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Meteorological and Hydrological Data as a Basis for Issuing Flood Warnings During the July Flood 2021 in Rhineland-Palatinate and North Rhine-Westphalia (Germany)

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ABSTRACT

The July 2021 flood event severely affected western Germany, particularly Rhineland-Palatinate and North Rhine-Westphalia, with rainfall intensity and water levels exceeding the 100-year return period in many areas. This study analyzes the performance of flood monitoring and forecasting systems during this extreme event, focusing on the integration of meteorological and hydrological data within detection, monitoring, and forecasting processes. The findings reveal critical challenges in translating meteorological information into actionable flood warnings, including discrepancies between predicted and observed precipitation, underestimation of maximum discharges (exceeding the 100-year return period by up to 730% in some areas), and the absence of comprehensive flood forecasting systems in key regions. Approximately 60% of the investigated gauging stations experienced exceedances of all defined flood warning thresholds within 6 h or less, highlighting the rapid escalation of the event and the constrained response time for emergency measures. The results of the study underline the need to redesign flood information and warning systems: especially for extreme situations warnings must not be based only on measured data and not on single forecast values but mainly on potential risks and communicated uncertainty/probability.

1 | Introduction

Flood events are increasing in frequency and intensity due to climate change (IPCC 2021). These trends highlight the importance of adapting monitoring, detection, and forecasting systems to mitigate impacts on lives and property. Providing sufficient lead time is a critical function of these systems, enabling proactive emergency responses and risk mitigation. Past flood events have had devastating impacts on people and property (van Loenhout et al. 2020). Between 1980 and 2020, hydrological events, including flooding, caused over 5000 fatalities in Europe (European Environment Agency 2022). The July 2021 flood in western Germany provides a key case to evaluate the performance of monitoring, detection, and forecasting systems under extreme conditions. The event affected the federal states of RLP and North Rhine-Westphalia, resulting in substantial damages and loss of life. The scale and rapid escalation of the event underscored challenges in flood warning processes, especially regarding lead times and the integration of hydrometeorological data. Probabilistic forecasting systems, such as Ensemble Prediction Systems (EPS), play a vital role in identifying extreme precipitation risks. During the July 2021 flood, these tools provided early indications of significant rainfall up to 4 days in advance, supporting pre-warning systems and informing decision-making (European Centre for Medium-Range Weather Forecasts 2021). The coupling of probabilistic precipitation forecasts with proven hydrological models, as already documented in earlier studies

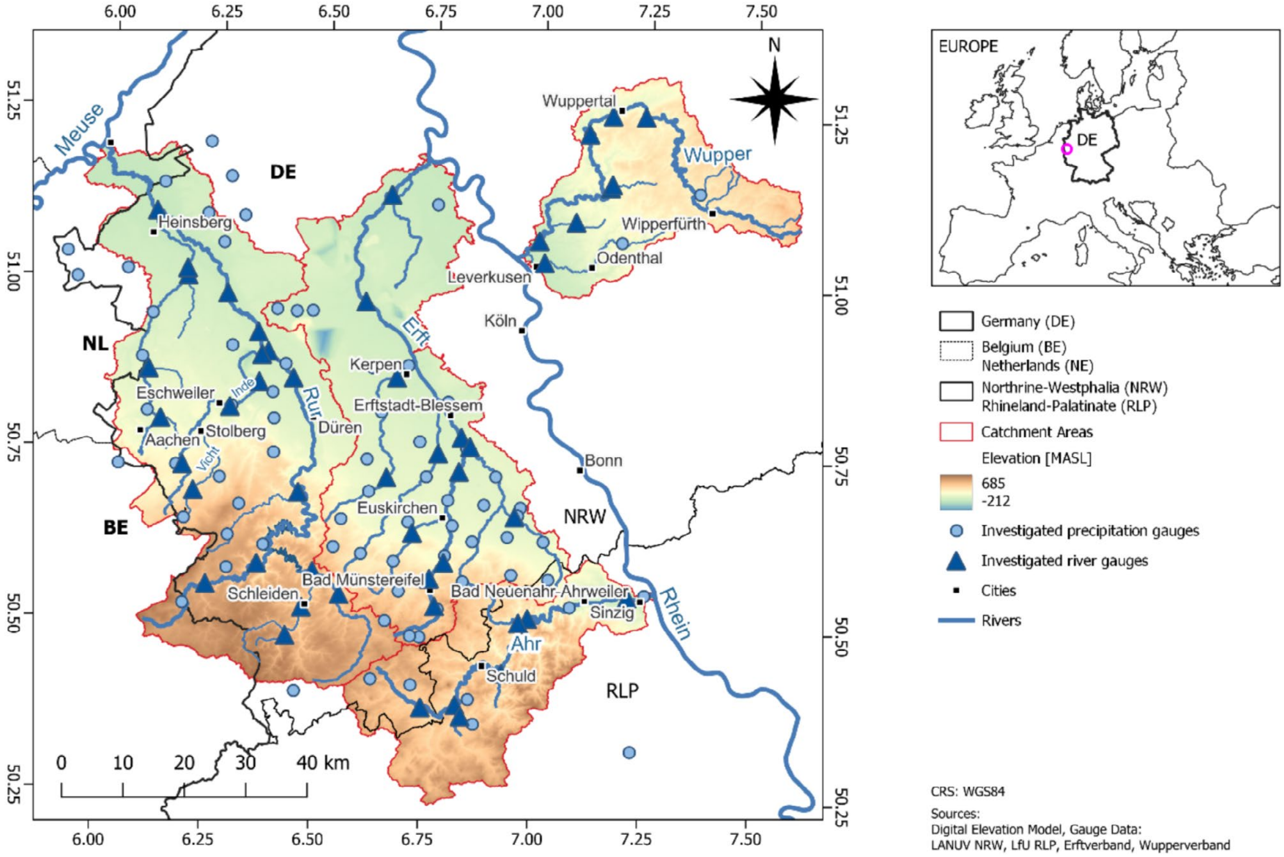

FIGURE 1 | Overview map of the investigated precipitation measuring stations and gauge measuring stations in the catchment areas of the rivers Wupper, Rur, Erft, and Ahr.

(Kardhana et al. 2007; Verkade and Werner 2011) enables an early estimation of peak discharges and thus provides the basis for a significant extension of lead times, even if the practical implementation still has potential for optimization. Despite these capabilities, the July 2021 flood event highlighted the potential to improve the translation of early signals into actionable flood warnings, emphasizing the value of integrating meteorological forecasts with hydrological systems.

The event severely affected the western part of Germany and parts of the Netherlands, Belgium, and Luxembourg. The intensity of the precipitation and the water levels exceeded well beyond a 100-year event (event with a statistical recurrence time of 100 years), a common value for protection in flood risk management. According to the authorities, the July 2021 flood event statistically corresponded between a 200-year and 1000-year event (Landesamt für Umwelt Rheinland-Pfalz 2022). In Germany, the consequences of the flood event involved more than 180 casualties (Thieken et al. 2022) and monetary damages amounting to 33.1 billion euros (Trenczek et al. 2022). In June and early July 2021, the investigated catchment areas in Germany (see Figure 1) experienced above-average precipitation, as evidenced by high soil moisture immediately before the event in the week beginning July 10, 2021. After continuous precipitation until July 13, 2021, there was very heavy and persistent precipitation on July 14 and 15, 2021. The large amounts of precipitation in combination with the orographic conditions, as well as saturated soils led to the severity of the July 2021 flood event (Junghänel et al. 2021).

Already on 10 July 2021, and thus 4 days before the flood event, the German Weather Service Deutscher Wetterdienst (DWD) had first indications of a severe and large-scale precipitation event (DWD 2021). The population was warned by the defined warning hierarchy and the highest warning level was declared on July 13, 2021, at 9:40 a.m. (see Chapter 2.1). Nevertheless, about one-third of the affected population states that they did not receive a warning about an approaching flood event (Thieken et al. 2023).

While Section 79 of the German Federal Water Act (Wasserhaushaltsgesetz, WHG) assigns flood warning management to state-level authorities, this study focuses on how hydrological and meteorological data are processed within these frameworks to support warning systems. It examines the state-specific organizational structures that regulate this process and how those responsible for managing flood events receive timely information about potential hazards. Additionally, it considers how and to what extent the public is informed and warned in the event of a flood. Furthermore, a distinction must also be made between risk communication and crisis communication in the context of flooding. According to Article 6 of the European Union Floods Directive, Member States are required to produce flood hazard and risk maps at the level of river basin districts, showing the extent of flooding, water depths, and flow velocities for low, medium (likely return period ≥ 100 years) and high probability (Directive 2007). These maps are an effective means of communicating the risks in the respective river basin districts, even if there is no current flood situation. A real-time situation cannot be taken from the maps, and the flood warning process in Germany is not linked to the published hazard and risk maps, so a transfer of the flood warnings to the catchment area is not possible (Jüpner 2022). The task of presenting the current hydrological situation is taken over by the responsible water management authorities of the respective federal states. In North Rhine-Westphalia (NRW), the State Agency for Nature, Environment and Consumer Protection (LANUV) takes over the task of determining the basic data for water management and operates the flood information service. Hydrological data are collected, stored, validated, and processed in addition to operating water and flood gauges, as well as precipitation and climate measuring stations.

If defined water levels (flood reporting value 1–3; not related to the annual flood discharge but only descriptive: value 1 = "first overflowing of watercourses", value 2 = "Danger of flooding of single properties or infrastructure facilities", value 3 = "Risk of flooding of the built environment or infrastructural facilities on a larger scale") are exceeded at the LANUV flood gauges in North Rhine-Westphalia, the affected municipalities, as well as other responsible public agencies, are notified about the exceedance level. The information is additionally published on the internet in the form of a hydrological situation report by LANUV. A flood forecast in the sense of a forecast of expected water levels has in NRW only been in test operation since 2016 and was not in operational use during the July 2021 flood event. Based on the data of the LANUV as well as the meteorological forecast data of the DWD, notifications of approaching flood events are issued by the flood notification services of the district governments. The LANUV summarizes the flood situation for North Rhine-Westphalian authorities via specialized information systems and federal state situation reports are published online. If thresholds (flood reporting values) are exceeded at flood gauges on the watercourses, the responsible authorities start the active reporting service and inform the affected municipalities. Apart from that, relevant authorities, such as fire departments and disaster management authorities, are responsible for protection and flood defense measures.

In the federal state of RLP, the flood reporting and warning process is carried out in a similar way as in North Rhine-Westphalia. This study focuses on evaluating how hydrological data collection, validation, and dissemination differ between the two states and how these differences affected flood detection and forecasting during the July 2021 event. The State Office for the Environment (LfU) of RLP operates a flood forecast service. There are differences to NRW in the definition and number of flood reporting values as well as an additional publication of flood forecasts. For this purpose, level-related flood reports and the severe weather warnings of the meteorological services have been supplemented by a region-related early flood warning for small catchment areas since 2008. This water level forecast is not available for every gauge. During the July 2021 flood event, a forecast was available only at the Altenahr gauge (Figure 7) of the Ahr-river catchments studied in this paper. A warning map on the internet presented information about an expected exceedance of discharge thresholds ($>HQ_2$, $>HQ_{10}$, $>HQ_{20}$, $>HQ_{50}$; comparable with the flood reporting value 1–3 in NRW) in the next 24 h as well as already exceeded thresholds at RLP flood gauges. Floodplains are not included in the published flood forecast information in Rhineland-Palatinate, as the forecasts are limited to expected discharge levels at gauging stations and do not contain spatial inundation extents.

This study examines the hypothesis that during the July 2021 flood event, significant potential existed to extend lead times through the optimized use of hydrological and meteorological data. Based on the presented results, the study evaluates how these data were utilized for monitoring, detection, and forecasting during the flood. The analysis focuses on data collection, threshold exceedances, and forecasting performance to explore mechanisms that could have extended lead times, as a critical component of effective flood warning processes. Published weather forecasts, severe weather warnings, measured precipitation data, and water levels are examined, while aspects of communication and public response are excluded.

2 | Methodology

2.1 | Description of the Study Catchment Areas

This study focuses on the western part of Germany affected by the July 2021 flood event. In the federal state of North Rhine-Westphalia, the catchment area of the Rur, which flows into the Meuse in Roermond (Netherlands), and the catchment area of the Erft, which flows into the Rhein near Düsseldorf, are examined. In addition, the catchment area of the Wupper, which flows into the Rhein at Leverkusen, is examined in NRW. These catchments represent a variety of hydrological and topographical conditions, offering valuable insights into the adaptability of flood monitoring and forecasting systems. In the federal state of RLP, the catchment area of the Ahr is examined, which flows into the Rhein at Sinzig. The sources of the Rur, Erft, and Ahr rivers are located in the same region in the semi-mountainous range of the Eifel on the border of North Rhine-Westphalia, Rhineland-Palatinate, and Belgium. The source of the Wupper is located in the semi-mountainous region of Sauerland in the northeastern part of the Rhenish Slate Mountains. (See Figure 1).

The catchments vary in size and topography, influencing flood dynamics and monitoring challenges. Their areas range from 813 km^2 (Wupper) to 2361 km^2 (Rur), with the Ahr and Erft catchments having steeper average bed slopes (4.9‰ and 4.7‰, respectively) compared to the Rur (3.9‰) and Wupper (3.5‰) (Figure 2).

The varying slopes and catchment sizes influence the speed and intensity of flood events, which pose challenges for real-time monitoring and forecasting accuracy. These differences are considered in the analysis to assess the adaptability and limitations of current monitoring and forecasting systems in these catchment areas.

2.2 | Data

The study focuses on the period between July 10, 2021, and July 16, 2021. It is based on data from 62 precipitation gauging

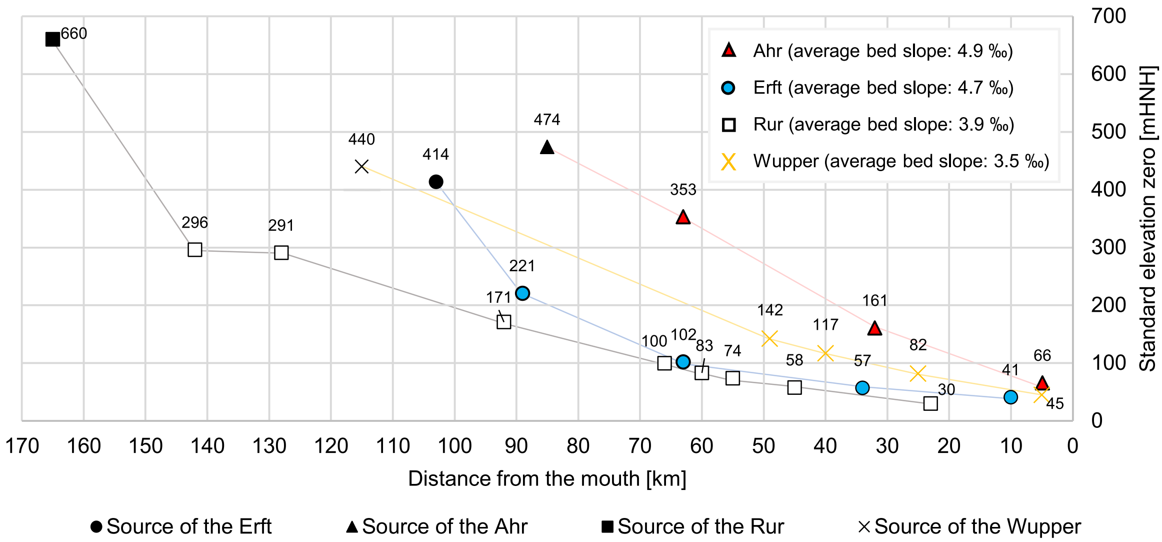

FIGURE 2 | Position of the flood gauges along the respective longitudinal river profiles of the investigated main watercourses Ahr (red triangle), Rur (white square), Erft (blue dot) and Wupper (yellow cross); own representation based on freely available information on the respective gauges (see https://hochwasserportal.nrw NRW and https://www.hochwasser.rlp.de/RLP).

stations and water level data from 61 river gauges (with a focus on 30 flood reporting gauges, referring to Figure 8). The data were provided by the responsible water management authorities. These are the environmental agencies of the federal states NRW (LANUV) and RLP (LfU) as well as the water management authorities Wasserverband Eifel-Rur, Wupperverband, and Erftverband. The data of the precipitation measuring stations were available in 1- to 5-min period steps. The water level data of the flood gauges in NRW were available in 5-min period steps, and the water level data of the LfU in RLP were available in 15-min period steps.

Weather forecasts provided by the German Weather Service DWD form a key component of our analysis by offering probabilistic precipitation predictions and lead times extending up to several days. In parallel, the DWD issues severe weather warnings following a four-stage design—comprising initial information, preliminary warnings, severe weather warnings, and extreme severe weather warnings. These alerts, together with additional notifications via the Modular warning system[1] (MoWaS) from agencies such as the Federal Office of Civil Protection and Disaster Assistance (BBK) and the Warning and Information System for the Population (KATWARN), are critical for understanding the timing and dissemination of warnings preceding the flood event.

2.3 | Analysis

The study evaluates how hydrological and meteorological data were integrated into real-time flood monitoring and forecasting systems. The analysis examines precipitation and water level data to evaluate temporal differences in water level increases, threshold exceedances, and peak water levels in relation to precipitation sequences. By analyzing the water level time series together with the timing at which predefined warning thresholds are exceeded, we can assess the steepness of the flood's escalation.

Furthermore, predicted precipitation amounts from the DWD's meteorological warning reports are analyzed to evaluate their role in operational flood monitoring and forecasting. While detailed numerical weather prediction models are beyond the scope of this study, the focus lies on the use of published precipitation forecasts and observed trends as central components of flood monitoring and forecasting systems. Our analysis, based on observed data and published forecasts, discusses the potential of probabilistic tools (e.g., Ensemble Prediction Systems) to extend lead times and improve spatial accuracy, though we do not generate new probabilistic forecasts.

The methodology emphasizes the timing and magnitude of threshold exceedances at flood gauges, exploring how these could have been utilized to enhance flood information processes and increase lead times. To this end, the study examines the timing and content of warnings issued by the German Weather Service DWD, the Federal Office of Civil Protection and Disaster Assistance (BBK), and the KATWARN. These warnings are systematically aligned with observed precipitation and water level trends to identify potential delays or inconsistencies in data acquisition, processing, and warning issuance. This alignment reveals opportunities to optimize the data-to-warning process and enhance the responsiveness of flood warning systems.

Finally, the analysis assesses the potential to extend warning times in four key areas: observed water levels, observed precipitation, predicted water levels and predicted precipitation. In this way, a comprehensive assessment is made of how each type of data can contribute to more effective flood warning systems. This approach is also integrated into the technical pillar of the 'Early Warning for All' framework proposed by the World Meteorological Organization, bringing the analysis in line with the internationally recognized United Nations methodology (World Meteorological Organization 2023). The Early Warning for All framework is an integrated approach that combines hazard monitoring, forecasting, risk assessment, communication, and preparedness to enable timely, actionable warnings. By emphasizing coordinated, real-time data integration and effective uncertainty communication, it aims to extend lead times and improve disaster response at all scales.

3 | Results

The results evaluate how flood monitoring and forecasting systems performed during the July 2021 flood event, with a focus on the timing, accuracy, and integration of hydrological and meteorological data. The analysis follows the technical pillar of the Early Warning for All framework and examines data responsiveness, threshold exceedances, and the relationship between precipitation trends, issued warnings, and observed water levels.

3.1 | Weather Forecast and Severe Weather Warning

The severe weather warning of the DWD is set up in a four-stage design. On 10 July 2021, the first indications of a severe precipitation event were identified and announced by the DWD for the affected regions. These are warnings that have been issued for the respective federal state. On Sunday, 11 July 2021, at 11:00 a.m., initial information and, thus, a specification of the first indications took place. Based on meteorological ensemble models, extreme rainfall was predicted for a delimited area most likely on Wednesday and Thursday of the following week. Thus, in addition to the early initial information, the preliminary information on 12 July 2021 at 10:20 a.m. and the first severe weather warning on 12 July 2021 at 05:55 p.m., the highest warning level (extreme weather warning) was issued for the first time on 13 July 2021 at 09:40 a.m. and has been extended to a larger area on 14 July 2021 at 7:40 a.m. The extreme weather warnings of the DWD were further disseminated by the MoWaS on 13 July 2021 at 11:36 and on 14 July 2021 at 09:08 a.m. (See Table 1).

The deterministic weather warnings accurately reflected the severity of the precipitation event, while probabilistic forecasting models, such as the EPS, highlighted additional opportunities for hydrological simulations. These models provided spatial and temporal forecasts of high precipitation areas, which offered the potential to anticipate hydrological responses in the affected catchments. The probabilistic weather forecasts pointed out predicted extreme precipitation for the affected regions as early as 10 July 2021, with ensemble forecasts exceeding the 99th percentile of historical climatological records by 11 July 2021 (European Centre for Medium-Range Weather Forecasts 2021). For the 48-h event between 13 and 15 July 2021, ensemble median precipitation predictions reached up to 107 mm, closely aligning with the observed station average of 120 mm in the most affected areas (see chapter 3.2).

3.2 | Precipitation Measurement

In the catchment area of the Rur, 11 precipitation gauges were analyzed. Precipitation amounts in the range of approx. 8–25 mm were already recorded on 10 July 2021. After no precipitation was recorded on 11 July 2021 and 12 July 2021, despite predicted precipitation amounts of 30 mm and 40 mm,

TABLE 1 | Staged severe weather warnings in the run-up to the July 2021 flood event issued by the German Weather Service (Deutscher Wetterdienst) in the period between 11 July 2021 and 14 July 2021, valid for a large area in western Germany (DWD 2021).

Date	Warning level		Content	Information on expected precipitation amounts (excerpt)
Sunday, 11 July 2021	1	Initial information (11:00 a.m.)	Increased risk of severe weather due to heavy and continuous rainfall	Continuous rain partly over 100 mm in 24 h
Monday, 12 July 2021	2	Preliminary information (10:20 a.m.)	A first indication of a weather situation with high severe weather potential; The occurrence and local containment are still very uncertain.	In the next 48 to 60 h, localized rainfall amounts of up to 200 mm may occur.
	3	Severe weather warning (05:55 p.m.)	Profuse continuous rain with interruptions; Several thundery heavy rain areas	Precipitation amounts between 30 and 60 mm within a few hours or up to 30 mm in a short period
Tuesday, 13 July 2021	4	Extreme severe weather warning (09:40 a.m.)	Extremely heavy continuous rain with interruptions	Precipitation amounts between 80 mm and 180 mm expected in 48 h
Wednesday, 14 July 2021	4	Expansion extreme severe weather warning (07:40 a.m.)	Extremely heavy continuous rain with interruptions	Rainfall amounts of 30 to 70 mm in a few hours; cumulatively up to 180 mm are possible in 48 h, selective > 200 mm not excluded

TABLE 2 | Times of the first exceedance of the respective thresholds at gauges in the investigated catchments.

	Threshold 1	Threshold 2	Threshold 3	Threshold 4	>HQ_{100}
Rur	13.07. 09:20 p.m.	14.07. 00:25 a.m.	14.07. 00:55 a.m.	Not applied in NRW	14.07. 03:55 p.m.
Erft	13.07. 11:20 p.m.	14.07. 00:15 a.m.	14.07. 05:40 p.m.	Not applied in NRW	14.07. 06:45 p.m.
Wupper	14.07. 04:30 p.m.	14.07. 04:55 p.m.	14.07. 05:15 p.m.	Not applied in NRW	14.07. 05:20 p.m.
Ahr	14.07. 02:15 p.m.	14.07. 03:15 p.m.	14.07. 03:45 p.m.	14.07. 04:30 p.m.	14.07. 04:45 p.m.

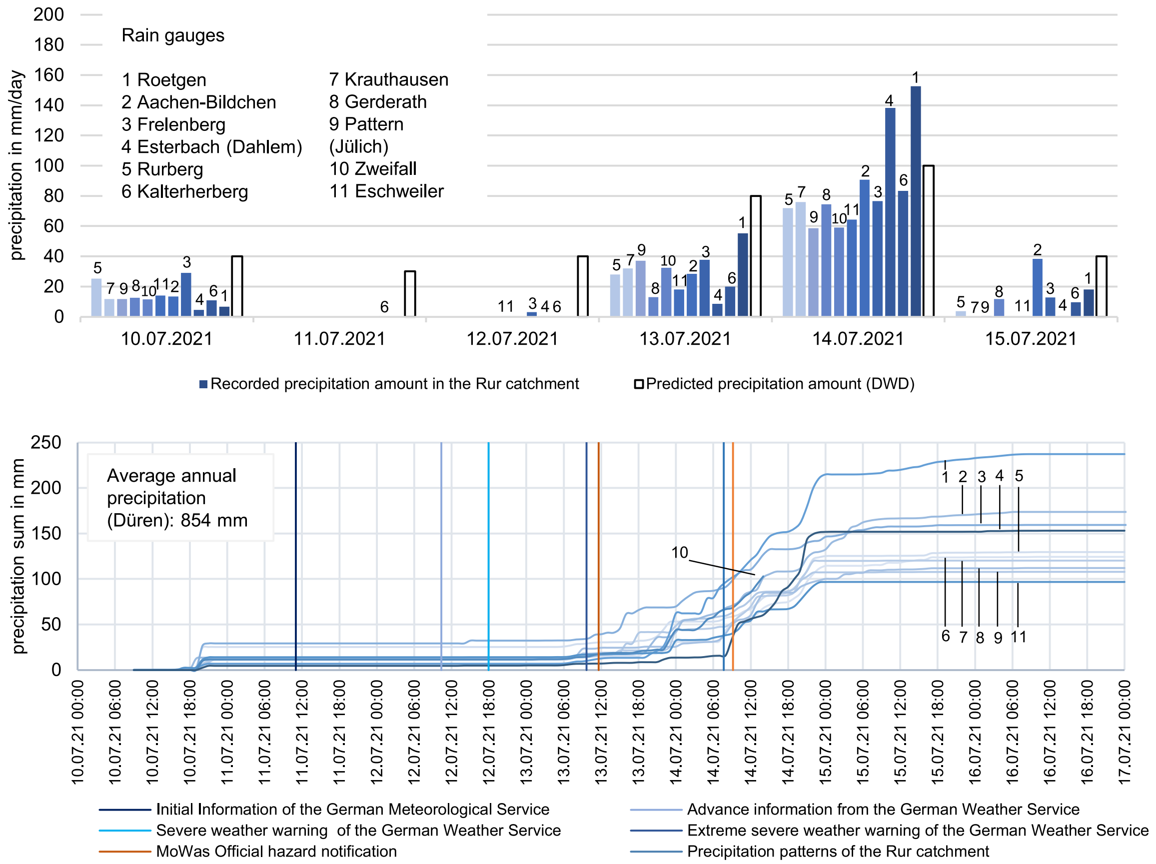

FIGURE 3 | Results of the data analysis of the precipitation data in the Rur catchment (above: Daily precipitation amounts measured at the investigated rain gauges between 10 and 15 July 2021; below: Precipitation sum of the rain gauges and the timing of weather warnings by the DWD and the hazard notification of the MoWaS).

precipitation amounts in the range of approx. 9–55 mm (forecast: 80 mm) were recorded on 13 July 2021 and approx. 35–153 mm (forecast: over 100 mm possible) on 14 July 2021. On the following 15 July 2021, values up to approx. 18 mm of precipitation were recorded. The beginning of a heavy precipitation event can be defined at noon on 13 July 2021. At the same time, the extreme severe weather warning (see Table 2) of the DWD was issued. During the night of 13 July 2021 to 14 July 2021, the first high increase in precipitation can be identified in a short period. In the early morning of 14 July 2021, two significant increases follow shortly in the afternoon of 14 July 2021 and in the late evening or midnight on 14 July 2021. On the morning of 15 July 2021, isolated precipitation can be recognized in the catchment area of the Rur. The largest precipitation amounts in the catchment area of the Rur were recorded in the semi-mountainous region in the area of the municipalities Roetgen and Hürtgenwald. In total, precipitation amounts between 40 mm (Wassenberg-Rothenbach) and 195 mm (Roetgen) were recorded in the period of 38 h between the evening of 13 July 2021 and the morning of 15 July 2021. (See Figure 3).

In the Erft catchment area, precipitation amounts in the range of approx. 2–21 mm were already recorded on 10 July 2021. After no precipitation was recorded on 11 July 2021 and 12 July 2021, despite predicted precipitation amounts of 30 mm and 40 mm, precipitation amounts in the range of approx. 12–44 mm (forecast: 80 mm) were recorded on 13 July 2021 and approx. 82–179 mm (forecast: > 100 mm possible) on 14 July 2021. On 15 July 2021, values of only about 4 mm of precipitation were recorded. Based on the precipitation data, there seem to be two rain events. The first event can be identified on the morning of 13 July 2021. In the same period, the first extreme severe weather warning of the DWD was issued. Precipitation amounts between approx.

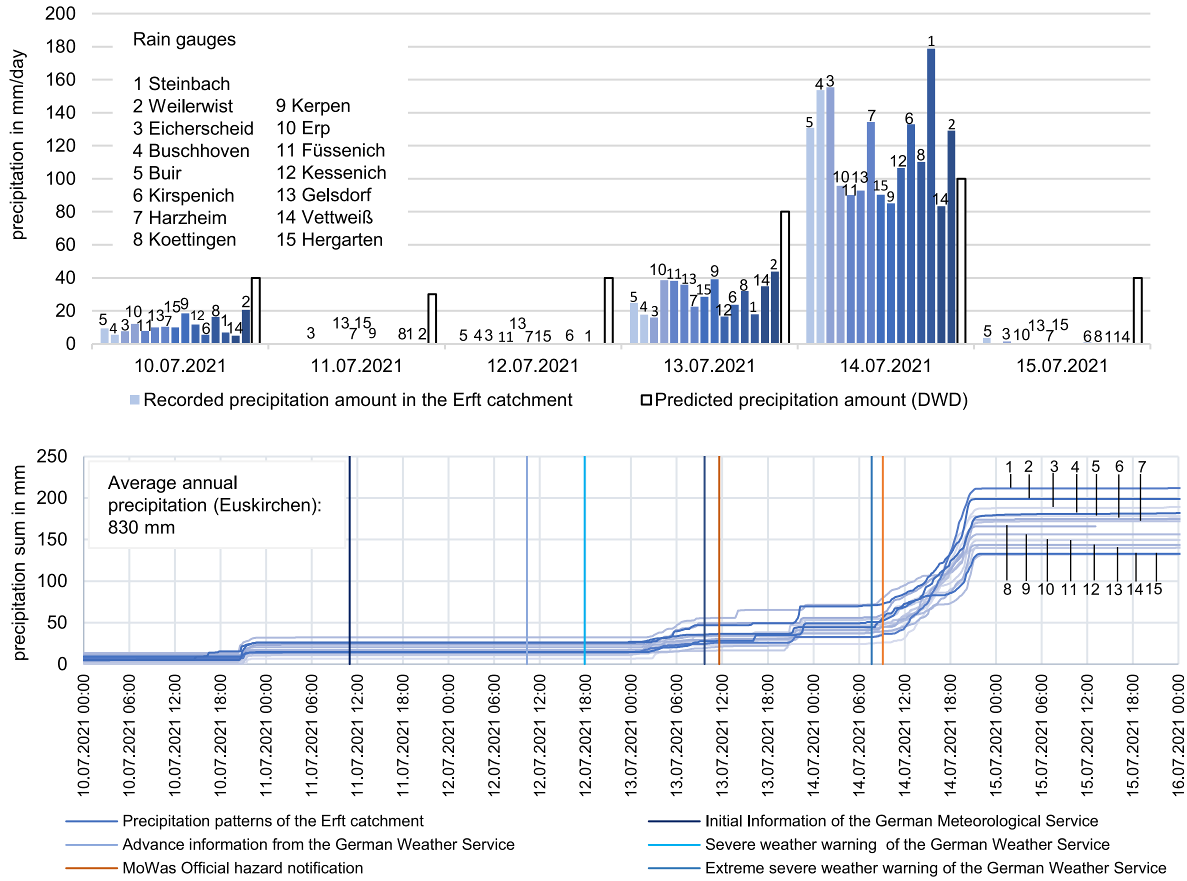

FIGURE 4 | Results of the data analysis of the precipitation data in the Erft catchment (above: Daily precipitation amounts measured at the investigated rain gauges between 10 and 15 July 2021; below: Precipitation sum of the rain gauges and the timing of weather warnings by the DWD and the hazard notification of the MoWaS).

25 mm and 40 mm are reached within a few hours, sporadically and around 9 p.m. From 0:00 a.m. in the night to 14 July 2021, no further precipitation was recorded until about 07:00 a.m. After the extreme severe weather warning was extended to a larger area at 7:40 a.m., high precipitation amounts of up to 160 mm (Eicherscheid) and 180 mm (Steinbach) were recorded from the morning of 14 July 2021 until 10:00 p.m. (See Figure 4).

In the catchment area of the Wupper, precipitation amounts in the range of approx. 5–12 mm were already recorded on 10 July 2021. After no precipitation was recorded on 11 July 2021 and 12 July 2021, despite predicted precipitation amounts of 30 mm and 40 mm, precipitation amounts in the range of approx. 4–12 mm (forecast: 80 mm) were recorded on 13 July 2021 and approx. 137–147 mm (forecast: over 100 mm possible) on 14 July 2021. On the following 15 July 2021, no precipitation was recorded. Based on the precipitation data, a short precipitation event can be identified on the morning of 13 July 2021. Shortly thereafter, the first extreme severe weather warning has been issued by the DWD. From 0:00 a.m. on the night of 14 July 2021 until about 6:00 p.m., precipitation between 137 mm (Lindscheid) and 147 mm (Buchenhofen) has been recorded. (See Figure 5).

In the catchment area of the Ahr in Rhineland-Palatinate, precipitation amounts in the range of approx. 5–18 mm were already recorded on 10 July 2021. After no precipitation was recorded on 11 July 2021 and 12 July 2021, despite predicted precipitation amounts of 20 mm and 35 mm, precipitation amounts in the range of approx. 7–22 mm (forecast: 70 mm) were recorded on 13 July 2021 and approx. 42–121 mm (forecast: over 100 mm possible) on 14 July 2021. On the following 15 July 2021, only about 3 mm of precipitation was recorded. Based on the precipitation data, a first precipitation event can be identified on the morning of 13 July 2021. In the same period, the first extreme severe weather warning of the DWD was issued. No heavier precipitation is recorded during 13 July 2021, but precipitation amounts up to max. 22 mm. From 0:00 a.m. on the night of 14 July 2021, no precipitation is recorded until about 07:00 in the morning. After the extreme severe weather warning has been extended to a larger area at 7:40 a.m., high precipitation amounts up to 90 mm (Rodder) and 120 mm (Blankenheim) are recorded from the morning of 14 July 2021 until 10:00 p.m. (See Figure 6).

During the week before the occurrence of the flood event on 13 July 2021, forecasts and warnings from the GWS were continuously disseminated with references to a rare and severe weather event. Already on Sunday, 11 July 2021, the first information was issued by the GWS with the indication of an increased risk of severe weather due to heavy continuous rain as well as an expected precipitation amount of partly more than 100 mm in the course of the following week (see Table 1). Further official severe weather warnings followed up to the issuance of the highest warning level on 13 July 2021, which the BBK also disseminated as official hazard reports.

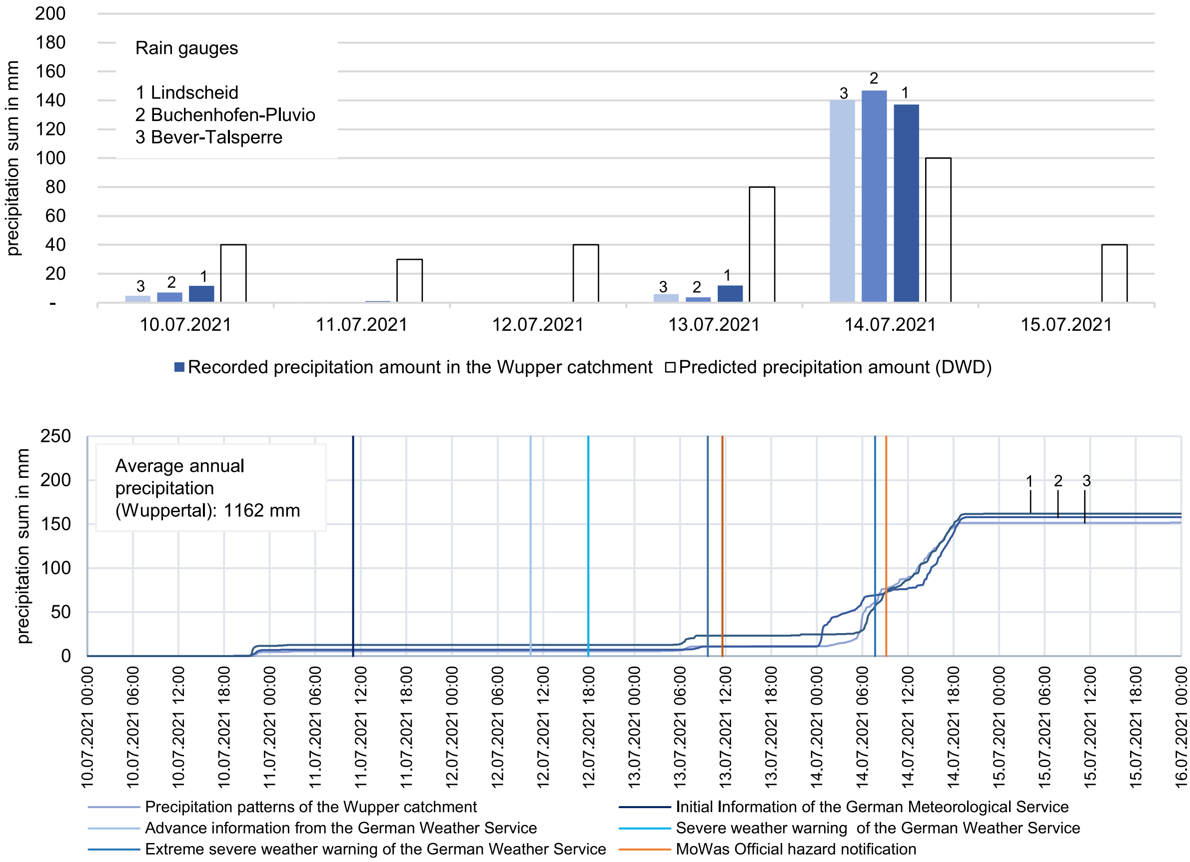

FIGURE 5 | Results of the data analysis of the precipitation data in the Wupper catchment (above: Daily precipitation amounts measured at the investigated rain gauges between 10 and 15 July 2021; below: Precipitation sum of the rain gauges and the timing of weather warnings by the DWD and the hazard notification of the MoWaS).

The predicted precipitation amounts by the GWS showed variances compared to the locally recorded values at precipitation measuring stations (see Figures 3–6). These deviations between predicted and observed precipitation highlight the challenges of translating large-scale forecasts into accurate localized assessments. However, the observed precipitation trends, particularly the rapid intensification on July 13 and 14, could have been integrated earlier into real-time warning systems. This integration might have supported a dynamic adjustment of warnings, potentially extending the lead time for downstream areas.

In the catchment area of the Rur, precipitation amounts in the range between approx. 70 and 220 mm of rain were recorded between 10 July 2021 and 16 July 2021. The main part of these precipitation amounts fell over the day on 14 July 2021. In the catchment area of the Erft, precipitation amounts between 180 and210 mm were recorded in the same period. In contrast, the main part of the precipitation amounts fell in the second half of 14 July 2021. In the catchment area of the Wupper, precipitation amounts between 150 and 160 mm were recorded mainly in the first half of the day of 14 July 2021. Comparing the catchments, the lowest amount of precipitation in the range of about 110-140 mm fell in the Ahr catchment during the week between 10 July 2021 and 16 July 2021, with the main part of these amounts also falling in the second half of the day of 14 July 2021. A comparison of the (respectively highest) precipitation sum lines with the average annual precipitation of the investigated catchments shows that approx. between 17% and 26% of the annual precipitation fell in 6 days (Rur: 26.4%; Erft: 25.4%; Wupper: 13.9%; Ahr: 16.7%) during the July 2021 flood event. Investigations of the severity level of the precipitation event in July 2021 show that it was just the fourth most extreme event from 2001 to 2021, while the impact of the July 2021 flood event was unique (Lengfeld et al. 2023). During the flood event, 18 precipitation gauging stations failed in the investigated catchments due to power fluctuations, short circuits, water ingress in the basement of the gauging stations, or destruction.

3.3 | Flood Forecast

Information on a possible imminent flood event in NRW is under the responsibility of the flood reporting service of the LANUV as well as the district governments. No flood forecasting was published in NRW during the July flood of 2021 since the forecasting service of LANUV is still in test operation (see Chapter 1). The LfU organizes the flood forecasting and information service in RLP. As already mentioned, floodplains are not included in the flood reporting data of RLP, but are based on threshold values that are defined by the discharge at flood reporting gauges. The first flood forecast regarding the exceeding of HQ_2 ("moderate flood hazard") in the next 24 h for the Ahr catchment was issued at the Altenahr gauge in the early afternoon of 13 July 2021. On 14 July 2021 at 11:17 a.m. the message about the expected exceeding of the HQ_{20} ("High flood hazard") for the Ahr catchment area was issued. This information

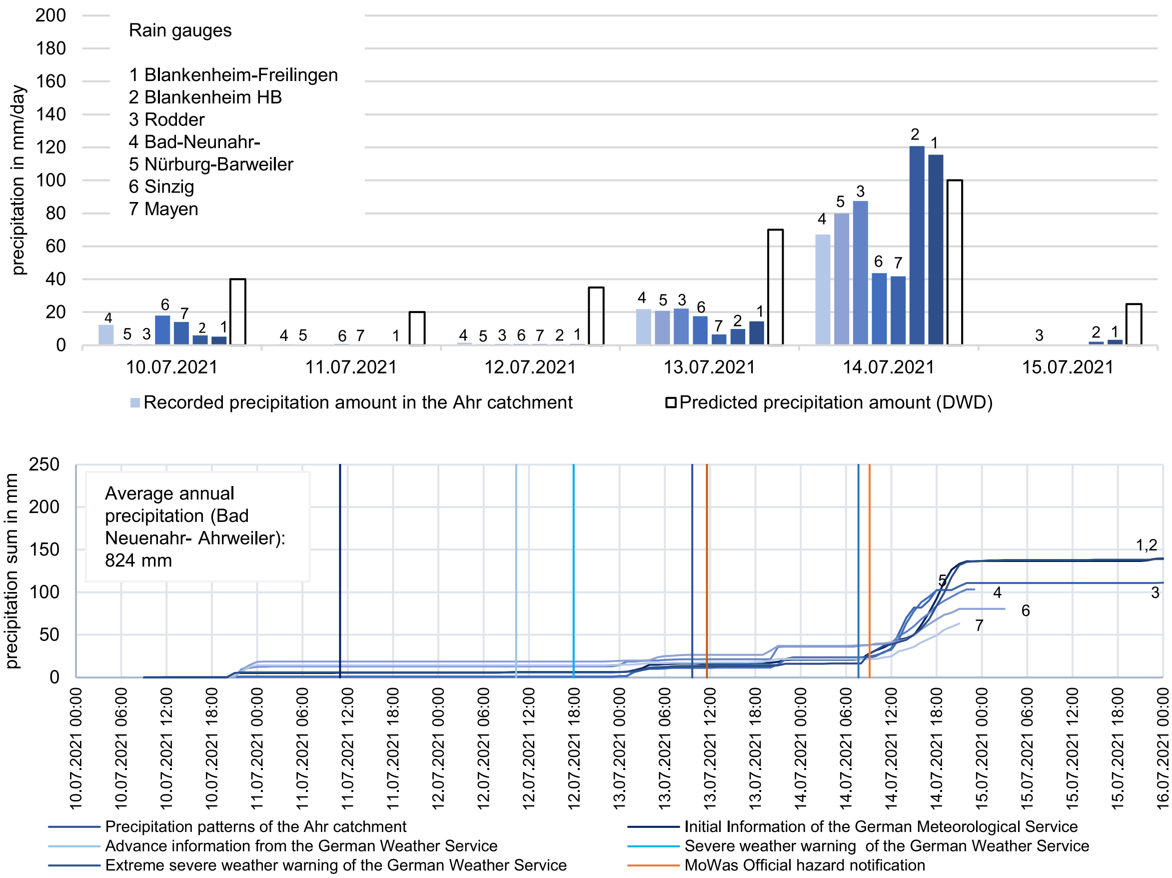

FIGURE 6 | Results of the data analysis of the precipitation data in the Ahr catchment (above: Daily precipitation amounts measured at the investigated rain gauges between 10 and 15 July 2021; below: Precipitation sum of the rain gauges and the timing of weather warnings by the DWD and the hazard notification of the MoWaS).

was additionally issued at the same time via the warning app KATWARN. At 05:17 pm on 14 July 2021, the expected exceedance of HQ_{50} ("Very high flood hazard") in the following 24 h and thus the highest forecast level for the Ahr catchment area was issued, also disseminated via KATWARN. (Landesamt für Umwelt Rheinland-Pfalz 2022).

Thus, there were only about 24 h between the issuance of the first ($>HQ_2$) and the highest flood forecast stage ($>HQ_{50}$) for the Ahr catchment. The period between the issuance of the forecast of a high flood hazard ($>HQ_{20}$) and a very high flood hazard ($>HQ_{50}$; the highest warning threshold) was only 6 h. In addition, the predicted maximum water level at the Altenahr gauge was underpredicted by about 3 m (forecast: around 7 m) (Landesamt für Umwelt Rheinland-Pfalz 2022). The highest water level ever measured before the event in July 2021 was 3.71 m and was measured on 2 June 2016.

3.4 | Water Levels and Exceedances of Flood Reporting Values

As a result of the partly already saturated soils (see Chapter 1) and the intense precipitation on July 13 and July 14 (see Chapter 3.2), the water levels in the investigated catchment areas Rur, Erft, Wupper, and Ahr rose in a very short time. The first exceedance of a flood reporting value occurred in the catchment area of the Rur during the evening of 13 July 2021 at 09:20 pm. Shortly thereafter, the first flood reporting value was also exceeded in the Erft catchment area on 13 July 2021 at 11:20 p.m. In the catchment areas of the Wupper and Ahr, the first flood reporting value exceedances occurred in the afternoon of 14 July 2021 at 02:15 p.m. (Ahr) and 04:30 p.m. (Wupper). A statistical evaluation of the estimated maximum discharges shows that between 210% (Opladen, Wupper catchment area) and 730% (Bliesheim, Erft catchment area) of the respective HQ_{100} discharge was achieved (Mohr et al. 2023). Because of the high amount of failed flood gauges, the LfU calculated reconstructed water levels after the flood event (Landesamt für Umwelt Rheinland-Pfalz 2022). When these recalculated flood magnitudes are compared with the warning thresholds, the intensity of the July 2021 flood event becomes clear (see Figure 7). In the Ahr Valley in particular, the water ultimately rose significantly higher than the water level related to the reporting values (HQ_2, HQ_{10}, HQ_{20}, HQ_{50}) were set. Apart from that, a quarter of the examined warning gauges in the Ahr Valley failed hours before the magnitude of the flood was reached. The estimated average return period of the maximum discharge at the Müsch gauge was > 500 years, at the Altenahr gauge approx. 850 years, and at the Bad Bodendorf gauge approx. 500 years (Landesamt für Umwelt Rheinland-Pfalz 2022).

If all catchment areas are compared with each other, the exceedances of the highest flood reporting value (flood reporting

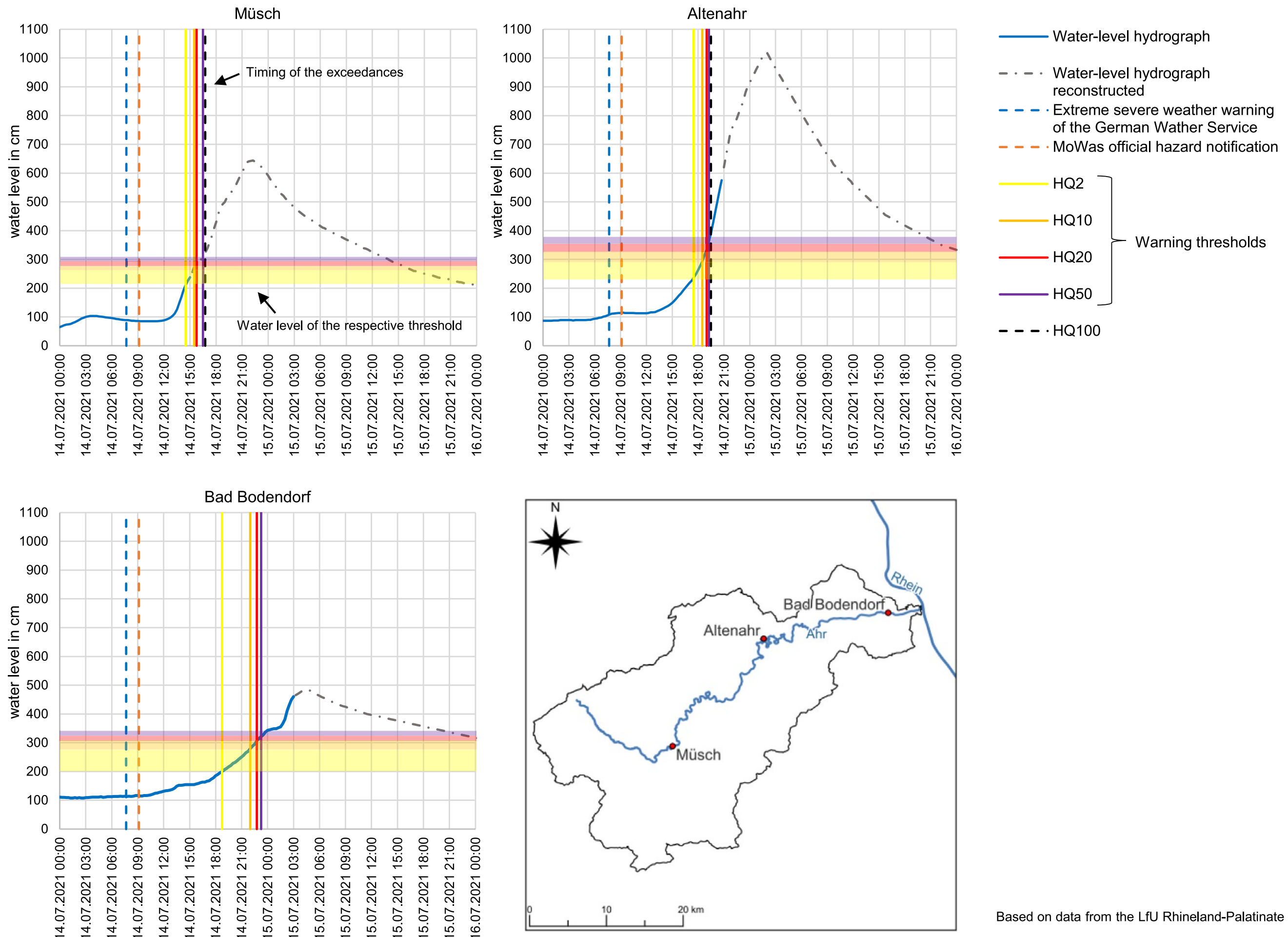

FIGURE 7 | Water levels in the upper, middle, and lower part of the Ahr during the July 2021 Flood event at the respective gauges, including the water level of the respective flood reporting value (vertical) and the timing of their exceedances (horizontal).

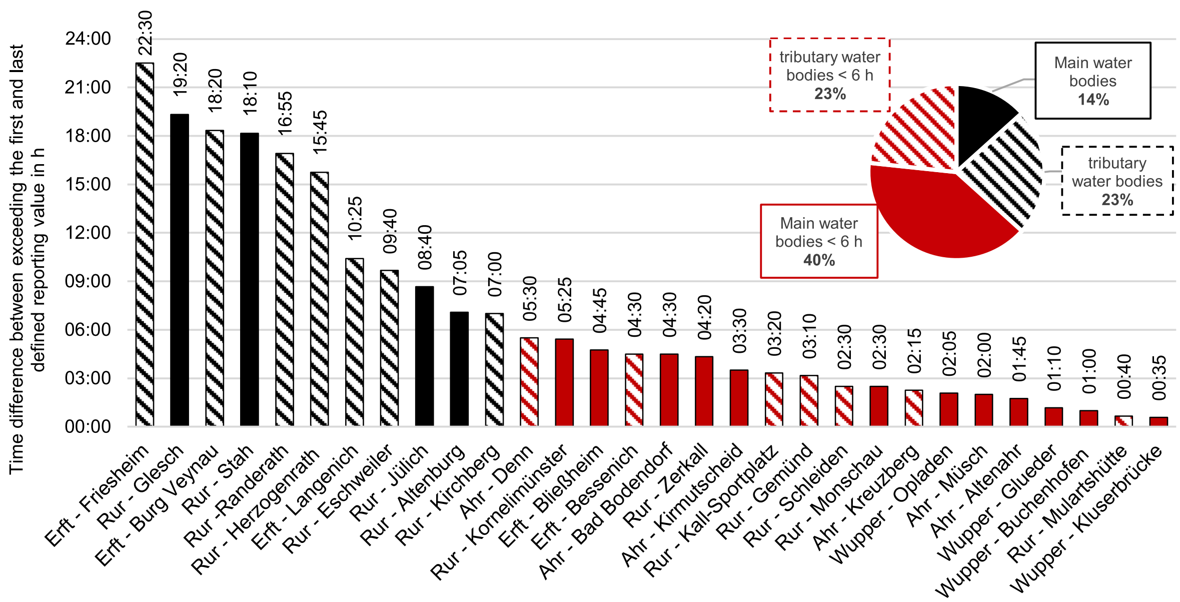

FIGURE 8 | Comparison of all examined gauging stations (that have exceeded the highest flood reporting value) in North Rhine-Westphalia and Rhineland-Palatinate shown according to their time difference between exceeding the first and last defined flood reporting value (Differentiated by color: Black = exceedance took more than 6 h; red = all flood reporting values were exceeded within 6 h).

value 3 in NRW; HQ_{50} in RLP) occurred in a short time. In the catchment area of the Wupper, there are approx. 35 min between the exceeding of the first and the third flood reporting value (Kluserbrücke) and approx. 40 min at the gauge Mulartshütte in the catchment area of the Rur. In the catchment area of the Ahr, 2 h and 15 min lie between the exceeding of the first (HQ_2) and the highest flood reporting value (HQ_{50}). Especially in the Ahr valley (see Figure 7) as well as in the semi-mountainous regions of the catchment areas of the Rur, Erft, and Wupper, there were only a few hours between the exceedance of the first and the highest flood reporting value. The timing of flood reporting value exceedances reveals opportunities to extend lead times. For instance, at the Altenahr gauge, the exceedance of HQ_2 occurred at 2:15 p.m. on 14 July, followed by HQ_{50} at 4:30 p.m.

If the temporal differences between the exceedances of the first and the last flood reporting value of all investigated flood gauges are considered, it can be stated that at 63% of the investigated flood gauges an exceedance of all defined flood reporting values occurred within 6 h or less (red color). For one-third of the flood gauges, this occurred after a period of 3 h (Figure 8). About half of all level exceedances occurred in the evening or at night (between 6 p.m. and 6 a.m.).

In addition, about a quarter of the examined gauges failed. The reasons include power failures, failures in data acquisition/remote data transmission, or destruction of gauging stations. The failures occurred mainly in the semi-mountainous regions in NRW and along the entire Ahr Valley in RLP (5 out of 8 gauges) (Figure 9). The failures did not only occur exclusively in sections with high gradients, but also in the lowlands. The gauges Horchheim and Jülich also failed outside the semi-mountainous areas. The failure of multiple gauging stations during the flood event highlights the challenges in maintaining continuous monitoring under extreme conditions. These outages not only disrupted real-time data acquisition but also hindered the ability to provide warnings in affected regions.

4 | Discussion

The results demonstrate the potential for increasing lead times during extreme flood events by integrating observed and predicted hydrological and meteorological data. The findings emphasize opportunities for improvement across four key areas: observed water levels, observed precipitation, predicted water levels, and predicted precipitation. By addressing these areas systematically, flood warning systems can align more closely with international benchmarks, such as the Early Warning for All framework, and enhance their responsiveness to extreme conditions.

The rapid exceedance of flood reporting values in all investigated catchments highlights the critical role of real-time water level monitoring in flood warning systems. For example, in the Wupper catchment, all flood reporting thresholds were surpassed within 35 min at the Kluserbrücke gauge (see Chapter 3.4). Such

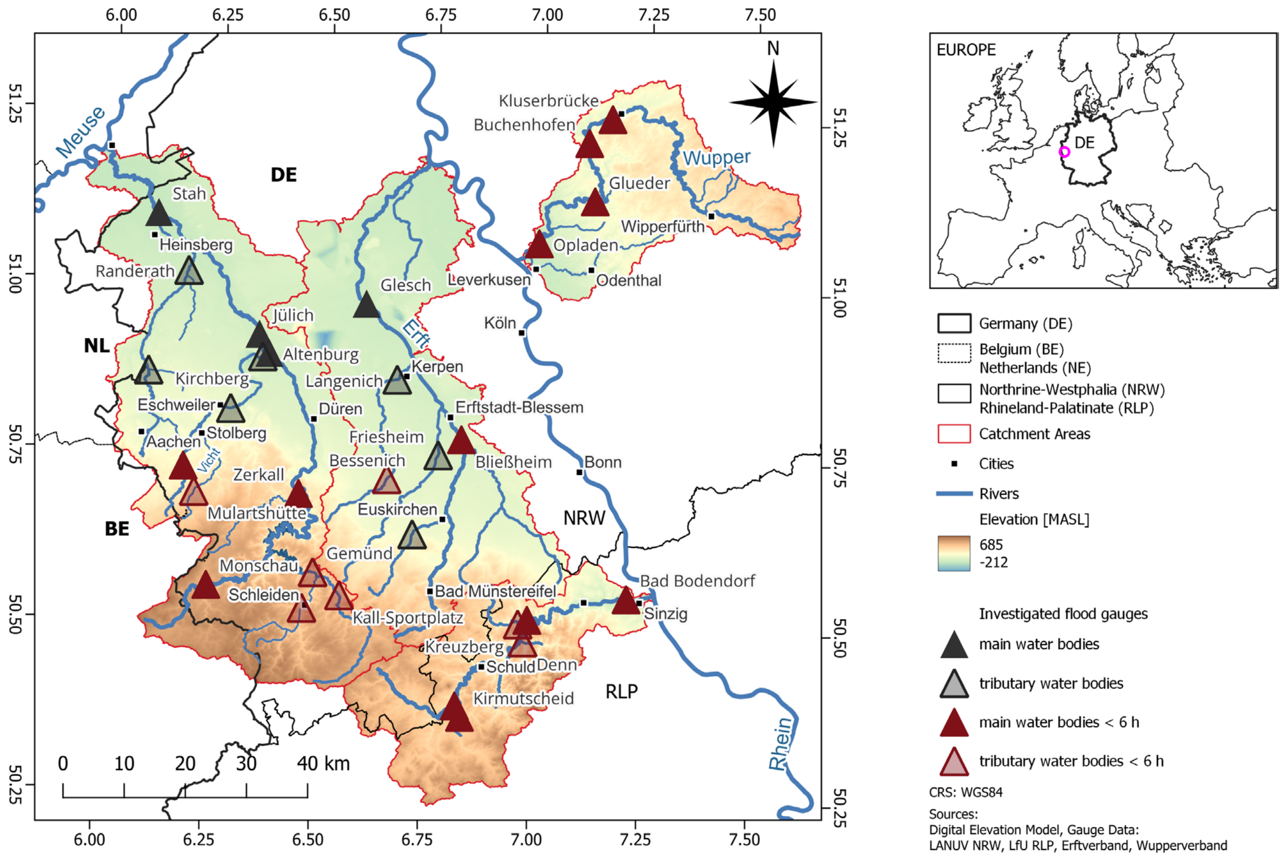

FIGURE 9 | Overview of all examined gauging stations in North Rhine-Westphalia and Rhineland-Palatinate, differentiated by color whether there were more (black) or less (red) than 6 h between the exceedance of the first and the last defined flood reporting value.

rapid changes left limited time for downstream communities to respond, emphasizing the need for robust infrastructure and data integration to support timely warnings. The widespread failure of gauging stations, particularly in semi-mountainous regions like the Ahr valley, further underscores the vulnerability of current systems to extreme events. Approximately 25% of gauging stations failed due to power outages or physical destruction, severely limiting real-time monitoring capabilities (Landesamt für Umwelt Rheinland-Pfalz 2022). Investments in robust and redundant infrastructure such as waterproof installations and backup power supplies are essential to maintain data collection under extreme conditions. Strengthening real-time water level monitoring systems could extend lead times by enabling earlier detection of critical situations and supporting more proactive interventions. In our analysis, around 50% of threshold exceedances occurred between 6 p.m. and 6 a.m., which clearly shows that a rapid rise in flood levels mainly occurred at night. The main challenge is the speed of the rise, as even daytime events can overwhelm response structures. Our results underscore the need for earlier detection and prediction of these rapid changes. However, since our study focuses on analyzing available data rather than directly evaluating local response capabilities, further research is needed to quantify the additional lead time that can be realistically achieved, particularly addressing the communication challenges associated with nocturnal events.

The observed precipitation data revealed significant deviations from forecasts, with rainfall intensities often exceeding predictions. For instance, in the Erft catchment, observed precipitation amounts exceeded forecasts by over 40%, with cumulative totals of up to 180 mm recorded on 14 July 2021 (see Chapter 3.2). Despite these deviations, the observed trends, particularly the rapid intensification of rainfall within short periods, provide critical insights for real-time adjustments in warning systems. As recent studies demonstrate, it is the detailed spatial and temporal distribution of rainfall that is decisive in triggering hydrological responses in flood-prone catchments. Integrating observed precipitation trends dynamically into hydrological models could support more accurate updates to flood warnings. For example, the concentration of rainfall in semi-mountainous regions, such as the municipalities of Roetgen and Hürtgenwald in the Rur catchment, underscores the importance of localized monitoring. This approach could extend lead times by enabling more precise and region-specific interventions, particularly in downstream areas.

Although the observed precipitation data revealed significant deviations from forecasts, these discrepancies highlight not only the inherent uncertainty in current forecasting products but also the critical importance of detailed rainfall distribution. For example, in the Erft catchment, observed rainfall exceeded forecasts by over 40%, with cumulative totals reaching up to 180 mm on 14 July 2021 (see Chapter 3.2). As recent studies (Voit and Heistermann 2024; Macdonald et al. 2025) demonstrate, it is this spatial and temporal detail that ultimately drives hydrological responses in flood-prone catchments. While quantifying these uncertainties fully remains challenging, the observed rapid intensification of rainfall provides valuable insights that, if integrated with localized hydrological models, could support more accurate and timely flood warnings, thereby potentially extending lead times for downstream communities.

Hydrological forecasts during the July 2021 flood were notably limited. In North Rhine-Westphalia, operational flood forecasts were unavailable, while in Rhineland-Palatinate, forecasts at the Altenahr gauge underestimated peak water levels by approximately 3 m. In Rhineland-Palatinate, the predicted maximum water level of 6.5 m was substantially lower than the observed height, which exceeded 10 m (Landesamt für Umwelt Rheinland-Pfalz 2022). These underpredictions underscore the challenges of translating meteorological inputs into accurate hydrological outputs under extreme conditions. Expanding forecasting capabilities to additional gauges and integrating probabilistic precipitation forecasts into hydrological models to simulate runoff scenarios could provide critical lead times for downstream communities. This approach, in line with state-of-the-art methodologies that couple numerical weather models with hydrodynamic simulations (Kardhana et al. 2007; Verkade and Werner 2011; Nikhil Teja et al. 2023) highlights the need for closer coupling between meteorological and hydrological frameworks to enhance flood forecasting effectiveness.

Historical flood events, such as those in 1804 and 1910, represent significant instances of severe flooding in the affected regions (Roggenkamp and Herget 2022). However, these events were not incorporated into the continuous time series used to calculate return periods and, consequently, had no direct influence on the flood warning processes for the July 2021 event. Recent flood events at the Altenahr gauge in 2003 (288 cm), 2007 (254 cm), and 2016 (371 cm) validated the thresholds used in the current warning systems, demonstrating their reliability for frequent to moderate events. Nevertheless, the inclusion of historical events could provide valuable insights for defining additional warning thresholds, particularly for extreme and rare scenarios that exceed the design parameters of current systems. Moreover, recent research (Wright et al. 2020; Voit and Heistermann 2024; Macdonald et al. 2025) highlights promising approaches for refining the estimation of return levels and periods, which could further enhance flood warning strategies.

Probabilistic precipitation forecasts, such as those provided by EPS, offered valuable early insights into extreme rainfall, accurately predicting significant amounts as early as 10 July 2021 (e.g., 107 mm forecast versus 120 mm observed; see Chapter 3.1). Despite their accuracy, these forecasts were not fully integrated into hydrological models or operational workflows. In some areas, such as the Ahr valley, observed precipitation totals exceeded forecasted maxima, while in other regions, predictions closely aligned with observations (Landesamt für Umwelt Rheinland-Pfalz 2022). This variability highlights the challenges of using ensemble forecasts in real-time flood forecasting, particularly due to uncertainties in the spatial and temporal distribution of precipitation (Voit and Heistermann 2024; Macdonald et al. 2025).

In principle, coupling ensemble forecasts with hydrodynamic simulations could extend lead times by simulating runoff scenarios and predicting peak discharge timing, potentially enabling targeted warnings several hours earlier, especially in rapidly responding catchments like the Ahr and Erft. However, as post-event analyses have shown, the effective use of probabilistic forecasts in operational flood management requires addressing key challenges in uncertainty communication. Research has demonstrated that forecast uncertainty can hinder decision-making if not properly conveyed, limiting its usability for emergency planning (Demeritt et al. 2007; Beven and Hall 2014; Thiboult et al. 2017; Hosseini-Shakib et al. 2024). Improving how these uncertainties are represented and communicated is critical to ensuring that probabilistic forecasts can be effectively integrated into hydrological models and used for real-time decision-making (Mohr et al. 2023; Nikhil Teja et al. 2023).

Despite these opportunities, the implementation of a comprehensive flood forecasting system is not without challenges. Establishing and operating such a system based on meteorological ensemble predictions requires substantial financial and technical resources. The complexity of integrating probabilistic forecasts into operational workflows, coupled with the need for advanced computational infrastructure, presents significant barriers to implementation. Moreover, the inherent uncertainties within forecasting systems remain a critical limitation. Probabilistic models, while valuable for scenario planning, carry the risk of producing false alarms or underestimating extreme events. Frequent false alarms could erode public trust in flood warnings, potentially reducing the effectiveness of future alerts and emergency responses. Balancing the need for timely warnings with the minimization of false alarms is therefore a critical consideration in designing and operating such systems.

5 | Conclusion

This study highlights significant opportunities to improve flood warning systems by systematically addressing observed and predicted hydrological and meteorological data. The results indicate that integrating these datasets into unified workflows has the potential to extend lead times, improve spatial precision, and enhance community preparedness for extreme flood events. To achieve this, several key advancements are necessary.

First, investments in robust and redundant monitoring infrastructure are essential to ensure continuous data flow during extreme conditions. The widespread failure of gauging stations during the July 2021 flood event underscores the vulnerability of current systems. Enhancing infrastructure resilience through waterproof installations, backup power supplies, and improved remote monitoring capabilities would mitigate the risk of data loss and strengthen situational awareness during future events. The study also highlights the importance of aligning warning systems with the specific hydrological and topographical characteristics of each catchment area (Werner, Schellekens et al. 2005). Semi-mountainous regions, such as the Ahr valley, require rapid-response protocols and infrastructure capable of handling extreme gradients and flow velocities. The widespread failure of measurement infrastructure during the event, particularly in these high-risk areas, underscores the need for robust systems that maintain critical data flow under catastrophic conditions.

Second, developing workflows that dynamically link observed data, such as water levels and precipitation trends, with predicted data, such as probabilistic forecasts and hydrological simulations, is critical. This integration would enable real-time adjustments to flood warnings, ensuring they remain accurate and actionable even as conditions evolve. Moreover, the absence of high-threshold warning values, such as those for events surpassing HQ_{50} or HQ_{100}, limits the system's ability to issue warnings proportional to the event's severity. Expanding flood warning thresholds to include very high-intensity events would significantly enhance early warning capacities. These thresholds would enable more precise communication of event severity and facilitate proactive emergency responses.

Third, while probabilistic forecasts offer great potential for improving early warning systems, their operational integration into hydrodynamic models remains challenging, particularly due to the need for clear communication of uncertainties. As discussed earlier, addressing these challenges is essential to ensuring their usability for decision-makers and emergency response planning.

Finally, expanding hydrological forecasting capabilities, particularly in North Rhine-Westphalia, would enhance the comprehensiveness of flood warning systems. Coupling probabilistic weather forecasts with hydrological and hydrodynamic models could improve estimations of flood extents, peak discharges, and timings across critical catchments. This integrated approach, aligned with international frameworks such as the Early Warning for All initiative, has substantial potential to enhance both the spatial precision and lead time of warnings. Improved forecasts would also facilitate more effective resource allocation and strengthen public communication in pre-warning phases (Werner, Reggiani, et al. 2005).

In summary, while the integration of observed and predicted datasets represents a promising avenue for extending lead times and improving flood warnings, these advancements must be approached with a clear understanding of their operational and technical limitations. Future efforts should prioritize not only the enhancement of system capabilities but also the development of communication strategies that effectively convey the probabilistic nature of forecasts. Overall, the findings underscore the urgent need to enhance operational frameworks by adopting integrated flood forecasting systems that combine meteorological ensemble models with real-time hydrological data. This approach aligns with international standards, such as the Early Warning for All framework, and emphasizes the importance of robust and redundant measurement infrastructure to mitigate future flood risks. By addressing these gaps, this study contributes to advancing flood early warning systems, ultimately reducing vulnerability to extreme flood events.

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Data Availability Statement

The data utilized in this study were generously provided by the responsible authorities, including LANUV, LfU, and the water management authorities Wasserverband Eifel-Rur, Wupperverband, and Erftverband. We extend our sincere thanks to these organizations for their support.

Researchers or practitioners interested in accessing the data for further analysis or validation purposes may request access by contacting the corresponding author. We hope that the findings of this study will contribute valuable insights for the continued development and improvement of flood management processes.

Endnotes

[1] The Modular Warning System (MoWaS) in Germany is a nationwide, government-operated alert system that disseminates emergency warnings via various channels, including sirens, radio, TV, apps, and digital billboards, ensuring rapid public communication in crises.

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