Comparing Flood Forecasting and Early Warning Systems in ~~Transboundary River Basins~~Northwestern Europe

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Abstract. This study compares operational Flood Forecasting and Early Warning Systems (FFEWSs) in transboundary river basins in Northwestern Europe, covering parts of Luxembourg, Germany, The Netherlands and Belgium. This region was hit by an extreme flood event in 2021 with over 200 fatalities. Due to the high death toll and the high share of people not receiving warnings, FFEWSs were heavily criticized in the aftermath. This study shows ~~Expert interviews from the region revealed~~ strong improvements of the FFEWSs after ~~this~~ the flood event in all countries. Expert interviews across the region reveal that warning thresholds have been optimized, some regions included new warning thresholds for extreme events (e.g dark purple), and flood crisis management plans have been improved. ~~Moreover~~In addition, ~~All regions have invested in probabilistic flood forecasting systems , and~~ all countries now use mobile phone-based alerts using cell broadcasting technology. The assessment of warning systems showed strong differences within and between the countries, with different ~~Strong differences in~~ flood warning levels and warning color codes used ~~exist across and within the countries.~~. We recommend ~~to~~ investigating~~e~~ to what extent international harmonization of flood warnings can improve~~s~~ communication and decision-making. ~~In response to the 2021 flood, some regions have introduced an additional purple warning level.~~ The interviews also revealed that the uptake of operational impact-based forecasts remains challenging, while these are crucial for translating hydrological forecasts to effective actions. For example, interviewees highlighted the need for operational flood inundation forecasts. However, Flanders is the only region where such forecasts are provided. One of the four main recommendations is ~~It is recommended~~ to enhance forecasts with impact-based information, including inundation maps delineating the population~~people~~ and objects at risk. This can improve the early actions taken by first responders and the affected population~~eople~~.

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1 Introduction

The extreme flood event of July 2021 in North-Western Europe caused over 200 fatalities and around €40 billion~~bn~~ of damage (Lehmkuhl, et al., 2022). The frequency and severity of such flood events may increase in the future because of climate change and socio-economic developments (Tradowsky et al., 2023). To reduce avoidable damage and casualties, there is a call for more reliable early warning systems to protect Europe from flood impacts (European Environment Agency, 2024). Forecast-based actions are vital to reduce disaster risk, as they can effectively reduce the exposure and vulnerability of communities to floods (Pappenberger et al., 2015). For example, based on forecast information, the government may issue an evacuation order for communities in predefined flood zones or may advis~~c~~e households and businesses to protect properties and infrastructure with emergency flood protection measures (e.g. sandbags and pumps). The benefits of forecast-based actions are often much higher than their costs (Global Commission on Adaptation, 2019). Pappenberger et al. (2015) even claim a benefit in the order of 400 Euro for every Euro invested. The 2021 flood further showcased the potential of early warning systems. Extreme precipitation was predicted by weather models, such as the model operated by the German Weather Service (DWD, 2021; Mohr et al., 2023), which issued extreme weather warnings 1-2 days in advance (DWD, 2021; KNMI, 2021). Despite these promising numbers, the impacts of the flood event were devastating and raised questions about the functioning of the operational flood warnings and the effectiveness of early actions taken.

1.1 A Flood Forecasting and Early Warning System (FFEWS)

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A flood forecasting and early warning system (FFEWS) consists of a chain of components (Fig. 1). Hydro-meteorological data is used as input to weather and flood forecasting models, which jointly predict whether warning thresholds are surpassed with a certain probability (e.g., Alfieri et al., 2019). These thresholds can be, for example, pre-defined rainfall amounts or water levels with a certain return period. Surpassing a threshold may lead to a warning to the public or crisis managers who make decisions on how to respond (Fig. 1). Meteorological and hydrological warning levels are often depicted with colors, as shown in Fig. 1. Each warning level can be connected to a set of pre-defined actions, outlined in crisis management plans. Responses at the governmental level include, for example, closing a certain parking garage because it might be flooded, or in severe cases issuing an evacuation alert or order. Households may decide to install flood protection measures such as sandbags or mobile protection systems (Cao et al., 2024).

Uncertainty is present in each component of the FFEWS. In the forecasting part, uncertainty can be partly ~~covered~~displayed by using~~represented by using~~ ensemble weather forecasts (Fig. 1, left). In addition, uncertainty of forecasts increases with lead time (i.e., the time between issuing a forecast and the real event) - usually one or a few days ahead of the event (Jiang et al., 2023). Further uncertainties in the system lie in the communication, decision-making, and response stages, and whether decision-makers can process warning signals into effective actions on the ground (Bischiniotis et al., 2020). A key challenge in developing and implementing a FFEWS is that uncertainty in one component can cascade down to the next component, all the way to the last component (Parker and Priest, 2012). For example, uncertainty in the collection and processing of meteorological data (Fig. 1, Left) may lead to a 'missed' ~~forecast~~ event, where thresholds in the system were not surpassed, while observed water levels reached extreme heights (Cloke and Pappenberger, 2009). By contrast, uncertainties can also lead to so-called false alarms, where the

predictions suggest that warning thresholds may be exceeded, while effectively they are not.

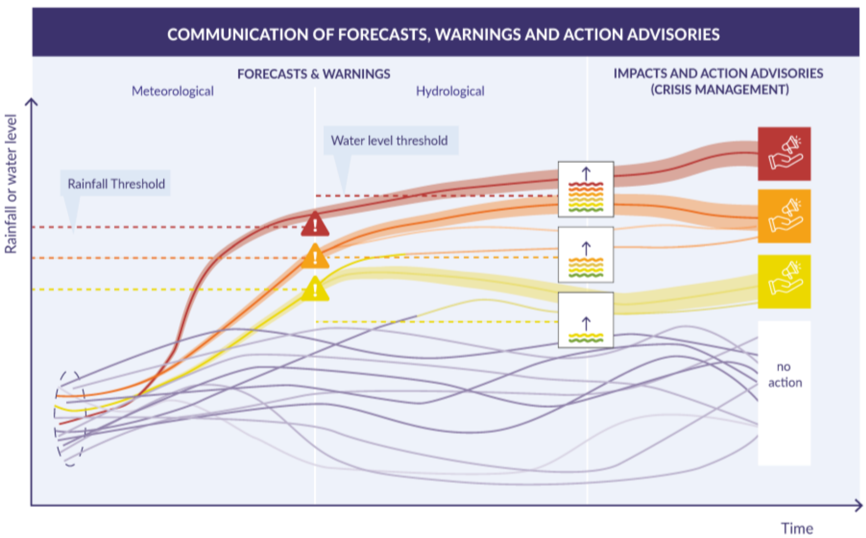

Figure 1: Conceptual representation of a flood forecasting and early warning system (FFEWS). Rainfall ensemble forecasts (*left*) are used in hydrological models to predict river water levels (*middle*). Warnings are issued if a share of the ensembles exceed the specified rainfall or water level threshold, which results in triggering (sometimes pre-determined) early actions (*right*) (adapted from: Busker, 2024).

The quality of meteorological forecasts is challenged by the inherent uncertainties in atmospheric processes and initial conditions, which can lead to errors in spatio-temporal or intensity estimates ~~the related inaccuracies in both spatio-temporal estimations of initial conditions and forecast simulatio ns~~ (e.g., Leutbecher and Palmer, 2008). The first source of error relates to input data for forecasting models, while the second arises from the imperfect physical parametrization and (coarse) resolutions of models (Buizza, 2019). Numerical weather prediction models have improved greatly in recent decades (Bauer et al., 2015). For example, the Integrated Forecasting System (IFS) operated by the European Centre for Medium-Range Weather Forecasts (ECMWF) showed strong improvements over the last 25 years (Buizza, 2019). They started with ensemble forecasting in 1992 (Buizza, 2019), and now produce a ~~produces a~~ 51-member ensemble forecast for both the medium-range

(15 days ahead) and seasonal range (7 and 12 months ahead), and a 101-member forecast for the sub-seasonal-range (46 days ahead)~~,~~. As with meteorological forecasts, the quality of the hydrological forecasts is affected by various factors, such as meteorological observations or hydrological characteristics (e.g. ground- and soil water volume). Over the last decade, ensemble and post-processing techniques have been increasingly used to estimate the uncertainty in hydrological forecasts. Ensemble forecasts are used to calculate the probability of~~n~~ certain events, in case some (or all) ensemble members exceed a certain threshold of heavy precipitation intensity~~such as 20 millimeter (mm) / hour (h)~~. Forecast users can now incorporate the probability of~~n~~ a certain event as additional information in the decision-making process. Therefore, ensemble forecasts have higher value for forecast users than deterministic forecasts (Richardson, 2003). It is expected that ensemble forecasts will be widely integrated in operational forecasting chains in the near future (Pappenberger et al., 2016). ~~which can be used to derive probabilities. Applying these data to derive information needed for warning systems requires the definition of a threshold, for example rainfall greater than 20 mm/h. The predicted probability of such a precipitation event could be defined as the percentage of ensemble members exceeding this threshold.~~

1.2 Current challenges in FFEWS

~~As with meteorological forecasts, the quality of the hydrological forecasts is affected by various factors, such as meteorological observations or hydrological characteristics (e.g. ground- and soil water volume). Over the last decade, ensemble and probabilistic techniques have been increasingly used to estimate the uncertainty in hydrological forecasts. Despite advances, early warning systems only have value if they lead to effective early actions (Golding et al., 2019). Here, the communication of flood warnings to first responders and the public appears challenging (Dasgupta et al., 2024; Parker and Priest, 2012; Scolobig et al., 2022).~~ During the 2021 floods, a large share of affected people were not warned. For example, following an in-depth investigation of official parliamentary documents, Thieken et al. (2023b) showed that around a third of the flood-related fatalities in the German region North Rhine-Westphalia (NRW) were likely not warned~~, despite having early-warning systems in place~~. In addition, from the people that were warned, 85% did not expect severe flooding (Thieken et al. 2023a). In the Netherlands, 75% of people with flooded homes in the heavily affected Geul catchment were not warned (Endendijk et al., 2023a). In some regions, the 2021 flood extended beyond the defined static flood hazard zones (as defined in spatial planning policies), giving citizens a false sense of security, even if they received warnings. This led to households outside of the flood zone being caught by surprise in the NRW and the Rhineland-Palatinate (RLP) regions in Germany (Rhein and Kreibich, 2025; Thieken et al. 2023b), and the Walloon region in Belgium (Dewals et al., 2021). Since households ~~not~~ living outside~~ in~~ the official flood zones have lower risk perceptions, their responses are also lower than those living in flood zones (Aerts et al., 2018). ~~In the valley of the Vesdre river in the Walloon region of Belgium, households were unexpectedly hit by the flood as the flood event was much larger than the official flood zone delineated by governmental zoning policies (Dewals et al., 2021). In Germany, 50 to 75% of flood fatalities happened outside of the marked flood hazard zones in NRW and Rhineland-Palatinate (RLP), respectively (Rhein and Kreibich, 2025; Thieken et al. 2023b). Flood risk awareness and risk perception are important~~

drivers of adaptation: since households not living in flood zones have lower risk perceptions, their responses are also lower than those living in flood zones (Aerts et al., 2018). Empirical data on flood zone residentsin the affected areas in The Netherlands (Limburg) show that households who received a flood warning were 23% up to twice as likely to take emergency flood risk reduction measures as those who did not receive a warning (Endendijk et al., 2023a). However, this also means that some warned people did not evacuate or take other precautionary measures. ThisThese examples points to the importance of clear and tailored communication of the expected flood, the expected impacts, and of providing recommendations for responses (e.g., Thieken et al., 2023a). Furthermore, many countries and regions have not yet homogenized their FFEWS protocols, which can further hamper clear and consistent cross-border communication (Coughlan de Perez et al., 2022). This is caused by, for example, differences in institutional settings and geographical characteristics in the respective regions countries. The Council of the European Union states that a better integration of activities and cooperation between countries in cross-border river-basins is crucial to further develop FFEWSs (Council of the European Union, 2024).

Research stresses the

These findings underline the importance of the provision of timely warnings that include predicted impactsthe provision of providing impact (Najafi et al., 2024) and actionable action information in a forecast (Najafi et al., 2024; Kreibich et al., 2021)information (Kreibich et al., 2021). Impact-based forecasts are more specific and tangible (Merz et al., 2020), trigger change in people's risk perceptions, and consequently their intention to respond (Endendijk et al. 2023b; Red Cross Red Crescent Climate Centre, 2020). Moreover, Iimpact-based warnings provide crisis managers and first responders with more tailored information necessary to act (Apel et al., 2022; Boult et al., 2022; Red Cross Red Crescent Climate Centre, 2020; Meléndez-Landaverde et al., 2020, Merz et al., 2020, Rhein and Kreibich, 2025, Poolman et al., 2018). However, the practice of impact-based forecasting is still in its infancy (Merz et al., 2020). Only about 30% of the national meteorological and hydrological services in Europe use impact-based models (Kaltenberger et al., 2020; Schroeter et al., 2021).

This points to the importance of clear communication of the expected flood, the expected impacts, and of providing recommendations for responses (e.g., Thieken et al., 2023a). In addition, many countries have not yet homogenized their FFEWS protocols, which can potentially hamper clear and consistent cross-border communication (Coughlan de Perez et al., 2022). This is caused by, for example, differences in institutional settings and geographical characteristics in the respective countries. The Council of the European Union states that a better integration of activities and cooperation between countries in cross-border river-basins is crucial to further develop FFEWSs (Council of the European Union, 2024).

1.3 Research gap and aim

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Given these challenges, it is crucial to compare and assess the current state of operational FFEWSs. Only very few studies assess operational FFEWSs in detail (e.g. Kaltenberger et al., 2020; Schroeter et al., 2021), and to the best of our knowledge none of them has assessed all components of the FFEWSs chain, including communication and crisis management. Moreover, a transboundary analysis (e.g. an international comparison of warning levels) is lacking. Therefore, the main goal of this study is to assess and compare the ~~compare~~ FFEWSs in transboundary river basins in Northwestern Europe. We intend to gain and share knowledge on FFEWSs in a transboundary context and to develop recommendations based on insights from semi-structured interviews and a literature review. We focus on two questions related to the use of FFEWSs: (a) "what are the differences in the warning levels across countries and how are they defined?", and (b) "how can the communication of early warning information and the translation into effective action be improved?". We focus on the areas hit by the July 2021 flood, specifically The Netherlands (Limburg), the Rhineland-Palatinate (RLP) and North Rhine-Westphalia (NRW) federal states in Germany, Belgium (Flanders and Wallonia) and Luxembourg. ~~We will now further introduce the 2021 event and the impact on these regions.~~~~. We intend to gain and share knowledge on FFEWSs applications in a transboundary context and to develop recommendations for their further improvement. We focus on two questions related to the use of FFEWSs: (a) what are the differences in the warning levels across countries and how are they defined?, and (b) how can the communication of early warning information and the translation into effective action be improved? We collected our data through semi-structured interviews and a literature review about FFEWSs in The Netherlands, Germany, Belgium and Luxembourg.~~

2 Case study region and approach

2.1 Case study region

~~*Figure 2: The study area in Northwestern Europe with the transboundary Rhine and Meuse rivers, shared by The Netherlands, Germany, Luxemburg and Belgium. These countries and sub-regions were severely impacted by the extreme flood event in July 2021, especially in smaller transboundary rivers such as the Geul, Vesdre and Ahr (red polygons).*~~

The July 2021 flood event

The flood event of summer 2021 severely hit the area shown in Fig. 2, which is compriseds of ~~compromises~~ several countries that share the Meuse and Rhine basins. The event was caused by an atmospheric low-pressure system delivering a total precipitation amount of about 200 mm in the Ardennes-Eifel region over 48 hours (Lehmkuhl et al., 2022, Mohr et al., 2023). The impacts were the largest in the valleys of smaller tributaries such as the Ahr and Vesdre (red polygons), with the most severe damage in the Ahr V~~v~~alley, where 135 people lost their lives (out of total 190 fatalities in Germany; see Thieken et al. 2023b). In Belgium, parts of the Vesdre valley were devastated, where in total 39 people lost their lives (Journée et al., 2023). For The Netherlands, no fatalities were reported, but damage amounted to more than half a billion euro –particularly in the Geul tributary (ENW, 2021). Also in Luxembourg, river gauges re~~ported~~corded unprecedented water levels ~~(> HQ_{100})~~exceeding 100-year return period ~~which~~that led to widespread inundation. In the Vesdre, Ahr and Geul catchments, a significant share of the local population ~~was not reached by~~did not receive warnings (see Introduction). ~~and evacuation orders (AGE, 2021)~~Although official evacuation orders or advices were eventually given over most of the region, they were mostly ~~arrived~~issued too late~~, and~~ just before the peak floodwaters arrived, such as in the Ahr catchment (Thieken et al., 2023a, Rhein

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and Kreibich, 2025), in the Geul catchment in the south of T~~t~~he Netherlands (Endendijk et al., 2023a), and in the Vesdre catchment in Belgium (Dewals et al., 2021).~~.~~

Figure 2: The study area in Northwestern Europe with the transboundary Rhine and Meuse rivers, shared by The Netherlands, Germany, Luxemburg and Belgium. These countries and sub-regions were severely impacted by the extreme flood event in July 2021, especially in smaller transboundary tributaries such as the Geul, Vesdre and Ahr (red polygons).

~~Flood risk management responsibilities~~Governance of Flood Forecasting and Early Warning Systems (FFEWS)

Strong differences in ~~F~~FFEWS ~~lood risk management~~approaches are present across the study area ~~is organized quite differently in the riparian countries of the Meuse-Rhine area~~. In The Netherlands, the national government is managing the large waterways (e.g., Rhine and Meuse), while regional governments (including regional water authorities: "waterschappen"~~water boards~~) are responsible for the smaller regional water systems. Special administrative regions are formed for the crisis management organizations, the so-called "Safety Regions" (Dutch: veiligheidsregios). In Germany, flood risk management is the responsibility of each of the ~~sixteen~~16 federal States (e.g., Becker et al., 2015). ~~Hence,~~ Here, we particularly focus ~~here~~ on flood forecasting and warning deployed in the riparian states of RLP and NRW in Germany. In Belgium, the two federal states (Flanders and Wallonia) both have the mandate to develop and enforce flood risk management regulations. In Luxembourg, flood ~~risk management~~forecasting is addressed at the national level by the Water Management Administration (AGE), which is part of the Ministry of the Environment, Climate and Biodiversity.

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2.2 Approach

We collected information on FFEWSs in the riparian regions from literature reviews and interviews with 13 experts in the countries of the case study area. We applied a literature search with ~~using~~ Google Scholar and Scopus, using (combinations of) these main keywords: ~~such as~~ #flood, #forecast, #~~threshold~~warning, #communication, #response, #evacuation, #residents, #government, #rainfall, #precipitation, #extreme, #waterlevels, #actions, #alerts, #perception, #Belgium, #Luxembourg, #Netherlands, and #Germany. To describe the current state of flood early warning systems, we selected 16 scientific peer-reviewed articles for an in-depth analysis. We also manually ~~scanned~~analyzed 14 country-specific reports that describe or evaluate flood forecasting systems in national languages. The reports were primarily selected by experts from the case study regions, wh~~ich~~o ~~comprised of both~~were either co-authors ~~and~~or interviewees. Additionally, 13 key-informant interviews ~~Interviews~~ were held with ~~13~~ flood forecasting experts from national hydro-meteorological agencies or with agencies and experts involved in crisis management (Appendix A). For every country, we searched for at least one~~1~~ forecasting expert at a governmental forecasting agency and one~~1~~ person directly involved in crisis management, to ensure diversity in the organizations involved. For the interviews, we developed a semi-structured questionnaire (Supplement S1) to inquire about specific questions related to evaluating current FFEWSs. We structured the interview in the five different FFEWS pillars, as outlined by WMO (2023): (1) data collection, (2) forecasting, (3) communication, (4) decision making, (5) action/response. The division of the interview into five pillars facilitated a thematic analysis (Kiger & Varpio, 2020). Within each pillar, we manually synthesized the responses, identifying patterns, commonalities, and differences between the different organizations, based on the audio recordings obtained with the participant's consent. All interviewees were comfortable in speaking English, so translation of the recordings was not necessary. We included an additional iteration of the synthesized material with most interviewees, to ensure correct interpretation of the interviews. To contextualize our findings, we integrated insights from the literature, comparing ~~them~~ our findings with state-of-the-art scientific research. Below, we discuss the results for each country. ~~To contextualize our findings, we integrated insights from the literature, comparing them with state-of-the-art scientific research.~~

3 Key characteristics of the operational FFEWS

In this section, the key characteristics of FFEWS are presented based on recent literature and the expert interviews. First, we ~~will~~ present a general overview of the different systems (Section 3.1), after which we ~~will present~~discuss the warning levels used (Section 3.2), a detailed overview per country (Sections 3.3-3.6), and finally provide an overview of collaborations between the different regions (Section 3.7).

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3.1 Overview of the operational FFEWS

Table 1 summarizes the key characteristics of FFEWS over the region hit by the 2021 flood event. The meteorological agencies use different forecasting systems, and all use Ensemble Prediction Systems (EPS) to represent uncertainty (Table 1).

Table 1. Characteristics of Flood Forecasting and Early Warning Systems (FFEWS) in different European regions and countries.

	Country	Germany (RLP)	Germany (NRW)	Luxembourg	The Netherlands	Belgium (Flanders)	Belgium (Wallonia)
Meteo forecasts	**Forecast agency**	DWD		Meteolux	KNMI	RMI	
	Main ensemble model(s)	ICON-D2-EPS and ICON-EPS		ICON-(D2-)EPS, ECMWF-ENS, AROME-EPS	HarmonEPS and ECMWF-ENS	ECMWF-ENS (AROME-EPS under development)	
Flood forecasts	**Forecasting agency**	LfU	LANUK	AGE	WMCN and regional water authorities	HIC and VMM	SPW
	Main hydrological and model(s)	LARSIM	LARSIM	LARSIM	HBV and SOBEK	NAM and MIKE11	Hydromax
	Discharge (D) or flood inundation (I) forecast (lead time)	D (48h)	D (10 days)	D (24-48h)	D (5-days and 15-days)	D (10-day), I (48h)	D (lead time dependent on catchment size)
	Post-processing technique on discharge forecasts	ProFoUnD analysis (Haag et al., 2013).	Unknown	Yes, bias correction	Ensemble dressing (Verkade et al., 2017)	Non-parametric (Van Steenbergen et al., 2012)	Unknown
	Probabilistic forecasts?	Yes	Yes	Yes	*National level (WMCN)*: Yes *Regional water authorities*: Not always	Yes	Yes
	Online portal(s)	www.hochwasserzentralen.de *RLP*: https://www.hochwasser.rlp.de *NRW*: https://hochwasserportal.nrw (only observations; forecasts in preparation)		https://www.inondations.lu/map	https://waterinfo.rws.nl	*Flanders*: https://www.waterinfo.be *Wallonia*: https://hydrometrie.wallonie.be (only observations)	
Crisis	**Emergency management plans for floods**	Yes	Yes, but not specifically for floods	Yes	Yes	Yes, but not specifically for floods~~, Provincial Emergency and Intervention plans~~~~Unknown~~	Yes, but not specifically for floods

	Primary warning communication system (start date of operation)	MoWas (October 2001) and DE-alert (February 2023)	LU-alert (October 2024)	NL-alert (November 2012)	BE-alert (June 2017)

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The hydrological forecasting agencies also use different hydrological models for flood discharge forecasting. In the German regions RLP and NRW and in Luxemburg, the LARSIM hydrological model is used. The main forecast models in T~~t~~he Netherlands are HBV and SOBEK, run on the Delft-FEWS system. In Belgium, ~~a~~ different systems are~~is~~ used in Flanders ~~(~~(NAM and MIKE11~~,~~ on the FEWS-Flanders system) and Wallonia (Hydromax) (Table 1). Most operational flood forecasting centers use probabilistic forecasts to account for ~~the~~ uncertainty (except for some regional water authorities in the Netherlands) and use post-processing methods to correct forecast output, based on historical forecast errors ~~(Table 1)~~. Where the other regions rely on discharge forecasts and thresholds, Flanders is the only region where flood inundation forecasts run operationally ~~(~~for ~~their short-term~~ 48h forecasts~~, 48h)~~. The two lowest rows of Table 1 show information related to crisis management. All regions have emergency management plans for floods. ~~Since the 2021 flood event, all regions also have a cell phone-based alert system and have online portals with flood warning information, which are updated regularly during flooding situations.~~ In Germany and Luxembourg, a cell broadcasting system was installed in response to and after the July 2021 flood, whereas all other regions had such a system in place prior to the 2021 flood. All regions have online portals with flood warning information, which is updated regularly during flood situations. Publicly available flood forecasting information is available via online portals for all regions but NWR and Wallonia, where only gauge-based measurements and respective warnings are published. ~~In the next section, we will present an overview of the warning levels and thresholds used.~~

3.2 Warning levels ~~in the region~~

Meteorological warnings~~Figure 3 and Table 1 provide an overview of different characteristics of the FFEWSs in the regions and countries hit by the 2021 flood event.~~ ~~**Figure 3 shows that flood warning levels differ between countries, as well as between regions. For example, Flanders and Wallonia, or NRW and RLP, have different color codes, which are defined in a different way.**~~

Meteorological warnings are issued based on clearly defined rainfall intensity and duration thresholds (Fig. 3). The thresholds are chosen based on expected impacts to society~~,~~ and are ~~therefore~~ different across countries. Moreover, as those impacts are highly dependent on the situation (e.g. day or night, location, large events), the thresholds are ~~in practice~~ mostly used only as guidance in practice. ~~With regards to meteorological warnings, t~~The meteorological agencies generally use three~~3~~ rainfall thresholds, except for Luxembourg where four~~4~~ levels are used. In T~~t~~he Netherlands and Belgium, yellow-orange-red colors are used as warning levels. Already before 2021, t~~T~~he German Weather Service (DWD) in Germany deploys an additional purple warning for ~~events of~~ "extreme weather" events. ~~As a~~In response to~~on~~ the 2021 flood~~s~~, Luxembourg implemented a new warning level for “immediate danger” in November 2024, with a purple color. This warning requires “immediate action”, such as with rapidly-developing flash-floods.Luxembourg and Germany recently added an extra warning level (dark purple) to represent events with immediate danger. For the lowest threshold level, all countries use valuesthresholds of ~30mm/hr or ~40mm/6hrs, whereas the highest threshold is often related to an event of 80 to 100mm/24hrs (among other thresholds). Only in The Netherlands, the red warning level is not distinguished from orange based on rainfall but only based on expected impacts. These impacts are estimated in an impact-team meeting with key stakeholders (see Section Sect. 3.3).

Hydrological warnings

Figure 3 shows that flood warning levels differ between countries, as well as between regions. For example, Flanders and Wallonia, or NRW and RLP, have different color codes, which are defined in a different way. The number of hydrological warning levels varies between 3 in Wallonia to 6 in RLP (Fig. 3). Hydrological thresholds are mostly clearly defined in all regions, based on specific discharge or water level thresholds, except for Wallonia. Here, solely expert judgement is used to determine the warning level, and the warning thresholds can therefore differ among different events. In the other regions, the thresholds are based on either return periods (e.g., in RLP), or local flood impacts (e.g., in NRW, Luxembourg, Flanders). Warnings in Flanders slightly deviate from the other countries and use different water level thresholds for: (a) Alarm States, based on impact to water infrastructures, and (b) Flood Warnings, based on the distance between the water level and dike crest (Fig. 3 and SectionSect. 3.4). Red is the highest warning level in all regions, except for in the German federal state RLP region. As a In response toon the 2021 floods (in autumn 2023), the flood forecasting servicecenter in RLP (Landesamt für Umwelt Rheinland-Pfalz) subdivided the already existing purple category for extreme events into purple (> 1/50 year event) and dark purple (>1/100 year event) to create the opportunity to point out an “extremely dangerous flood event” (Landesamt für Umwelt Rheinland-Pfalz, 2025). where a dark purple level was added to represent catastrophic floods (with a 100-year return period and beyond). The thresholds are based on either return periods (e.g., in RLP), or local flood impacts (e.g., in NRW, Luxembourg, Flanders). Warnings in Flanders slightly deviate from the other countries and use different water level thresholds for: (a) Alarm States, based on impact to water infrastructures, and (b) Flood Warnings, based on the distance between the water level and dike crest (Fig. 3 and Section 3.4).

Table 1 shows that most FFEWSs follow a probabilistic approach to account for the uncertainty in the forecasting system. Where the other regions rely on discharge forecasts and thresholds, Flanders is the only region where flood inundation forecasts run operationally (for their short-term forecasts, 48h). The three columns on the right of Table 1 show information related to responses. All countries except Wallonia and Luxemburg have mandatory flood emergency plans. Meanwhile, all regions also have a cell phone-based alert system and have online portals with flood forecast information, which are updated regularly

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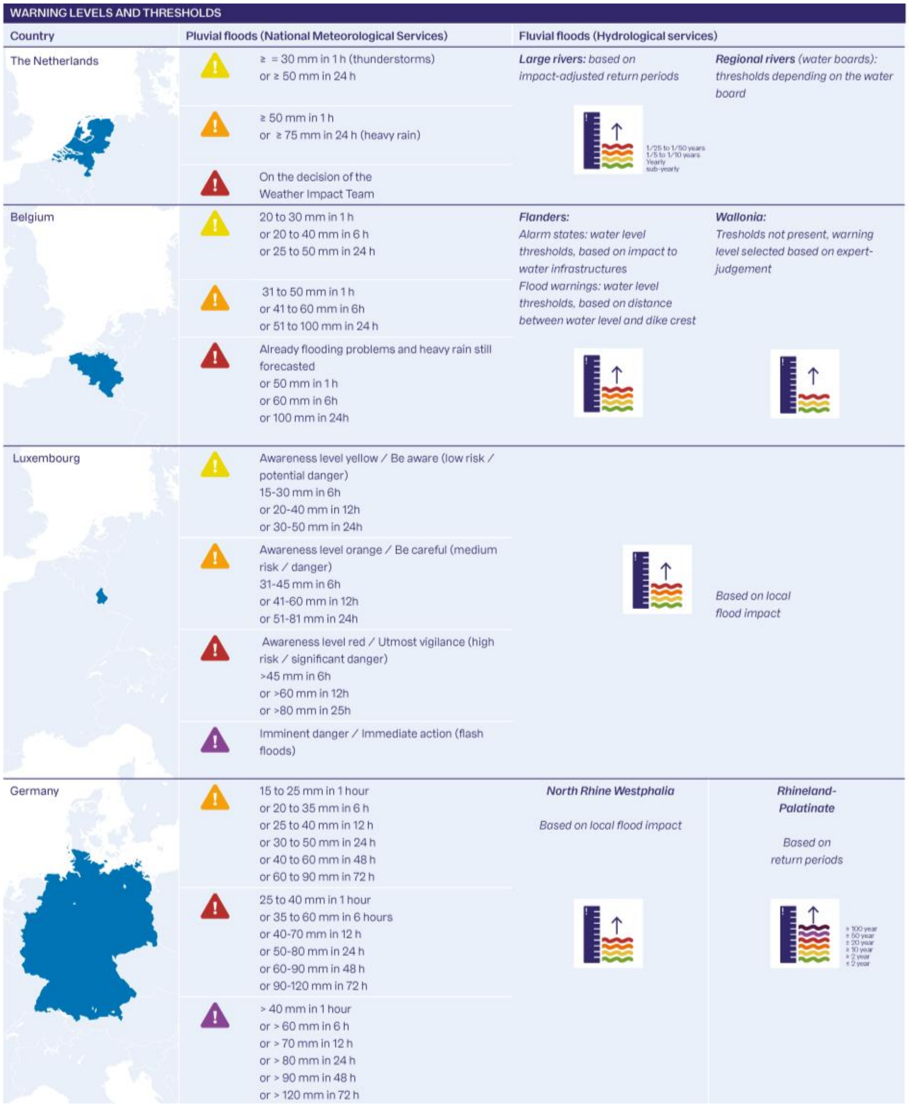
during flooding situations. In Germany and Luxembourg, a cell broadcasting system was installed in response to and after the July 2021 flood.

We now proceed with an overview per country with (a) a general description of the FFEWSs and a more in-depth assessment of the current (b) meteorological and (c) hydrological forecasts, and (d) discussion on the characteristics of crisis management and communication, with an emphasis on experiences during the 2021 flood event.

Figure 3: An overview of the operational ~~early-~~warning levels for pluvial (left) and fluvial (right) floods. The ~~warning~~ colors shown for warning levels correspond to the colors used operationally.



WARNING LEVELS AND THRESHOLDS

Country	Pluvial floods (National Meteorological Services)	Fluvial floods (Hydrological services)	
The Netherlands	≥ = 30 mm in 1 h (thunderstorms) or ≥ 50 mm in 24 h	*Large rivers:* based on impact-adjusted return periods 1/25 to 1/50 years 1/5 to 1/10 years Yearly sub-yearly	*Regional rivers* (water boards): thresholds depending on the water board
	≥ 50 mm in 1 h or ≥ 75 mm in 24 h (heavy rain)		
	On the decision of the Weather Impact Team		
Belgium	20 to 30 mm in 1 h or 20 to 40 mm in 6 h or 25 to 50 mm in 24 h	*Flanders:* Alarm states: water level thresholds, based on impact to water infrastructures Flood warnings: water level thresholds, based on distance between water level and dike crest	*Wallonia:* Tresholds not present, warning level selected based on expert-judgement
	31 to 50 mm in 1 h or 41 to 60 mm in 6h or 51 to 100 mm in 24 h		
	Already flooding problems and heavy rain still forecasted or 50 mm in 1 h or 60 mm in 6h or 100 mm in 24h		
Luxembourg	Awareness level yellow / Be aware (low risk / potential danger) 15-30 mm in 6h or 20-40 mm in 12h or 30-50 mm in 24h		Based on local flood impact
	Awareness level orange / Be careful (medium risk / danger) 31-45 mm in 6h or 41-60 mm in 12h or 51-81 mm in 24h		
	Awareness level red / Utmost vigilance (high risk / significant danger) >45 mm in 6h or >60 mm in 12h or >80 mm in 25h		
	Imminent danger / Immediate action (flash floods)		
Germany	15 to 25 mm in 1 hour or 20 to 35 mm in 6 h or 25 to 40 mm in 12 h or 30 to 50 mm in 24 h or 40 to 60 mm in 48 h or 60 to 90 mm in 72 h	*North Rhine Westphalia* Based on local flood impact	*Rhineland-Palatinate* Based on return periods ≥ 100 year ≥ 50 year ≥ 20 year ≥ 10 year ≥ 2 year ≤ 2 year
	25 to 40 mm in 1 hour or 35 to 60 mm in 6 hours or 40-70 mm in 12 h or 50-80 mm in 24 h or 60-90 mm in 48 h or 90-120 mm in 72 h		
	> 40 mm in 1 hour or > 60 mm in 6 h or > 70 mm in 12 h or > 80 mm in 24 h or > 90 mm in 48 h or > 120 mm in 72 h		

~~We now proceed with~~In the following we provide an overview per country with (a) a general description of the FFEWSs and

Country	Deterministic or probabilistic hydrological forecast	Type of hydrological forecast (D, I)	Lead time (h)	Flood emergency plans (Y/N)	Primary alerting system	Flood forecast online portal
Germany (RLP)	PF	D	48 hours	Y	MoWas and DE-alert	National: www.hochwasserzentralen.de https://www.hochwasser.rlp.de/
Germany (NRW)	PF	D	10 days	Y		https://hochwasserportal.nrw/lanuv (Only observations)
Luxembourg	PF	D	24-48h	Y	LU-alert	https://www.inondations.lu/map
The Netherlands	DF (5-day forecast) PF (15-day forecast)	D	5- days and 15 days	Y	NL-alert	https://waterinfo.rws.nl/#/ waterberichtgeving.rws.nl
Belgium (Flanders)	PF	D (10-day forecast) I (48h-forecast)	48h and 10-days	Y	BE-alert	https://www.waterinfo.vlaanderen.be/
Belgium (Wallonia)	PF	D	Depending on cathment size	Y but not for all areas		https://hydrometrie.wallonie.be/home.html

D= Discharge
I = Inundation
DF=Deterministic forecast
PF=probabilistic forecast
Y=Yes
N=No

a more in-depth assessment of the current (b) meteorological and (c) hydrological forecasts, and (d) discussion on the characteristics of crisis management and communication, with an emphasis on experiences during the 2021 flood event.~~Table 1. Characteristics of Flood Forecast and Early Warning Systems (FFEWS) in different European regions and countries.~~

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3.~~1~~3 Germany

General FFEWS setup

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At present, the legal responsibility for weather forecasting, ~~of~~ flood forecasting, and response ~~forecasting and warning of hydro-meteorological events~~ in Germany is split between the German Weather Service (DWD), flood forecasting centers in the ~~F~~federal ~~s~~States (Länder), and flood emergency management in the counties (Landkreise), respectively. The DWD is mandated to issue~~s~~ weather forecasts and provides severe weather warnings. Federal state f~~F~~lood forecasting centers translate the ~~upcoming~~ weather forecast into hydrological forecasts and disseminate~~provide their interpretation into~~ warning messages for affected catchments~~watersheds~~. In April 2024, the Federal Act on the DWD (Gesetz über den Deutschen Wetterdienst) was changed so that the DWD is now allowed to also disseminate warnings other than severe weather warnings, which include flood warnings. A national natural hazards online portal to share this information was released in 2025 (www.naturgefahrenportal.de)~~is currently under development; its release is expected in 2025~~. Local emergency management authorities interpret the information from forecasting agencies and translate it to impact-specific warnings and are responsible for decision making and triggering specific emergency actions, such as evacuation. Warnings are disseminated to the public via the centralized Modular Warning System (MoWaS), operated by The German Federal Office of Civil Protection and Disaster Assistance (BBK).

Meteorological forecasts~~ing~~

In Germany, ~~the~~ DWD ~~is mandated by law to provide the official weather forecasts and severe weather warnings. Their~~uses two ensemble forecast models, the ICON-D2-EPS (for the next ~~27~~48 hours) and ICON-EPS (for the next 7.~~,~~5 days) ~~models provides a~~n ~~20-member ensemble forecast~~s ~~for the upcoming 48 hours~~. More recently, ~~T~~the DWD has developed a so-called "seamless" forecasting system to better forecast small-scale convective events and flash floods, called SINFONY. This system integrates ensemble weather forecasts and nowcasting techniques (based on real-time radar measurements) over shorter lead times (Blahak et al., 2024). Forecasts from DWD are delivered to the environmental offices and flood forecasting agencies of the f~~F~~ederal s~~S~~tates and to water associations ('Wasserverbände'). These contain a description of the characteristics of severe weather events and the amount of expected precipitation. The thresholds and warning levels for heavy rainfall as used by the DWD are summarized in Fig. 3.

Hydrological forecasts~~ing~~

~~Ensemble weather predictions are used as input for hydrological~~ Ensemble flood forecasting models are operational at 10 flood forecasting centers in the f~~F~~ederal s~~S~~tates. ~~Additionally~~Next to those, regional flood forecasting centers~~, specifically for large navigable rivers such as the Rhine,~~ are in operation, specifically for large navigable rivers such as the Rhine. ~~Data exchange between flood forecasting centers and neighboring countries is implemented, for example by sharing gauging station data. An overview of flood forecasting models, and t~~The locations of gauging stations at which the hydrological discharge and water level forecasts are issued are provided ~~in~~ by the ~~Report of the German~~German Working Group on water issues of the f~~F~~ederal s~~S~~tates (LAWA-Commission; ~~(~~LAWA, 2020). The national web portal (Table 1) was established after the severe flood in August 2002 and provides an overview of gauges with up-to-date flood forecasting and warning information. Moreover, it serves as a gateway to the specific web services of flood forecasting centers in the f~~F~~ederal s~~S~~tates. It also disseminates written interpretations of the forecasts (in so-called "Lageberichte"). The LAWA (2020) report further contains a detailed overview of the frequency of forecast updates for specific gauges in case of flooding, which typically ranges between 2 and 24 hours.

In Germany, a~~A~~ variety of different hydrological ~~forecasting~~ models and warning configurations are used by ~~the~~ many regional and federal state forecasting centers (Demuth and Rademacher, 2016). ~~Here, we focus on the regional flood prediction in the German Federal States of NRW and RLP (Fig. 2).~~ The environmental office in RLP (Landesamt fur Umwelt, LfU) is responsible for flood forecasting. They issue forecasts and warnings with a 48-hour lead time, based on a 20-member ensemble forecast from the DWD ICON-D2-EPS model. LfU uses a post-processing method to correct model outputs, based on the Program to assess the Forecast Uncertainty of Discharge (ProFoUnD) analysis (Haag et al., 2013). The forecasts are updated every three hours ~~(~~, which is the same frequency as the DWD forecasts~~)~~. In NRW, the responsibility for flood forecasting belongs to the ~~Landesamt für Natur, Umwelt und Verbraucherschutz~~ Landesamt für Natur, Umwelt und Klima Nordrhein-

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Westfalen (LANUK~~V~~). A new flood forecasting team was formed in LANUK, as a response to~~n~~ the 2021 floods. Currently, water level observations at some gauges in NRW are accessible in near-real-time, but forecasts are not publicly available (Table 1). In NRW, ~~LANUV~~LANUK runs hydrological ensemble forecasts operationally every 3 hours.~~ for 10 days in the future.~~ These predictions are based on the Large Area Runoff Simulation Model (LARSIM) hydrological model and use weather forecast data from the ICON-D2-EPS (20 ensemble members) and ICON-EPS (40 ensemble members) models. ~~-~~The two regions, NRW and RLP, use different color codes and warning levels (Fig. 3). While the warning thresholds in RLP are based on water level return periods, the thresholds in NRW are based on local impacts to buildings and communities. NRW defines four different warning levels, while RLP uses six. NRW is in the process of adding an additional purple warning level as well, which represents a risk of catastrophic floods. This would better streamline the hydrological warnings of NRW and RLP and the meteorological warnings from DWD, which also include a purple level (Fig. 3). Besides some prototypes in pilot areas, near-real-time flood inundation and impact forecasting are not yet implemented in the operational flood forecasting and warning systems in Germany (Merz et al., 2020).

Crisis management and communication

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Warnings from the federal hydrological flood forecasting centers (e.g. ~~LANUV~~LANUK in NRW) are sent to the county (Landkreis) crisis response centers. Based on laws regarding general civil assistance and disaster management all counties, municipalities, and ~~free~~ independent cities~~-~~ in Germany, which are not affiliated ~~belonging~~ to a count~~ies~~y, are required to have a ~~general flood warning and preparedness plan~~disaster management plan (DKKV, 2024; Ministerium des Innern und für Sport Rheinland-Pfalz, 2020). ~~For example,~~ RLP has developed a specific flood emergency management plan: the Rahmen-, Alarm- und Einsatzplan Hochwasser (Ministerium des Innern und für Sport Rheinland-Pfalz, 2020). The county crisis response centers (not the federal state hydrological forecasting centers) are responsible for dissemination of the warnings to the public. ~~In practice, while these plans are required it is only in the aftermath of a disaster that it is revealed whether the plan is realistic, can be implemented, and is effective for crisis management in the county (DKKV, 2024).~~

Both~~ the~~ DWD and flood forecasting centers can activate MoWaS in case of an expected catastrophic flood and further disseminate information to other channels such as warning apps (Meine Pegel, NINA or KATWARN), radio, and television (IIASA, 2022). Since February 2023, the population can be warned using a new cell broadcasting system (DE-alert), which does not require the installation of an application and is connected to the MoWas system. In terms of online information, residents show a clear preference for maps in warning messages (Lindenlaub et al., 2024a).

3.24 Luxembourg

General FFEWS setup

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Meteorological forecasts are used by the flood forecasting department (Service de prévision des crues) of the water management authority (Administration de la gestion de l'eau, AGE). The AGE produces forecasts for the main rivers systems (the Alzette, Chiers, Moselle, Sûre and Syre), but also for the Mosel in France, which are publicly available via the web portal (Table 1). In case of a large flood, a crisis team is activated to coordinate emergency management activities. Civil protection activitiesmeasures and the organization of the response during normal floods are conductedcarried out by the national fire brigade: the CGDIS (Corps Grand-Ducal D'Incendie et de Secours). In November 2024, LU-alert was launched, which is a new national warning system based on cell-broadcasting alerts on mobile phones and supports the geo-located SMS services (Le gouvernement du Grand-Duché de Luxembourg, 2025). The SMS service has the additional advantage that it enables to monitor the number of people in a certain area, which CGDIS can use to monitor how many people have been evacuated. This system was launched as a directin response to the 2021 floods. With the launch of this new system, Luxembourg also added a new purple warning level for events with "immediate danger" which require "immediate action", such as for flash floods. This new purple level can be issued by the meteorological agency (Meteolux) and the crisis management, but not by the hydrological agency AGE.Recent developments include the LU-Alert warning system for mobile phones. In addition, warning levels and color codes have been recently streamlined between the meteorological and hydrological forecasts, and the crisis management.

Meteorological forecastsing

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The national meteorological service Meteolux does not run a separateits own weather model but instead uses different weather models from neighboring countries (from ECMWF, DWD, and MeteoFrance), like the ICON-(D2-)EPS, ECMWF-ENS, and AROME-EPS. A severe weather risk assessment unit (Cellule d'évaluation du risque intempéries, CERI) can be initiated to estimate the societal impacts. The CERI includes representatives from the AGE, MeteoLux, the national government (Haut-Commissariat à la protection nationale), and CGDIS. Meteolux As described above, Meteolux adopted new warning levels in November 2024recently adopted new warning levels: yellow-orange-red-purple (Fig. 3). The largest change is the inclusion of a purple warning. This can generally only be issued in case of severe flash floods with imminent danger, requiring immediate action.

Hydrological forecasts~~ing~~

Hydrological forecasts and warnings are provided by the flood forecasting department of AGE. They use a wide range of meteorological forecasts as input, from~~ the~~ DWD, ECMWF, and MeteoFrance. The ensemble forecasts are made with the LARSIM model and can be updated every hour. They have a lead time of 24 hours for smaller streams, and 48 hours for the large rivers (e.g., Moselle, L~~l~~ower ~~-~~Sauer). Ensemble discharge forecasts are optionally bias-corrected for current observation–simulation differences in discharge, soil moisture, precipitation, and temperature. They are generally updated every three hours during normal situations and every hour during emergencies. AGE only publishes the deterministic forecasts on the portal, while multi-model ensemble forecasts are used internally. Warning levels in Luxembourg have recently been revised, and AGE now uses three different levels: yellow ("Cote de vigilance"), orange ("Cote de pré-alerte") and red ("Cote d'alerte"). Those are in line with the warning levels of Meteolux, and the crisis management (see below). However, the hydrological service (AGE) is not mandated to issue a purple warning in the new system. This is reserved for the meteorological forecasting service or crisis management. Interviewees from Luxembourg stressed that the new warning levels are based on expected impact, derived from flood maps and/or consultations with local authorities and firefighters (Fig. 3).

Crisis management and communication

Luxembourg has a specific emergency management plan for extreme weather and floods (Le gouvernement du Grand-Duché de Luxembourg, 2025). During regular floods, flood response is managed by CGDIS, who are in constant exchange with the flood forecasting service. When the flood risk is deemed high, a Crisis Cell is activated, led by the High Commission for National Protection (HCPN) and comprising representatives from various bodies, such as the Police, Army, and Government. During a crisis, the AGE flood forecasting department is in constant exchange with CGDIS and the High Commission for National Protection (HCPN). The HCPN manages the actions required during a crisis (European Commission, 2024). Four crisis management phases are specified: normal, vigilance, pre-alert, and alert (Le gouvernement du Grand-Duché de Luxembourg, 202~~4~~5). Those are in line with the hydro-meteorological warnings described above. In the 'pre-alert' phase, local flooding is expected and in the 'alert' phase widespread flooding is expected with a significant impact on people and property (Le gouvernement du Grand-Duché de Luxembourg, 202~~4~~5). These alert phases are also coupled to specific water levels. In the '(pre-)alert phase', flood bulletins are circulated which include warnings and a textual interpretation. At the 'alert phase', the prime minister (or his/her delegate) can activate a Crisis Unit Cell (Le gouvernement du Grand-Duché de Luxembourg, 2025~~4~~). The CGDIS pointed out that the procedures have greatly improved since the July 2021 floods. For example, before the 2021 flood event, communication between municipalities and CGDIS often failed. Nowadays, flood alerts are sent to the local fire stations along with a request to contact the (deputy) mayor of the municipality.

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~~To improve warnings to the public, the new LU-aalert system has recently been launched (on 17 October 2024), which supports both cell broadcasting and geo-located SMS services (Le gouvernement du Grand-Duché de Luxembourg, 20245). The SMS service has the additional advantage that it enables to monitor the number of people in a certain area, which CGDIS can use to monitor how many people have been evacuated.~~

3.5~~3~~ The Netherlands

General FFEWS setup

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The Royal Netherlands Meteorological Institute (KNMI) is responsible for the severe weather warnings in The Netherlands. KNMI and national hydrological forecast information is transmitted to the regional authorities, the regional water authorities (Dutch: “Waterschappen”) ~~Water Boards~~, who are responsible for forecasts in the smaller streams and catchments. They advise the crisis management organizations (the so-called ‘Safety Regions’) about the risk and the implementation of protection measures.

Meteorological forecasts~~s~~

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Among the meteorological models used are the HARMONIE-AROME (Frogner et al., 2019) and ECMWF (Haiden et al., 2018) weather models. The HARMONIE model provides hourly, and the ECMWF model 6-hourly forecasts. The ensemble model-version of HARMONIE is called HarmonEPS, which produces a subset of ensembles at every hourly run (‘a running ensemble’). This is different from ECWMF-ENS ~~EPS~~, which runs full ensembles every 6 hours. Meteorological warnings are classified into the yellow-orange-red color code (Fig. 3). The KNMI developed an in-house system to calculate maps of exceedance probabilities for an ensemble weather forecast: the Probabilistic Alert System for the Concurrence of Adverse Weather Elements (PASCAL) system (Kok, 2022).

The KNMI works towards impact-oriented forecasting. To enhance the knowledge and experience on those impact-oriented forecasts, the KNMI launched an Early Warning Centre in 2015. In case an orange or red warning is predicted by the ensemble models (> 60% probability), the KNMI initiates an online multi-disciplinary weather-impact team meeting. This team includes key organizations such as ProRail, the National Crisis Centre (NCC), the Netherlands Traffic Center (VCNL) and the National Operational Coordination Centre (LOCC). This team provides advice to the KNMI on the selected warning level, which is in practice always followed. The stakeholders in the team also fill in an impact questionnaire, which results in an impact score per economic sector. The final warning level is decided by the operational lead at the KNMI. To allow for an early engagement of the impact team, the KNMI can already inform the impact team up to seven days in advance when a warning is not yet generated, but possible (using a 30% probability threshold). In case a rainstorm is predicted only at the last moment, the KNMI issues a warning without first consulting the impact team.

Hydrological forecasts

The national Dutch Water Management Center (WMCN) produces 5-day (validated) and 15-day (automatic) forecasts for the river Rhine (gauge Lobith) and river Meuse (gauge Sint-Pieter), using the HBV and SOBEK models. Those models are run on the Delft-FEWS platform for the whole (international) Rhine and Meuse basins. Forecasts 5-days ahead are deterministic, while the 15-day forecasts are ensemble products. These forecasts use multiple weather models as input: DWD COSMO-LEPS model, DWD ICON-EU ~~(5-days)~~, DWD ICON ~~(5-days)~~, the EC~~W~~MWF-ENS ~~Ensemble Prediction System (EPS)~~, and ECMWF-HRES (deterministic) forecasts. Meteorological uncertainty is included by using ensemble forecasts, where every ensemble member is used as input to the hydrological model. For a small portion of stations (approximately 5%), a post-processing technique is used on the discharge forecasts (Verkade et al., 2017) to include the hydrological uncertainty. This is done by correcting ('dressing') an individual streamflow ensemble member based on historical hydrological model errors. In addition, the WMCN uses ~~European EFAS~~ forecasts from the European Flood Awareness System (EFAS; Smith et al., 2016), which is part of the Copernicus Emergency Management Service.~~and additional information from neighboring countries.~~ Regional water authorities (Dutch: "waterschappen") run forecasts for the smaller Dutch rivers and tributaries. However, not all water authorities run forecasting models operationally and many different models are used.

The Dutch national protocol for high waters and flooding (LDHO) provides an overview of the different warning levels for the Dutch main rivers (WMCN, 2023). Four warning levels are in place (Fig. 3): green, yellow (elevated water levels, water nuisance possible), orange (high waters) and red (extreme high water). These are based on both water level and discharge thresholds, and expressed as return periods (WMCN, 2023, Appendix D). Different return periods apply to different rivers, as the strength of the dikes is different (WMCN, 2023). Therefore, Fig. 3 displays ranges of return periods. The exact return periods per river can be found in WMCN (2023, Appendix D). As multiple ensemble forecasts are made (using multiple models), expert judgement is needed to determine which warning level is eventually selected.

In case of orange or red warnings, an expert group gathers into a national committee: the Landelijke Commissie Overstromingsdreiging (LCO). These experts in meteorology and hydrology translate the water level forecasts into impacts and advise on required interventions. The LCO is mandated to evaluate the color code selected by WMCN and can increase the warning level if deemed necessary (e.g., in case of calamities, such as failures of water infrastructures). As a result of these decisions, information in a web-portal (Table 1) is updated and disseminated every day, which includes the hydrological forecasts, warning levels, and a textual interpretation. In case of orange and red warning levels, the online information can be

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updated multiple times per day. The orange warning level can be issued with a maximum lead time of 48 hours. However, the stakeholders can be informed up to 7 days in advance with a notice that the threshold will potentially be exceeded.

At the local scale, the regional water authorities (“Waterschappen”) ~~Water Boards~~ and Safety Regions are responsible for hydrological forecasting and responses, respectively. For example, the water authority in~~Water Board of~~ Limburg (Waterschap Limburg) runs operational forecasts to predict discharge and/or water levels, with a lead time of 5 days. Predictions are deterministic, although a strong need and wish exist~~s~~ to deploy probabilistic forecasting approaches. In Limburg, a variety of activities were triggered in~~as a~~ response to~~on~~ the 2021 flood~~s~~. A new large programme on flood safety ~~has been launched,~~ called "Waterveiligheid en Ruimte Limburg (WRL)" has been launched in 2022. In this programme, local authorities and the central government are working together to improve Limburg's flood resilience. As part of WRL, a separate early warning project has been started to improve the warning system of the regional water authority (Waterschap Limburg). This leads to input for developing a new impact-based forecasting system of the Waterschap Limburg and the Safety regions. ~~After the 2021 floods, the Water Board of Limburg developed clear warning thresholds for the smaller rivers (Veiligheidsregio Limburg-Noord & Zuid-Limburg, 2023). Those are identified based on the expected nuisance to the (urban) surroundings and thus take the strength of the dikes and the exposed assets into account (Veiligheidsregio Limburg-Noord & Zuid-Limburg, 2023).~~

Crisis management and communication

The Safety Regions are regional organizations responsible for crisis management for various kinds of hazards and the provision of information to the population. The Netherlands is the only country with such administrative units specifically designed for crisis management. Based on the estimation of LCO and the Departementaal Crisis Centrum (DCC) of the Ministry of Infrastructure and Water Management, the Safety Region and other stakeholders can be warned through the National Crisis Management System (LCMS). Actions (e.g., dike inspections) are linked to the warning levels ~~(e.g., dike inspections)~~, which are detailed in WMCN (2023) for the large rivers and in the protocols from the regional water authorities ~~Water Boards~~ for the small rivers. Some regions in The Netherlands have a dedicated emergency management plans for floods. Limburg~~, the Dutch~~ province~~, which was most heavily affected by the 2021 floods, developed an extensive flood emergency management plan~~updated the ~~Limburg~~ flood disaster management plan ~~-~~(Rampbestrijdingsplan Hoogwater Limburg, Veiligheidsregio Limburg-Noord and Zuid-Limburg 2023) ~~. This plan was updated~~ after the 2021 floods, by including clear warning thresholds for the smaller rivers ~~in Limburg~~. Those are identified based on the expected nuisance to the (urban) surroundings and thus take the strength of the dikes and the exposed assets into account (Veiligheidsregio Limburg-Noord & Zuid-Limburg, 2023). ~~After the 2021 floods, also the small rivers (e.g., Geul) were included in this plan.~~ In case of a flood crisis, the departmental (DCC) or national crisis management center (NCC) coordinates the crisis, and the LCO advises on measures to take (WMCN, 2023).

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The public is warned through multiple channels, of which the most important are NL-ALERT (Table 1) and the 4278 air raid alarm systems. The KNMI also actively disseminates warnings through the newly developed KNMI app, and through social media. They have a clear impact- and action-oriented warning approach (see ~~Section~~ Sect. 4.3~~5~~).

3.6~~4~~ Belgium

General FFEWS setup

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Meteorological forecast and warnings for Belgium are produced by the Royal Meteorological Institute of Belgium (RMI). River discharge forecasts are separately generated for Flanders and Wallonia, using RMI forecasts as input. The National Crisis Center (NCC) is responsible for managing national level crisis situations.

Meteorological forecasts

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At the RMI, ~~T~~the deterministic meteorological forecasts are produced by the ALARO ~~(Gerard et al., 2009)~~ model (Gerard et al., 2009). ~~As shown in Table 1, e~~Currently, ensemble forecasts from the ECMWF-ENS system are used and the ~~and~~ RMI develops a new ensemble system (~~HARMONIE~~-AROME-EPS; ~~(F~~Frogner et al., 2019) (Table 1) ~~models~~. ~~RMI is currently developing an ensemble prediction system RMI-EPS, which consists of a combination of AROME and ALARO with 11 ensemble members each (Smet, 2017).~~ However, operational meteorologists also use other models from other agencies ~~other weather centers~~ such as the UK Met Office and ~~,~~DWD~~, and ECMWF~~.

Warnings are generated using the yellow-orange-red color codes on a provincial level (Fig. 3). Warnings are issued if more than~~the~~ 65% of the ensembles are exceeding the rainfall thresholds for that specific color (Fig. 3), ~~probability threshold is exceeded~~ for > 25% of the provincial area. Warnings for a specific color can also be issued if there is a small chance (< 65% or < 25% of the area) on precipitation amounts belonging to the following color (for example, a yellow warning can be issued if there is a small chance on rainfall belonging to an orange warning). ~~, or the 65% probability threshold is exceeded of the following color code for < 25% of the area, or the 15-65% probability threshold is exceeded of the following color code for > 25% of the area.~~ These are guidelines, but the RMI can deviate from those based on the expected impact. The impacts are discussed in online impact team meetings, which can be called 2-3 times a day during severe weather conditions. These meetings involve the hydrological centers for Wallonia and Flanders (SPW and HIC/VMM, respectively), fire brigades, regional and national crisis centers and provincial governors. Although the RMI takes impacts into account in selecting the warning levels (e.g., a rainstorm approaching a festival), the interviewee stressed that the RMI is not mandated to provide impact- or action-oriented advisories. Four radars provide near real-time observations for nowcasting using the INCA-BE system. This system allows for the generation of so-called “flash warnings”, which are automatically generated warnings at the local level (i.e., municipal) with <1h lead time (Smet, 2017). These warnings are disseminated via the RMI app.

Hydrological forecasts

In Flanders, the Hydrologische Informatie Centrum (HIC) is responsible for ~~the~~ monitoring and forecasting of navigable waters. The non-navigable rivers (category 1) in Flanders are monitored and forecast are issued by the Vlaamse MilieuMaatschappij (VMM). Those observations and forecasts are publicly available on the official Waterinfo web-portal (Table 1). The HIC produces long-term (10 days ~~ahead~~) and short-term ~~forecasts~~ (48 hours ~~ahead~~) forecasts using the hydrological-hydraulic model NAM-MIKE11, run on the platform FEWS-Flanders. The long-term forecasts are based on deterministic ICON/ECWMF forecasts (2 times daily), while the short-term forecasts are derived from deterministic ~~HARMONIE~~ ALARO model runs (4 times daily). The HIC has ~~four~~ six hydrodynamic models for different catchments; 1) IJzer, 2) Leie and its drainage channels, 3) Dender, 4) Zenne-Zeekanaal, 5) the Scheldt estuary and 6) Demer~~: (1) Leie-Bovenschelde Gentse Kanalen, (2) Zeeschelde, (3) Zenne-Zeekanaal, (4) Demer~~. These models provide inundation forecasts, which are also visualized in the web-portal and disseminated to partners. Apart from the river Demer, HIC runs the F~~F~~EWS ~~system~~ for Flanders 4 times per day with input from the ALARO -model of RMI. The rainfall forecasts used as input for the hydrological model are deterministic. Probabilistic discharge forecasts are made using a hydrological post-processing technique, based on historical lead-time dependent model errors (Van Steenbergen et al., 2012). Two types of warnings can be generated 48 hours in advance for both the navigable and non-navigable rivers: alarm states and flood states. These warnings both follow the green-yellow-orange-red color codes~~.~~, for both ~~the warnings for the~~ navigable (provided by HIC) and non-navigable (provided by VMM) rivers. The flood warning states (Fig. 3) are visualized on so-called 'Vrijboordkaarten' and show the distance between the water level and the dike crest. The colors reflect the following situations: green: no floods; yellow: pre-warning; orange: warning, non-critical flooding would be possible; red: alarm, critical flooding would be possible. These flood warning states are based on water-level thresholds determined by the hydrological-hydraulic model forecasting results. The alarm states on the other hand are determined based on the impact on water structures (e.g., bridges), but do not reflect overall flood impacts to society. The forecasts and warning levels are displayed in near real-time on the Waterinfo portal (Table 1). In case of high discharges, ~~T~~the warnings are actively disseminated to the De Vlaamse Waterweg waterways authority, which distributes the warnings to other stakeholders and emergency management. After the 2021 flood~~s~~, the hydrological warning thresholds have been changed in consultation with De Vlaamse Waterweg, mainly to better streamline thresholds among the different regions in Flanders.

In Wallonia, the Direction de la Gestion Hydrologique (DGH) of the Walloon government public service (Service Public de Wallonie, SPW) is responsible for ~~the~~ monitoring, forecasting, and warnings. The DGH operates the Hydromax model using a network of 150 river gauging stations and 100 rain gauges (the 'Wacondah' network) as input (DGH, 2024). Hydrological forecasts are made using deterministic weather forecasts from different ALARO models. ~~As a response on~~ In response to the 2021 flood~~s~~, also ensemble weather forecasts from ECMWF-ENS are used. Five different percentiles are selected from the

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51-member ECWMF ensemble and used in Hydromax to produce hydrological forecasts, which are further post-processed ~~by comparison to~~considering forecast errors ~~in forecasting~~ of previous floods (DGH, 2025). The smaller tributaries (e.g., the Vesdre) are monitored by The Direction des Cours d'Eau Non Navigables (DCENN), which operates a measurement network called “Aqualim” (DGH, 2024). ~~The warnings~~Warnings follow a green-yellow-red color code (Fig. 3) and are issued ~~on~~at ~~a~~ catchment level. Yellow warnings are issued if one (or more) rivers in a basin are expected to cause localized and non-severe floods, and red warnings if one or more rivers ~~of~~in a basin are expected to cause major floods with an impact on infrastructure and local residents. The thresholds are not prescribed but defined by expert judgement depending on catchment wetness state, precipitation forecasts, discharge in upstream rivers and tributaries, and from past experience. ~~The warnings do not take the small tributaries into account. These smaller tributaries (e.g., the Vesdre) are monitored by The Direction des Cours d'Eau Non Navigables (DCENN), which operates a measurement network called “Aqualim” (DGH, 2024).~~ Observations and ~~the~~ flood warnings are displayed on the web-portal of the Walloon government (Table 1). The portal was updated after the 2021 flood, and now also includes the non-naviga~~ta~~ble waterways (from the Aqualim network)~~ along with flood warnings~~. None of the governmental hydrological and crisis management agencies in Wallonia produce and/or use inundation forecasts operationally. Nonetheless, inundation forecasts are produced for some pilot river sections; but currently these forecasts are not communicated to the public since they do not consistently cover the whole river network.

Crisis management and communication

Crisis management in Belgium is organized at three levels: municipal, provincial, and federal state level. At the federal level crisis management is coordinated by the Centre de Coordination des Risques et de la Transmission d’Expertise (CORTEX) for Wallonia and the Crisiscentrum van de Vlaamse overheid (CCVO) for Flanders.

In Wallonia, in case of an orange warning, CORTEX calls in a special flood expertise unit (CELEX) by videoconference. The CELEX unit was launched in~~as~~ response to~~of~~ the 2021 flood event. In case of (pre-) alerts, CELEX develops and shares flood reports with stakeholders (but not with the general public).~~, which~~These reports include an outlook of the consequences and required actions. In Flanders, each province has an Emergency and Intervention Plan (NIP~~ in Dutch~~), which is revised after the 2021 flood~~s~~ and regularly exercised. ~~This process started after the 2021 flood.~~ In case of a large flood disaster, such as in 2021, the federal level is initiated and the National Crisis Center (NCCN) takes over the coordination. The ~~Royal Meteorological Institute (~~RMI~~)~~ can directly send meteorological warnings to the NCCN. Furthermore, every municipality in Wallonia needs to have a general emergency management plan~~, which can also be developed for floods~~ (Plan Général d’Urgence et d’Intervention; PGUI). In May 2025, the Walloon government installed a Regional Crisis Management Plan, which can be applied during flood crises as well (Government of Wallonia, 2025). ~~However, these flood-specific plans are not mandatory.~~ Since June 2017, the public can be warned via mobile cell broadcasting system: BE-ALERT (Table 1).

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3.74 Coordination and data sharing across borders

All interviewees emphasized that data exchange between countries is already quite well organized. For example, the border between The Netherlands and Flanders is marked by the lower part of the Meuse river ('Grensmaas'). To provide a consistent warning for all households along the Grensmaas, Flanders adopts the warning levels used in the Netherlands. In addition, the Dutch water management center (WMCN) uses both the European data from the EFAS system and additional hydrological information from neighboring countries. In Germany, the exchange of meteorological and hydrological data and forecasts is well organized. Data is exchanged between different federal states and different neighboring countries (Poland, the Czech Republic, Austria, Switzerland, France, Luxembourg, and Tthe Netherlands) in near real-time (Demuth and Rademacher, 2016; LAWA, 2020). Several international agreements are in place to foster collaboration in transboundary river basins. The International Commission for the Protection of the Rhine (ICPR) fosters collaboration between the different states in the Rhine basin, and organises annual plenary assemblies, in which joint forecasting developments in forecasting systems are discussed (e.g., on uniform determinationharmonization of forecast uncertaintyies determination; Demuth and Rademacher, 2016). Germany also installed an automatic data exchange between flood forecasting centers from its neighboring countries.In 1987, the Internationalen Kommissionen zum Schutze der Mosel und der Saar (IKSMS) signed an intergovernmental agreement between France, Germany, and Luxembourg to improve flood detection and forecasting in the Saar and Moselle catchments (IKSMS, 2025). This strong collaboration results in hourly international data sharing to all flood forecasting centers, from rain gauges, discharge gauging stations, precipitation radar data, and weather forecasts between all flood forecasting centers (IKSMS, 2025). Moreover, joint data assimilation systems (such as the PLATIN data exchange server), models and forecasting systems are developed, technical trainings are organized, and language courses are offered to improve communication (IKSMS, 2025). Other transboundary basins, especially the for the smaller rivers, can learn from this strong and long-lasting collaboration agreement.

While not identified as a major issue in the FFEWS chains, some concerns were raised in the interviews. -While sometimes common models are developed (such as mentioned above), too often different meteorological and hydrological models are used in different countries (see Table 1) which can result in inconsistent and conflicting information to stakeholders in those transboundary regions. Furthermore,Some some important data is not always shared (efficiently). data exchange across countries faces challenges due to differences in the levels of responsibility for disaster coordination and communication. For example, better cooperation on modelling and the development of common models is needed to ensure consistency and provide tailored information within the same river system at different times, based on stakeholders' requirements. Furthermore, For example, HIC in Flanders –mentioned specificallythe need to suggests improvie ng the exchange of information oanbout upstream reservoirs in Wallonia. Often, information of reservoir levels is not shared, especially for energy-producing reservoirs (for energy companies, such as ENGIE). Further, Iinterviewees from Waterschap Limburg stressed the importance of an international exchange of flood warnings, which is currently lacking. These challenges highlight the need to continue efforts to streamline transboundary collaboration. ~~Below, we will outline the main challenges found in the study.~~

4. Main improvements and ~~Key~~ remaining challenges ~~of operational FFEWS~~~~remaining~~ after the 2021 flood

The interviews revealed that the FFEWSs in all regions are under strong and rapid development after the 2021 flood~~s~~ (Table 2). All regions now ~~use probabilistic forecasts for both rainfall and streamflow,~~ have emergency response plans for floods~~,~~ and use cell-broadcast services for alerting the population. A new flood forecasting team has been developed at LANUK in ~~the German~~ NRW ~~state~~ (Table 2). Moreover, all regions defined clear thresholds for the different hydrological warning levels, except for Wallonia (Fig. 3). In autumn 2023, the flood~~hydrological~~ forecasting center~~agency~~ (LfU) in the RLP ~~state in Germany (LfU)~~ added a new warning level for very extreme floods (> 100-year return period) with a dark-purple color (Fig. 3 and Table 2, top). The ~~hydrological~~ flood forecasting ~~agency~~center of Flanders (HIC) optimized their warning thresholds in close collaboration with stakeholders, such as the Vlaamse Waterweg waterways authority, and many provinces updated their Emergency and Intervention Plans. In Wallonia, a flood expertise unit (CELEX) has been established since the 2021 floods, which can provide tailored flood impact advice during crises. Furthermore, ensemble forecasts are now used to produce flood forecasts and the web-portal for floods has been renewed. In Limburg, ~~As a response to the 2021 floods,~~the ~~a new~~ flood disaster management plan ~~emergency response plan for Limburg~~ ("Rampbestrijdingsplan Hoogwater Limburg") now includes flood scenarios for small rivers (e.g. Geul river), including clear warning thresholds and corresponding actions. Moreover, a large programme has been launched in 2022 to improve flood safety ~~in Limburg~~: Waterveiligheid en Ruimte Limburg (WRL). In November 2024, Luxembourg ~~recently~~ implemented a new alerting system (LU-alert), harmonizing the warning levels of the meteorological forecasts ~~alerts~~ and ~~from the meteorological and hydrological forecasts, as well as~~ the crisis management. This includes a new level for "immediate danger" with a purple color. ~~While many of such improvements take place,~~ Even after those changes, the interviewees identified several issues ~~required~~ that require attention to ~~for~~ further ~~improvement~~ improve~~of~~ FFEWSs (Table 2, bottom). We will further outline those challenges below.~~.~~

Table 2. Most important changes of the Flood Forecasting and Early Warning Systems (FFEWS) triggered in ~~as~~ response to the 2021 flood~~s~~, and the ~~4~~ key challenges remaining in different European regions and countries.

Country	Germany (RLP)	Germany (NRW)	Luxembourg	The Netherlands	Belgium (Flanders)	Belgium (Wallonia)
Major changes since the 2021 floods	DE-alert system, and addition of extra warning level for very extreme floods (dark purple)	DE-alert system, and ~~initiatio~~establishment ~~n~~ of a new flood forecasting ~~team~~center	LU-alert system, including a new warning level for "immediate danger" (purple)	A new multi-year programme on flood safety in Limburg (WRL) and updated	Optimized hydrological warning thresholds (see Fig. 3) and revised Emergency and Intervention Plans	Flood expertise units (CELEX), updated flood portal and move from deterministic to ensemble forecasting ~~Asked~~

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	flood disaster management plan
Key challenges remaining after 2021	**Streamlined warning levels and thresholds** Different warning levels, thresholds, and color codes are used between and~~in the between and~~ within the different countries and organizations.
	Warnings for catastrophic events The highest thresholds are often too conservative (too low) and thus do not reflect major societal flood impacts.
	Impact-based forecasting While impact-based forecasting is recognized as crucial ~~to make forecast-informed~~for efficient decision-makings, such systems are not yet~~rarely~~ operationally implemented in most of the regions.
	Communication before and during the crisis phase Effective communication between different organizations (e.g., between meteorological agencies, ~~hydrological agencies~~flood forecasting centers, crisis management authorities) and to the population~~civilians~~ remains a challenge.

4.1~~1~~ S~~S~~treamlined ~~thresholds /warning levels~~warning levels and thresholds

The first challenge relates to the transboundary differences in meteorological and hydrological warning levels and thresholds. In general, the ~~amount~~number of warning levels, their color and the thresholds used ~~and color codes of meteorological and hydrological levels~~ differ between the different countries (Fig 3). Moreover, they frequently also differ within the different regions of a country and between the meteorological and hydrological ~~and meteorological~~ agencies of a country~~not only differ between countries but even within countries~~ (Fig. 3). For example, ~~T~~the number~~amount~~ of warning levels and their color codes are different in the two federal states of Belgium: Flanders and Wallonia (Fig. 3). In Luxembourg, MeteoLux and CGDIS apply a purple warning level for events posing immediate danger. They are mandated to do so as both maintain permanent operational offices (Fig. 3). While this level is also used by LU-Alert, the ~~hydrological~~ flood forecasting ~~agency~~center (AGE) is not mandated to use this level as they do not operate 24/7. Also, in Germany the warning levels are not consistent among f~~F~~ederal s~~S~~tates. For example, in RLP they are linked to flood return periods and in NRW to flood impacts (NRW, 2024) (Fig. 3) – the latter not necessarily corresponding to the same return periods as in the neighboring RLP (DKKV, 2024). While RLP now distinguishes six warning levels, other German states use just four (like NRW), including a green level for no warning (Fig. 3). Moreover,- the “red” color being ~~of~~ the highest warning level ~~among~~in some ~~hydrological agencies~~flood forecasting centers in Germany (e.g., LANUK in NRW) is inconsistent with the highest “purple” weather warnings from DWD. Interviewees in RLP also state that the number of alerts by ~~the German meteorological office (~~DWD~~)~~ have been high in the past during some periods of possible events and that it could be difficult for the recipients to estimate if a warning indeed results in a flood. Furthermore, DWD warnings are generally cleared at the end of a precipitation event, while ~~hydrological~~flood warnings can still be active because the flood did not yet end~~peak water levels in the rivers are not yet reached~~. According to the interviewees, such ~~a~~ situation happened in 2021 and confused~~ can be confusing for~~ local stakeholders~~ who are not aware of the time lag between rainfall and runoff processes in the catchments~~. Research shows that inconsistent visual and textual warnings from multiple sources are confusing ~~the~~for decision-makers and the public, which can ~~and~~ lead to ineffective communication and actions (Weyrich et al., 2019). We recommend ~~to~~ evaluating~~e~~ the consequences of the above inconsistencies for ~~clearly~~improvement of communication of~~ng~~ early warnings.

4.~~2~~2 ~~Forecasts~~ Warnings for catastrophic events

After the 2021 flood, some regions started a discussion to introduce a new (or additional) color code for extreme floods. In the German f~~F~~ederal s~~S~~tate of RLP, ~~T~~this discussion has led to ~~selecting~~ adopting an additional 'dark purple' level on top of the "purple" level ~~as the color for the highest warning level~~in Autumn 2023~~ in the German Federal State of RLP~~, based on ~~the~~ a 100-year return period threshold (Landesamt für Umwelt Rheinland-Pfalz, 2025). This adjustment was primarily done to improve the communication possibilities for "extremely high danger of flooding". However, recent research suggests that even the purple DWD warnings for the 2021 event were too abstract and that people did not link the warning with such extreme flood event (Ommer et al., 2024). The warning levels for Luxembourg also contain a new purple level, which can only be issued by the meteorological service MeteoLux and not by the ~~hydrological service~~flood forecasting center AGE (Fig. 3). The highest warning level of AGE is "Cote de vigilance rouge" (Red)~~,~~ which is often linked to small return periods. For example, gauge Bollendorf in the Sauer has a red warning threshold related to a water level of 4.25 m, which corresponds to~~is~~ less than a 5-year return period event. This suggests that extreme riverine floods could be better represented in the new warnings. Our interviewees in ~~Tthe Belgium region~~ Wallonia stated that ~~has also started a discussion on an additional warning level and states that~~ "…there should be a new discussion about the need for an extra level of warning (e.g., dark red) for really extreme situations". For the regional water authority in Limburg (Waterschap Limburg)~~Water Board~~, the highest warning level (red) is described as a "water nuisance" to people, rather than a high-impact catastrophic event. However, more extreme thresholds come with more uncertainty. Rare events will typically be forecast with only a few ensemble members. These low-probability and high-impact forecasts bring considerable decision-making challenges ~~are difficult to cope with for decision-makers~~ (Speight et al., 2021), as was also observed for the 2021 event. There is a need to better understand such extreme events, to better represent them in the models and forecasts, and to better predict potential impacts. This was raised by respondents in all countries.

Flood hazard maps can be used to estimate which areas are going to be flooded during an expected event (e.g., Dottori et al., 2017). However, the use of static flood hazard maps showed large deficiencies during the 2021 flood. Vorogushyn et al. (2022) showed that the inundated~~ion~~ areas in 2021 exceeded the most extreme official hazard maps in the Ahr V~~v~~alley and recommend developing more severe extreme scenarios. In Wallonia, responders and households in 'safe green or unmarked zones' faced the 2021 flood and did not know what to do. Many of the flooded areas directly along the Vesdre river (a tributary of the Meuse river) were marked as safe green zones or simply left unmarked in official flood hazard maps. As a result, many residents were not aware of the flood risk~~,~~ and were surprised, their houses were flooded up to the second floors (Rodríguez Castro et al., 2025).

4.~~3~~3 Impact-based forecasting

Our study confirms that the uptake of impact-based forecasting in operational systems is challenging. Most important reasons are the lack of relevant data (e.g., on flood vulnerability), institutional collaboration across sectors (e.g., between forecasting agencies and emergency management), and lack of computational power to run inundation models, especially for multiple ensemble members. The move towards impact-based forecasting is crucial to optimize warnings, as mentioned in the interviews. For example, in Wallonia the same warning level for different events can result in significant differences in impact (DGH, 2024). Moreover, interviewees indicated that impact-based forecasting is important in taking effective early actions. First responders require specific and detailed information, such as expected flooded areas, flood depths at critical infrastructures (e.g., hospitals or schools) and ~~even~~ predictions of expected damages. Therefore, ~~Impact-based warnings provide crisis managers and first responders with more tailored information (Apel et al., 2022; Boult et al., 2022; Red Cross Red Crescent Climate Centre, 2020; Meléndez-Landaverde et al., 2020, Merz et al., 2020, Rhein and Kreibich, 2025, Poolman et al., 2018). However, the practice of impact-based forecasting is still in its infancy (Merz et al., 2020). Only about 30% of the national meteorological and hydrological services in Europe use impact-based models (Kaltenberger et al., 2020; Schroeter et al., 2021). For example, the hydrological service in Wallonia emphasizes the need for impact-based forecasting and states that currently the same warning level for different events can mean different impacts on the ground (DGH, 2024). M~~many interviewees stressed that ~~estimates~~predictions of potentially flooded areas and affected buildings are a crucial component to move to effective impact-based forecasting ~~highly needed to improve the effectiveness of early actions.~~

~~**Citizens showed a clear preference for inundation maps in warning messages they receive, compared to other information types (e.g. a warning symbol; Lindenlaub et al., 2024a). Moreover, people tend to assess the flood magnitude higher when an inundation map is provided (Lindenlaub et al., 2024b). The high value of detailed flood inundation predictions for emergency management is also emphasized in England (Aldridge et al., 2020). However, it is not yet clear whether warning messages accompanied by information on flooded area lead to better protective behaviour of residents (Kuller et al., 2021).**~~ ***The importance of inundation forecasts***

~~Our study confirms that the operational uptake of impact-based forecasting is challenging, but crucial.~~ The HIC in Flanders is the only ~~operational~~ flood forecasting center included in this study which produces inundation forecasts operationally (~~visualized in their portal,~~ Table 1). However, these inundation forecasts are not used in any of the official warning levels (see Fig. 3). Flood inundation forecasts can be made using multiple methods, ~~including~~ by translating streamflow to event-based

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flood hazard maps using a pre-computed catalogue of hydrodynamic simulations (~~described in~~ Dottori et al., 2017), or by using operational hydrodynamic models ~~in real-time~~ (~~described in~~ Apel et al., 2022). Recent computational advances in flood modeling, such as the use of machine-learning, Graphical Processing Units (GPUs) and cloud computing make r~~eal-time~~operational inundation modelling realistic and affordable (Hofmann et al., 2021; Speight et al., 2021; Apel et al., 2022; Agerbeek et al., 2024). Apel et al. (2022) produced inundation forecasts (in a hindcast mode) for the 2021 flood event in the Ahr V~~v~~alley at 10 m spatial resolution in a timespan suitable for operational application (14 min on a GPU) and showed the potential~~strong added~~ value of these forecasts for operational crisis management. Estimates of inundated areas (and other flood variables~~factors~~, e.g., flow velocity) can be overlayed with exposed buildings and critical infrastructure, to support rapid mapping of flood impacts (e.g., Apel et al., 2022, Najafi et al., 2024~~, and~~ Dottori et al., 2017). Citizens show a clear preference for inundation maps in warning messages they receive, compared to other information types (e.g., a warning symbol; Lindenlaub et al., 2024a). Moreover, people tend to assess the flood magnitude higher when an inundation map is provided (Lindenlaub et al., 2024b). The high value of detailed flood inundation ~~predictions~~ forecasts for emergency management is also emphasized in England (Aldridge et al., 2020). However, it is not yet clear whether warning messages accompanied by information on flooded area lead to better protective behaviour of residents (Kuller et al., 2021).

~~For example, the hydrological service in Wallonia emphasizes the need for impact-based forecasting and states that currently the same warning level for different events can mean different impacts on the ground (DGH, 2024). Many interviewees stressed that estimates of potentially flooded areas are highly needed to improve the effectiveness of early actions. Citizens showed a clear preference for inundation maps in warning messages they receive, compared to other information types (e.g. a warning symbol; Lindenlaub et al., 2024a). Moreover, people tend to assess the flood magnitude higher when an inundation map is provided (Lindenlaub et al., 2024b). The high value of detailed flood inundation predictions for emergency management is also emphasized in England (Aldridge et al., 2020). However, it is not yet clear whether warning messages accompanied by information on flooded area lead to better protective behaviour of residents (Kuller et al., 2021). The HIC in Flanders is the only operational center included in this study which produces inundation forecasts operationally (visualized in their portal, Table 1). However, these inundation forecasts are not used in any of the official warning levels (see Fig. 3). Recent computational advances in flood modeling, such as the use of machine-learning, Graphical Processing Units (GPUs) and cloud computing make real-time inundation modelling realistic and affordable (Hofmann et al., 2021; Speight et al., 2021; Apel et al., 2022; Agerbeek et al., 2024). Apel et al. (2022) produced inundation forecasts for the 2021 flood event in the Ahr valley at 10 m spatial resolution in a timespan suitable for operational application (14 min on a GPU) and showed the strong added value of these forecasts for operational crisis management. Estimates of inundated areas (and other factors, e.g., flow velocity) can be overlayed with exposed buildings and critical infrastructure, to support rapid mapping of flood impacts (e.g., Apel et al., 2022, Najafi et al., 2024 and Dottori et al., 2017).~~

Best practices of impact-based forecasting

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Despite the challenge of operational impact-based forecasting, some best practices in the region should be outlined. Some regions, such as NRW in Germany, developed impact-based warning thresholds (Fig. 3). Here, the water level thresholds are chosen based on the expected impact to assets and people. To translate hydro-meteorological forecasts to impacts and advisories, ~~countries~~regions established flood expert teams which interpret and translate the forecasts to impacts and advisories for the local authorities. CELEX in Wallonia and the LCO in The Netherlands are examples of such groups, which provide an interpretation and translation of the meteorological and hydrological forecasts. After the 2021 flood~~s~~, the regional water authority in Limburg (Waterschap Limburg) launched a dedicated multi-year programme to develop an impact-based forecasting system. The KNMI is rapidly developing impact-based forecasting techniques ~~spearheading the development of impact-based warnings~~ through the development of the Early Warning Centre, involving a range of multi-sectoral stakeholders (KNMI, 2025). The KNMI also emphasized that their efforts on impact-based forecasting contribute to stronger partnerships and collaborations, with organizations which are all working towards the same goal of predicting (flood) impacts (Red Cross Red Crescent Climate Centre, 2020).

~~4.4 Coordination and data sharing across borders~~

~~All interviewees emphasized that data exchange between countries is already quite well organized. For example, the border between The Netherlands and Flanders is marked by the lower part of the Meuse river ('Grensmaas'). To provide a consistent warning for all households along the Grensmaas, Flanders adopts the warning levels provided by the Dutch Government. In addition, the Dutch water management center (WMCN) uses both the European data from the EFAS system and additional hydrological information from neighboring countries. Germany also installed an automatic data exchange between flood forecasting centers from its neighboring countries. Some data exchange across countries faces challenges due to differences in the levels of responsibility for disaster coordination and communication. For example, better cooperation on modelling and the development of common models is needed to ensure consistency and provide tailored information within the same river system at different times, based on stakeholders' requirements. Furthermore, HIC in Flanders specifically suggests improving the exchange of information on upstream reservoirs in Wallonia. Interviewees from Waterschap Limburg stressed the importance of an international exchange of flood warnings, which is currently lacking.~~

4.4~~5~~ ~~Communication of actionable information~~Communication before and during the crisis phase

One of the interviewees mentioned*: "Forecasts are not the problem anymore, the problem is to act*". Dasgupta et al. (2024) suggest that a key factor for inaction is ineffective communication of the forecasts, including their uncertainty. Here we elaborate on this challenge, specifically for communication to crisis managers and ~~the local public.~~the local population.

Communication between forecasters, crisis managers, and first responders ~~Communication with crisis management~~

Our results suggest that major challenges exist~~s~~ in ~~the~~ communication between hydrological forecasting agencies, crisis management authorities, and the first responders right before and during the crisis phase. Interviewees stressed that the information needs for emergency management are regularly not met. Interviewees in Wallonia noted that not all municipalities have specific flood emergency management plans, even if they are in areas of high flood risk. In The Netherlands, regional water authorities ~~local Waterboards (responsible for regional and local water management)~~ and Safety Regions (organization of first responders) stressed the challenge of interpreting the issued forecasts by national services (KNMI and WMCN). An evaluation of the 2021 floods in Germany already pointed out that there ~~is~~ was a lack of actionable information in the forecasts, which is highly needed for first responders and the population (DKKV, 2024; Thieken et al., 2023a). In Wallonia, this resulted in crisis managers not receiving highly needed information about the expected flood inundation extents. This has eroded trust between different stakeholders, which is detrimental for the functioning of an entire warning system (Seebauer and Babsicky, 2017). Moreover, DKKV (2024) points out that there was a lack of clear and consistent communication between different levels of governments. Our interviewees in Germany pointed out that, although improvements are seen since 2021, the communication between hydrological agencies to emergency management units is still insufficient, resulting from a non-effective communication chain and missing communication protocols. Therefore, the information needs ~~for triggering actions for~~ of first responders are still not met. ~~. They require more specific and detailed information, such as flood inundation and damage predictions. Also, in Wallonia during the 2021 flood, the crisis managers requested information about the expected flood inundation extents which could not be provided. This has eroded trust between different stakeholders. A loss of trust is detrimental for the functioning of the early warning system, as it hampers the coordination and the response in the field (Seebauer and Babsicky, 2017).~~

Multiple interviewees point to deficiencies in the communication chain of forecast agencies to crisis managers. In Flanders, the warnings from HIC are sent to the De Vlaamse Waterweg waterways authority, who distribute it further to other stakeholders. However, flood risk management is not a core business of ~~the~~ De Vlaamse Waterweg authority, and therefore, they lack specific expertise on flood risk. Consequently, warnings are sometimes misinterpreted and not well communicated further. Similar findings are reported from experts in Luxembourg, where communication between the crisis management (CGDIS) and ~~hydro~~ meteorological and hydrological agencies (MeteoLux and AGE) is sometimes challenging. Interviewees from Luxembourg suggested that a central Early Warning Center for Luxembourg will be highly valuable to condense the different forecasts into actionable warnings. In The Netherlands, evaluations after the 2021 flood show the need for centralized and streamlined information (COT, 2022). Our interviewees in The Netherlands stress that local stakeholders (e.g., municipalities) still suffer from fragmented pieces of information from multiple stakeholders such as the KNMI, water boards and the WMCN.

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Research shows that probabilistic information can lead to better decisions (Verkade & Werner, 2011). Most operational forecasting centers in the region use probabilistic forecasting (Table 1). However, probabilistic approaches are often lacking for smaller rivers in The Netherlands. Moreover, the communication of probabilistic forecasts can be challenging (Arnal et al., 2019). In Germany, Luxembourg and the Netherlands it was mentioned that local emergency responders often prefer one value (e.g., water level) to take action upon. However, this value can be misleading due to the inherent uncertainty. Therefore, it is crucial to invest in better communication and interpretation of probabilistic forecasts and translate them into action advice. The WMCN in the Netherlands is advancing on the communication of probabilistic forecasts by providing tables with exceedance probabilities for each discharge threshold (WMCN, 2024). It is recommended for other forecasting centers to follow this approach.

Communication to the local ~~public~~ population

Germany and Luxembourg installed a cell broadcasting system in response to the 2021 flood. Now all countries covered in this study have such systems in operation (Table 1). Despite the effectiveness of cell broadcasting, research shows the need of a multi-channel approach due to the risk of failure of one system (e.g., power shortages or hacks) (Mahdavian et al., 2020). This was also emphasized in our interviews, such as with the national fire brigade of Luxembourg (CGDIS). Moreover, the 2021 flood~~s~~ showed that people mentioned a wide variety of information sources, including social media in addition to official sources such as NL-ALERT, radio, and television). Air raid sirens are another ~~effective~~ means of mass-alerting the population. The countries in our study have a different perspective with regards to the air raid sirens. ~~The national fire brigade of Luxembourg (CGDIS)~~CGDIS emphasized the importance of ~~a multi-channel alerting approach, including~~ the air raid sirens to ensure a multi-channel approach to mass-alerting civilians. However, in Wallonia the sirens are not used, and The Netherlands plans to stop the system, mainly because of the high maintenance costs which due outweigh the societal benefits (Ministerie van Justitie en Veiligheid, 2024). In Germany, the sirens are being ~~reestablished~~renewed since the 2021 flood~~s~~. The different approaches of neighbouring countries to mass-alerting the population in case of a flood or other catastrophe are remarkable.

Color-coded rainfall warnings for the 2021 floods were sometimes perceived as too abstract or vague to increase people's risk perception and willingness to act (Ommer et al., 2024). People take more (effective) protective actions if warnings are impact-based (Meléndez-Landaverde et al., 2019), and even more if those warnings also include behaviour recommendations (Red Cross Red Crescent Climate Centre, 2020; Golding et al., 2019). Despite the importance of investing in warning communication, ~~M~~multiple organisations during our interview stressed that they lack capacity or knowledge to develop effective communication protocols to inform the public. ~~Multiple interviewees (e.g., KNMI and AGE) stressed the importance~~

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~~of tailoring the communication strategy to different target groups. For example, young people in The Netherlands receive information through social media, such as Instagram, and generally will not download the KNMI phone application.~~

The 2021 flood~~s~~ in Limburg showed that, while people aware of an evacuation advice evacuated significantly more often, not everyone follows the advices (Endendijk et al., 2023a). This highlights the importance of tailored and concrete evacuation advice. In Germany, 50 to 75% of flood fatalities happened outside of the officially delineated flood hazard zones in NRW and RLP, respectively (Rhein and Kreibich, 2025; Thieken et al. 2023b). This illustrates the importance of flood risk awareness and risk perception as important drivers of adaptation. Since households not living in flood zones have lower risk perceptions, their response rates~~s~~ are also lower than those living in flood zones and they require tailored communication strategies (Aerts et al., 2018). Multiple interviewees (e.g., KNMI and AGE) stressed the importance of tailoring the communication strategy to different target groups. For example, young people in The Netherlands receive information through social media, such as Instagram, and generally will not download the KNMI phone application. The German national flood portal (https://hochwasserzentralen.de, Table 1) recently included action recommendations as addition to the hydrological warnings. The Dutch meteorological office KNMI recently hired a communication expert (specialized in social media) to produce clear infographics on '*what can you expect*' and '*what can you do*' during emergency situations (KNMI, 2024). This is presented in plain language (B1 level). We identify this as a best practice that can be followed by other regions. ~~Multiple organisations during our interview stressed that they lack capacity or knowledge to develop effective communication protocols to inform the public. Multiple interviewees (e.g., KNMI and AGE) stressed the importance of tailoring the communication strategy to different target groups. For example, young people in The Netherlands receive information through social media, such as Instagram, and generally will not download the KNMI phone application.~~

5. Conclusions and recommendations

5.1 Conclusions

This study reviews the status of the Flood Forecasting and Early Warning Systems (FFEWSs) in the countries in western Europe hit by the July 2021 flood: Germany, Luxembourg, Belgium, and The Netherlands. Expert interviews ~~over~~in the region reveal that all systems are under strong and rapid development after the 2021 flood event. This includes an optimalization of warning thresholds (including new thresholds for very extreme hydrological events), improvement of online flood forecasting portals, new ensemble-based forecasting techniques, new flood forecasting teams, new national-scale cell broadcasting to send out phone-based alerts in case of immediate danger (such as LU-Alert) and updated disaster management plans (including for small rivers). ~~As a result,~~Now all regions, except ~~for~~ Wallonia, ~~countries now have probabilistic FFEWSs and, except for Wallonia, all regions~~ have clear pre-defined warning thresholds based on peak discharge or water levels. In most regions, those hydrological warning thresholds are determined based on expected local flood impacts. ~~Moreover, over the past years, online flood forecasting portals have been improved, emergency response plans updated (with a stronger focus on small rivers), and national scale cell broadcasting is implemented to send out phone-based alerts in case of immediate danger.~~

Strong differences exist in flood warning levels and color codes across and within the countries. Additional research is necessary to determine whether an international harmonization of the warning levels is desirable. As a response to the extreme flood event of 2021, Luxembourg and some regions of Germany have recently introduced an additional purple warning code for the most extreme weather and hydrological events. In countries where red is the maximum warning level, some experts suggested also adding a ~~dark~~ purple level to represent truly catastrophic impacts such as the 2021 floods. Despite having an extreme warning level can be helpful for indicating the potential disastrous consequences of an event, it is still under debate whether more warning levels support~~s~~ a more effective communication to the public and responders.

The implementation of operational impact-based forecasting and warning is challenging, both on a technical and institutional level. Although impacts are sometimes considered in the design of the hydrological warning thresholds, the thresholds are often too conservative (too low) and thus do not reflect major societal flood impacts. Moreover, meteorological, and hydrological forecasts often lack specific impact and action information, which is highly needed for first responders at the local level. The forecasts of river discharge, return periods, and corresponding warnings are often hard to interpret by local decision-makers, emergency services and local population. To trigger effective early actions, it is strongly suggested to enrich forecasts with impact-based information and to provide reliable predictions of inundated areas and risk hotspots. Flanders is the only region where operational flood inundation (i.e., flood maps) forecasts are provided. Recent computational developments in inundation modelling such as cloud computing, GPU-based parallelization and machine-learning will significantly reduce run times and pave the way for the operational implementation of inundation forecasts.

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5.2 Recommendations

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Resulting from the four key challenges outlined in this study, Oour study has four concrete recommendations:

1) *Streamlined warning levels*: investigate whether harmonization of pluvial and fluvialmeteorological and hydrological warning levels and color codes between different countries and within different regions of a country, improves communication and decision-making.

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2) *Warnings for catastrophic events*: Assess the added value of more extreme warning levels, such as the (dark) purple levels in Luxembourg and some German regions.

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3) *Impact-based forecasting*: accelerate the development of operational impact-based forecasting systems. This in turn requires an expansion of recommends expanding resources and knowledge on impact-based forecasting, and a and effective communication protocols, including tailored action advisories. This in turn will require stronger collaboration across sectors, such as between the forecasting agencies and emergency management authorities. More knowledge and insights are urgently needed to better understand the needs of forecasting agencies to accelerate impact-based forecasting.

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.4) *Forecast communication*: Implement a structural evaluation of warning communication chains, to ensure that warnings are consistently communicated and correctly interpreted betweeny different organizations, and to the local publicpopulation, and ensure that the information is tailored to their needs.

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Moreover, it needs to be fully understood what kind of impact and action information emergency managers and civilians need to make more effective decisions. These challenges need to be addressed to reduce the gap between early warning and early action duringfor impactful flood events.

Author contribution

TB: Conceptualization, Investigation, Methodology, Writing, Visualization, **JA**: Conceptualization, Investigation, Methodology, Writing, Funding acquisition, Project administration, **DRC, BD, SV, RL, JK, DZ, HM, AT**: Conceptualization, Investigation, Methodology, Writing, **KS:** Conceptualization, Investigation, Methodology, Funding acquisition, Project administration, **PW**: Investigation, Writing, **LF**: Writing, **JV:** Conceptualization, Investigation, Methodology.

Competing interests

The authors declare that they have no conflict of interest.

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Appendix A. Interviewed specialists

Netherlands

- Senior operational flood forecasting expert at Watermanagementcentrum Nederland (WMCN)
- Senior operational early warning specialist and program manager at –Royal Netherlands Meteorological Institute (KNMI)
- Senior flood early warning specialist at Waterschap Limburg

Belgium

- Professor at University of Gent and lead of the meteorological forecasting department of Royal Meteorological Institute of Belgium (RMI)~~**RMI**~~
- Senior operational flood forecasting expert at Flanders Hydraulics Research - Hydrological Information Centre (HIC) ~~**HIC Flanders**~~
- Two senior crisis managers at Le Service public de Wallonie (SPW)

Germany:

- Two senior operational flood forecasters at Landesamt für Umwelt Rheinland-Pfalz (LfU) ~~**LfU**~~
- Senior operational flood forecaster at Natur, Umwelt & Klima in Nordrhein-Westfalen (LANUK)~~**LANUV**~~
- Professor at University of Kaiserslautern-Landau (RPTU)

Luxemburg

- Senior flood forecasting and data management expert at Administration de la gestion de l'eau (AGE) ~~**AGE**~~
- General Director at Corps grand-ducal d'incendie et de secours (CDGIS)~~**CGDIS**~~

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Author contribution

TB: Conceptualization, Investigation, Methodology, Writing, Visualization, **JA**: Conceptualization, Investigation, Methodology, Writing, Funding acquisition, Project administration, **DRC, BD, SV, RL, JK, DZ, HM, AT**: Conceptualization, Investigation, Methodology, Writing, **KS:** Conceptualization, Investigation, Methodology, Funding acquisition, Project administration, **PW**: Investigation, Writing, **LF**: Writing, **JV:** Conceptualization, Investigation, Methodology.

Competing interests

The authors declare that they have no conflict of interest.

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