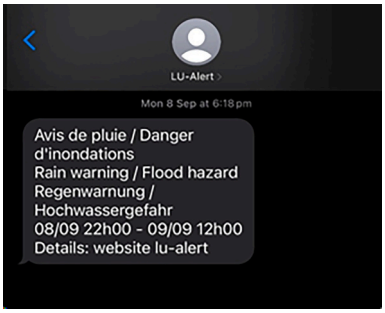
A.5. *inondations.lu warning message (screenshot 08.09.2025 at 20:55)*

Website display showing an orange flood warning for southern Luxembourg (available in French, German and English). The platform does not include weather warnings from Meteolux. However, Meteolux also published flood warnings.



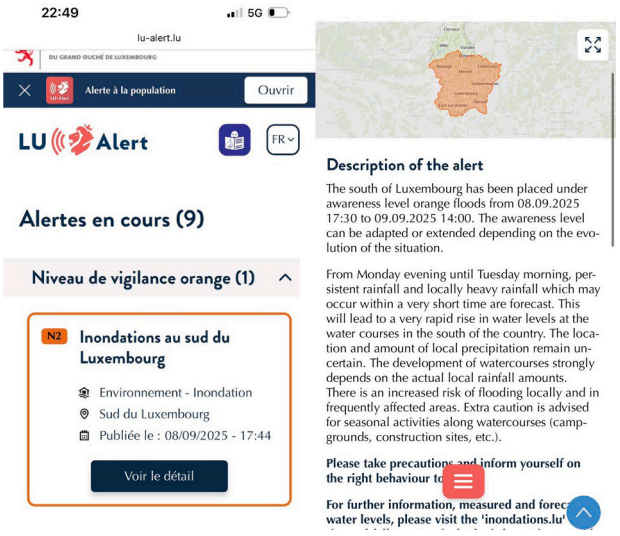
A.6. *LU alert SMS (screenshot 08.09.2025 at 18:18)*

Trilingual LU-Alert SMS received at 18:18 CET. The message contains no indication of warning level and includes an inactive hyperlink. It specifies the time of validity and refers users to the LU-Alert website. No subsequent SMS alerts were issued, although the warning level was later raised to red.



A.7. LU alert website (screenshot 08.09.2025 at 22:49)

LU-Alert website display (trilingual) showing an orange flood warning and the related description. The page does not mention the orange rainfall or red flood warnings issued at the same time.

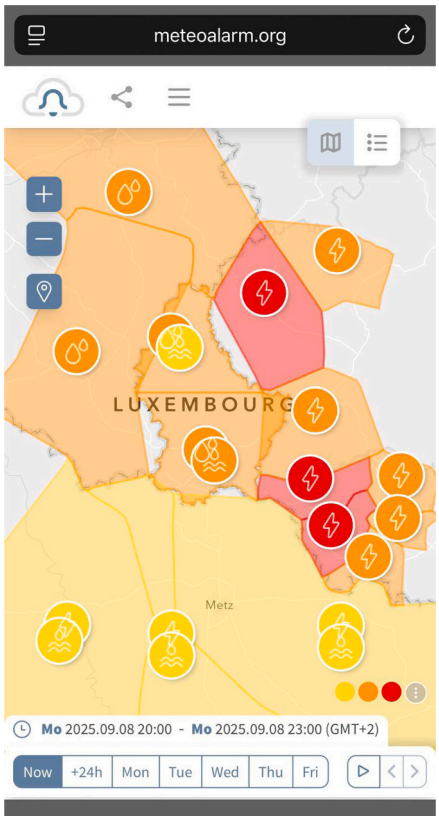


A.8. Meteolux website red flood warning (screenshot 08.09.2025 at 22:47)

Meteolux website at approximately the same time as A7, showing the red flood warning in place for Luxembourg.

A.9. Meteoalarm.org warning publication (screenshot 08.09.2025 at 21:00)

Meteoalarm.org interface showing Luxembourg warnings as relayed from Meteolux. Alert colour levels vary by country and region according to national thresholds.



Data availability

The data that has been used is confidential.

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