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Future Climate Change Assessment in Flood Risk Management: A Synthesis of Practices in Germany and the BeNeLux Countries

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ABSTRACT

Climate change, with its links to an intensified water cycle, heavier rainfall, and potentially higher flood peaks, raises concerns about the adequacy of current flood risk management. The devastating July 2021 floods in western Europe underscored these concerns, highlighting the need for transboundary cooperation and shared expertise in adapting flood risk management to climate change. However, uncertainty in future flood projections presents challenges for agencies and governments in upgrading existing measures or designing new ones. Here, we review how climate change information is integrated into flood risk management, focusing on flood design values and flood hazard and risk maps. Focusing on Germany, The Netherlands, Belgium, and Luxembourg—the countries significantly impacted by the 2021 floods—we examine regional practices, as flood risk management is often organized at the sub-national level. Specifically, we assess whether regions have published flood policy papers, developed future flooding scenarios under climate change, and translated these scenarios to flood hazard and risk maps and the design of protection measures. Our findings reveal that all 20 regions have adaptation plans addressing climate change and almost all regions have developed future flood projections but only three incorporate them into climate-adjusted design values and only one provides flood hazard and risk maps under future climate scenarios. Assessments of the future climate vary widely. For example, Flanders in Belgium uses a full range of CMIP5 emission scenarios (RCP2.6 to RCP8.5), while Baden-Württemberg and Bavaria in Germany rely on the worst-case scenario (RCP8.5). Similarly, The Netherlands adopts an approach using 33 global climate models and a dynamic adaptation pathway framework to address uncertainties, whereas Saxony in Germany argues that the spread of projections is too large to derive design values and emphasizes the need for standardized scenarios and methods. In summary, our synthesis highlights substantial gaps in climate-proofing flood risk management and significant regional variation in approaches. Enhanced and faster cross-border learning could improve the effectiveness of climate-informed flood risk management.

1 | Introduction

Floods are among the costliest natural hazards worldwide, with estimated annual average loss of 104 billion US dollars

(UNISDR 2015). The number of people affected by flood disasters has risen in most parts of the world in the past about 40 years (Merz et al. 2021). In the European Union (EU), floods account for the largest share of about 44% of the total economic

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damage associated with weather- and climate-related extremes in the period 1980–2023 (EEA 2024). In this period, several flood events caused among the highest losses: 1993 and 1995 in the Rhine basin, 1997 in the Oder basin, 2000 in England and Wales, and 2002 in the Elbe basin (Paprotny et al. 2024). The most impactful flood event in the recent past struck north-western Europe in the summer of 2021, where record rainfall in parts of Germany, Belgium, and The Netherlands caused almost over 230 casualties and €40–50 billion in financial losses (Szönyi et al. 2022). World Weather Attribution (WWA) estimated the return period of this rainfall event to be around 400 years and found that climate change has increased the likelihood of such a rainfall event to occur today by a factor of 1.2–9 compared to pre-industrial climate (Tradowsky et al. 2023). Another key feature of the 2021 flood event was its transboundary aspect, where a persistent low-pressure system and rainfall impacted multiple countries and catchments in the same event (Mohr et al. 2023; Szönyi et al. 2022). This aspect highlights the need for transboundary cooperation and to share expertise in addressing climate change in flood risk management practices (Heinrich and Penning-Rowsell 2020).

Historical global data already shows that the number of daily rainfall records in many parts of the world has increased since 1980 and is significantly higher compared to what can be expected in a stationary climate (Robinson et al. 2021). This rise demonstrates the influence of global warming, where a warmer atmosphere can hold more water according to the Clausius-Clapeyron relationship and even exceeds this scaling locally (Ali et al. 2021). The heavier rainfall leads to more extreme floods (Tabari 2020). In addition, some research suggests that atmospheric blocking (Tuel et al. 2022), associated with more persistent circulation patterns and prolonged rainfall, such as with the 2021 flood event, may occur more frequently under climate change (Mann et al. 2017). Historical analyses for Europe show increasing trends in river flood flows especially in north-western Europe (Blöschl et al. 2019). Such trends are projected to continue in the future under climate change (Hirabayashi et al. 2013), posing challenges for flood risk management (FRM). It is important to prepare for the changed conditions and develop adaptation measures and risk management options that are robust in the long term (Haasnoot et al. 2024). One of the key questions is therefore how to assess future changes in flooding, and how to incorporate these projected changes and their uncertainties into the FRM practice primarily focusing on flood protection and prevention aspects.

Comparable to integrated water management (Loucks and van Beek 2017), FRM can be considered by three dimensions: the natural, the infrastructural and the institutional system. With regards to the natural system, we are interested in the change in natural boundary conditions that determine the need and degree of adaption. The infrastructural system as part of FRM includes the entire portfolio of structural measures for flood protection and mitigation, for example, levees, reservoirs, and retention areas (e.g., Dottori et al. 2023; LAWA 2023) as well as nature-based solutions such as restoring natural river courses and floodplains (Lane 2017). The institutional system comprises laws, regulations and practices that set the legal and formal frame for FRM as well as the institutions that drive specific management actions. For example, zoning regulations to

enforce building codes for households living in designated flood hazard areas (e.g., Hudson and Botzen 2019) are part of the institutional system. In this work, we particularly focus on the natural dimension, that is, assessment of future flood changes, and partly on infrastructural and institutional measures, that is, how these assessments are used to set design values and derive flood maps. FRM measures are designed at local to regional scales, based on the expectation of extreme flood events in the short and long term (Merz 2017; Jongman 2018). To upgrade existing or design new measures, governments need to (1) estimate so-called “design water levels” and the associated return periods, and (2) develop flood hazard and risk maps (FHRMs). Design water levels provide a basis for the design of flood protection measures (Okoli et al. 2019). FHRMs show the extent, depth, and return period of the flood hazard and values at risk (de Moel et al. 2009). Estimating design values and FHRMs considering future climate conditions is urgently required because the time to implement such measures is often (very) long. However, both are not well developed within current European FRM practices (Holguin et al. 2021).

In the European Union, the EU Flood Directive (EU 2007) sets the frame for developing and regularly updating (1) flood risk assessments, (2) FHRMs, and (3) flood risk management plans (FRMPs). These updates follow a six-year cycle. Currently, the third iteration of FHRMs and FRMPs is due in December 2025 and 2027, respectively. According to Article 14(4) of EU (2007), the likely impact of climate change on the occurrence of floods should be taken into account for the three items in every revision cycle. The implementation of the EU Flood Directive in national legislation and in detailed practices varies across the Member States and even between regions within a single Member State (e.g., between German federal states). This also includes the way how climate change is considered in FHRMs and FRM. It should be noted, however, that the EU Flood Directive does not explicitly call for and prescribe approaches to account for effects of climate change in specific flood risk management measures such as, for example, defining new design values for water infrastructure. According to Gierk et al. (2014), there is no harmonization of approaches and practices for FHRMs and FRM plans required by the EU Flood Directive in the sense that they do not need to be uniform. However, there is a need for coordination of specific tasks and steps between the stakeholders in order to achieve common overarching goals specified by the Flood Directive. Some steps and tasks could even hardly be coordinated due to the different degree of implementation in various states and regions; for example, the federal states of Bavaria and Baden-Württemberg have implemented flood hazard maps even prior to the issuance of the EU Flood Directive. In this case, mutual information of stakeholders is the minimal requirement to be fulfilled (Gierk et al. 2014).

While it remains important to base measures to reduce flood risk on systematic observations and historical events (Boesmaier et al. 2022), new approaches have been and are being developed to incorporate information on future climate into FRM activities. Such approaches vary from simple “what-if scenarios” (Kitsikoudis et al. 2020; Wetzel et al. 2022) to “storyline methods” that describe a coherent future climate narrative (Shepherd 2019; Caviedes-Voullième and Shepherd 2023). Further, more technical methods exist to assess the effect of

climate change on flood hazards. Non-stationary flood frequency analysis is used to fit a statistical model to observed flood peaks, where distribution parameters depend either on time or climate covariates (Delgado et al. 2014; Salas et al. 2018; Schlef et al. 2018). In the first case, past trends in flood peaks can be extrapolated into the future. In the second case, projections of these climate covariates, such as sea surface temperature, can be derived from GCMs for future climate emission scenarios. Both approaches allow for estimating design floods for future periods, but they rely on strong assumptions. Consequently, the most widespread approach is a modeling chain that combines hydrological-hydrodynamic models with climate scenarios (e.g., Alfieri et al. 2017). This approach starts by selecting a series of representative concentration pathways (RCPs)/shared socio-economic pathways (SSPs) describing different socio-economic and greenhouse gas emission scenarios. Further, one or more global climate model runs associated with these RCPs/SSPs provided by the Coupled Model Intercomparison Project (CMIP) (Eyring et al. 2016) are selected to obtain ensembles of future meteorological boundary conditions (e.g., Hirabayashi et al. 2021). As these global climate projections are relatively coarse, they need to be downscaled to finer grid resolution—for example, by dynamic downscaling through regional climate models and bias correction methods (Tapiador et al. 2020) or by statistical downscaling (Maraun and Widmann 2018), including, for example, stochastic weather generators (Nguyen et al. 2024). Next, these time series of downscaled future climate scenarios are used as input to combined hydrological-hydrodynamic models to simulate river discharges, water levels, and inundation (e.g., Hegnauer et al. 2014; Bates et al. 2021). Finally, extreme value statistics can be applied to the discharge time series to estimate flood quantiles and associated return periods (Tabari 2021) for each of the climate projections.

While the modeling chain approach provides a bandwidth of possible future flood hazard values, which can be used to evaluate the performance of different FRM measures under future climate conditions (Hochrainer-Stigler et al. 2018), their uncertainties are often large (Lawrence 2020; Lane et al. 2022). In addition, the number of models, scenarios, and approaches is often larger than can be practically considered in management practice. Moreover, new climate projections or improved statistical methods and simulation models may change future design values. These issues pose a challenge for transboundary FRM when updating existing or designing new FRM measures. Given this uncertainty, flexibility in flood adaptation is recommended (Haasnoot et al. 2024). However, flexibility is sometimes difficult to achieve. For example, the maintenance and upgrading of flood defenses is expensive and time-consuming, and once investments have been made, new upgrades of flood protection usually take a long time (Kind 2013).

Regulatory authorities are increasingly requiring to consider climate change in flood design. However, the adaptation of flood estimation guidelines to include climate change varies strongly across countries, and many regions have yet to incorporate such adaptations. A review by Wasko et al. (2021) finds that guidelines often use climate change allowance, amplification or adjustment factors, which scale the flood peak or rainfall intensity under current conditions or under natural climate conditions to reflect climate change impacts. Depending on

the country or region, the factor is named differently. Here, we use the term “climate change factor” for both rainfall or flood peak adjustment and mean a multiplicative factor indicating the difference between future and historical periods. Many countries use these factors for IDF (intensity-duration-frequency) rainfall curves which are then used as input to hydrological models to estimate possible future flood peaks under climate change. Typically, these climate change factors are obtained from downscaled climate models projections in the case of precipitation or from modeling chains consisting of climate and hydrological models in the case of flood peaks. These factors may be spatially uniform across countries, like in Denmark and Australia, or they may vary between regions or river basins, like in England (Wasko et al. 2021). The treatment of uncertainty and whether climate change factors vary with return periods also differ widely. While some guidelines use different percentiles to represent uncertainty in the climate change factors, others provide a single value. Research shows that more extreme (Gründemann et al. 2022) and shorter-duration rainfall events (Fowler et al. 2021) tend to intensify more in a changing climate. Consequently, some countries apply higher climate change factors for more extreme and shorter events (Wasko et al. 2021). In summary, many countries and regions lack policies to account for climate change in flood design, and where such policies exist, they vary substantially.

In this paper, we review how the effects of climate change on flood hazards are assessed and how this information is used for estimating design values and developing FHRMs. Given the strong demand for climate-proofing FRM in the region affected by the 2021 flood, we focus on the current practices in the countries strongly affected by this event (Germany, Belgium, The Netherlands, and Luxembourg). Our synthesis is based on a literature review including grey literature and expert interviews through a screening form. It provides an overview of current practices, which may serve as a step toward a more climate-informed transboundary flood risk management.

2 | Case Study Region and Approach

2.1 | Case Study Region

The flood event of summer 2021 severely hit parts of Belgium, Germany, Luxembourg, and The Netherlands that share the Meuse and Rhine River basins (Figure 1). The flood disaster was caused by an atmospheric low-pressure system with a total precipitation of up to 300 mm in the Ardennes-Eifel region over 48 h in July 2021 (Lehmkuhl et al. 2022). Return periods for daily precipitation exceeded 500 years in some areas (Mohr et al. 2023). The total estimated damage in Germany and the BeNeLux countries was €40–50 billion and over 230 people lost their lives (Szönyi et al. 2022; Mohr et al. 2023; Endendijk et al. 2023; Kok et al. 2023). The impacts were the largest along the smaller tributaries of the Rhine and Meuse basins: in Germany, tributaries included the Ahr, Erft, Inde, and Rur, with the most severe damage in the Ahr valley. Here, flood inundations with water depths of several meters destructed many buildings and caused 184 fatalities (Lehmkuhl et al. 2022; DKKV 2022). In Belgium, in particular, the Vesdre valley was hit and in total 39 people lost their lives (Journée et al. 2023). For The Netherlands, no fatalities

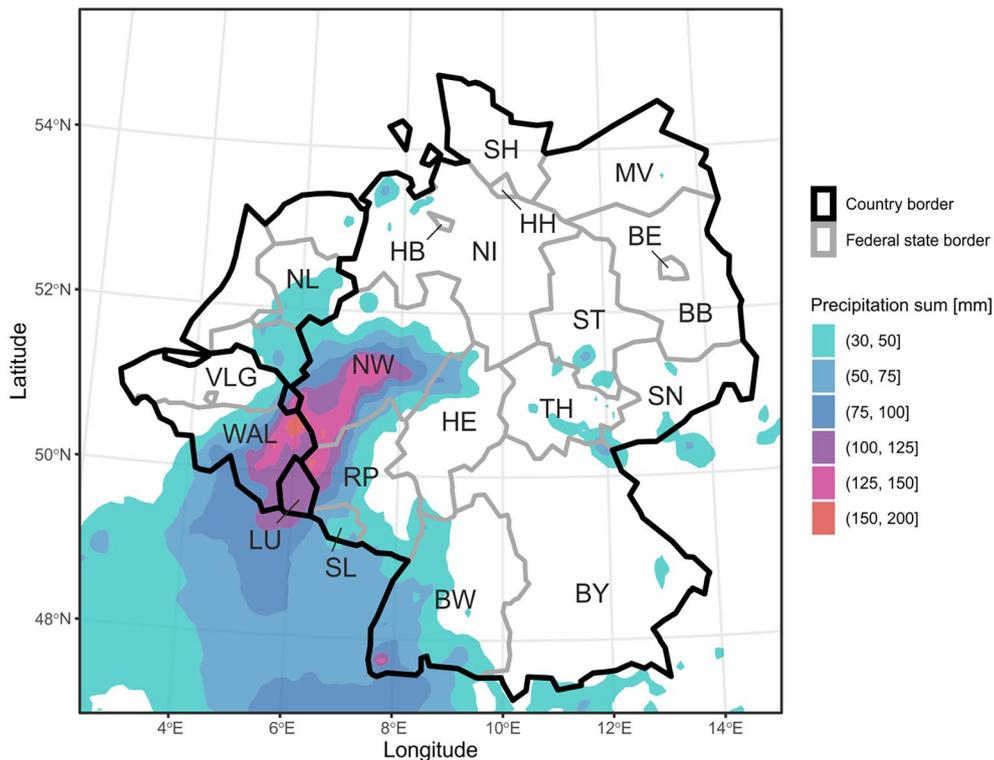


FIGURE 1 | Study area comprised of Belgium, Germany, Luxembourg, and The Netherlands. The four countries, regions, and federal states follow the ISO 3166-2 code: VLG—Flanders, WAL—Wallonia, SH—Schleswig-Holstein, HH—Hamburg, HB—Bremen, MV—Mecklenburg-Vorpommern, NI—Lower Saxony, NW—North Rhine-Westphalia, ST—Saxony-Anhalt, BE—Berlin, BB—Brandenburg, SN—Saxony, TH—Thuringia, HE—Hesse, RP—Rhineland-Palatinate, SL—Saarland, BW—Baden-Württemberg, BY—Bavaria, LU—Luxembourg, NL—The Netherlands. July 2021 flood event: 72-h total precipitation above 30 mm between July 12th and 14th July 2021 based on the $0.1^\circ \times 0.1^\circ$ E-OBS data (Cornes et al. 2018).

were reported, but damage amounted to more than half a billion euro in the Geul, Rur, and Meuse River basins (ENW 2021). Also, other countries sharing Meuse and Rhine River basins such as France, Switzerland, and Austria were affected by the 2021 event, but the impacts were comparably smaller (https://en.wikipedia.org/wiki/2021_European_floods, accessed 1 September 2025). We therefore focus our analysis driven by the Joint Cooperation programme for Applied scientific Research on flood and drought risk management in regional river basins (JCAR-ATRACE) on the involved countries: The Netherlands, Belgium, Luxembourg, and Germany. The study area includes in total 20 regions for which the reviews are carried out: two regions in Belgium, 16 German federal states, Luxembourg, and The Netherlands (Figure 1).

Floods are a natural and recurring phenomenon in the Rhine and Meuse rivers, especially during winter and early spring (Chhab 1995). In the smaller tributaries such as Ahr and Vesdre, floods in the summer half-year are not uncommon (Vorogushyn et al. 2022; Chakraborty et al. 2024). Until 2021, the highest ever recorded flood peaks in the Meuse occurred in winter 1993 and 1995; these events were the second and third highest floods for the River Rhine in The Netherlands. The 2021 flood event set a new record for the Meuse with $3310 \text{ m}^3/\text{s}$ at the gauging station of St. Pieter noord (RURA-Arnheim 2022). At the next downstream station Borgharen-dorp with a long-term record, the recorded peak flow of $3284 \text{ m}^3/\text{s}$ has an approximately 125-year return period (RURA-Arnheim 2022). While discharges were very high, little damage occurred along the Meuse because

a recent river widening project reduced flood levels and enabled accommodation of more extreme flood flows (Endendijk et al. 2023).

The 2021 flood event has sparked a renewed discussion regarding the differences and interdependences in cross-border FRM practices as the entire river basin needs to be considered for a balanced assessment of effective FRM measures. For example, the reservoirs situated within the upper parts of the Rur tributary in Germany have substantially reduced the flood peaks downstream near the City of Roermond in The Netherlands (JCAR 2024). Furthermore, upgrading levee systems upstream may increase flooding downstream. It has also led to recommendations for better cooperation and the use of uniform climate data and FRM approaches within river basins (Koma et al. 2022).

The cooperation across countries is challenging as FRM governance differs. For example, in The Netherlands, the national government is managing the large waterways (e.g., Rhine and Meuse), and flood protection standards are based on an acceptable probability of flooding and are anchored in the law. These probabilities differ depending on the exposed values in the protected area. These standards form the basis for the design of protection measures. The regional Dutch water authorities (incl. “water boards”) are responsible for FRM in the smaller regional water systems. Also here, flood protection standards for different land use types are anchored in regional legislation. In view of climate change, the Royal Netherlands Meteorological Institute

(KNMI) provides national climate change scenarios. These scenarios are used by all governmental agencies, including those responsible for FRM. Germany has directed FRM to the 16 federal states that have the mandate to set flood protection standards for all water bodies. They can also choose how to include climate information in FRM. As a result, differences in the use of data and climate change approaches exist across Germany (Becker et al. 2015). Since a few years, the German federal government plays a mediating role aiming at consistent FRM policies across the federal states and is synchronizing state policies (LAWA 2010). In Belgium, the two federal states (Flanders and Wallonia) both have the mandate to develop and enforce FRM regulations, whereas the federal government is responsible for crisis management and flood insurance (Mees et al. 2016). In Luxembourg, FRM is addressed at the national level by the Water Management Administration (AGE) which is part of the Ministry of the Environment, Climate and Biodiversity.

2.2 | Approach

We initially conducted a literature search using combinations of keywords such as flood, climate scenario, hydrological model, design water level, and hazard maps. However, it quickly became apparent that we missed relevant information from grey literature, which was only available in the languages of the respective countries in the case study area. We changed our search strategy and also scanned national and regional guidelines and regulations that indicate how climate change is considered in flood hazard estimates and incorporated into FRM. This scan was limited to flood hazard mapping and estimating flood design values. We compiled openly available information and further developed a structured screening form (see Supplement) to inquire specific questions related to, for example, the selection of climate scenarios and climate models for assessing future flood hazards, and procedures to determine or update flood design values based on available climate change information. This screening form, partly pre-filled with collected information, was sent to flood risk managers in various state authorities in the case study area, inquiring further details and additional information. The purpose of this screening was to complement the web search information with specific expert knowledge. We received feedback from Flanders and Wallonia in Belgium, Luxembourg and four German federal states (Mecklenburg-Vorpommern, Brandenburg, Saxony, and Saarland) with one expert each complementing pre-filled information. For other German federal states, the analysis was solely based on the literature review. In the Netherlands, three experts contributed to the screening forms. We interviewed 12 FRM experts in the different countries with experience of climate information and the use of climate scenarios in FRM and adaptation in the case study area. Both the feedback of the screening forms received and the interviews were synthesized together with the literature review.

3 | Results and Discussion

In this section, we describe the results of our literature search, the screening form feedback and interviews by country. In Section 3.1, we summarize how flood hazard under climate

change is estimated in the different countries (Table 1). Next, we show how these flood projections are considered in flood design and FHRMs (Section 3.2 and Table 3). In Section 3.3, we compare for selected regions how adaptation is organized, given the considerable uncertainty in future flood hazard projections. As many regions in the study area have not yet developed future flood hazard projections, these regions are not discussed in detail here. More detailed information on the current practices in the regions and their ambitions can be found in the Appendix A.

3.1 | Estimation of Climate Change Effects on Flood Hazard

In The Netherlands, Belgium, and Germany, specific climate model simulations have been officially selected and adopted by state agencies for estimating future flood hazards. In The Netherlands, the scenarios are provided by the Royal Netherlands Meteorological Institute (KNMI) since 2001, approximately every 7 years, most recently in 2023 (van der Wiel et al. 2024). In Flanders in Belgium, the responsibility lies with the Integrated Water Policy Coordination Committee (CIW). In Wallonia, the regional working group on floods (GTI), led by the water management authority SPW, has assigned the task to a committee of hydrological experts to consider new regional climate change projections such as those developed by Brajkovic et al. (2025) for updating flood design values and FHRMs. In Germany, the project “KLIWA—Climate change and consequences for water management” (www.kliwa.de, accessed 1 September 2025) provides climate projections and carries out hydrological simulations. Here, the federal states of Bavaria and Baden-Württemberg cooperate with the German Weather Service (DWD) since 1999. Rhineland-Palatinate joined the consortium in 2007, and since 2024, Hesse and Saarland are also part of KLIWA. The German Federal Institute of Hydrology (BfG) has a guest status. In the following, we review KLIWA practices only in Bavaria, Baden-Württemberg, and Rhineland-Palatinate, where they have been implemented so far. Currently, Luxembourg considers engagement in the German KLIWA consortium to advance its assessments of climate change on hydrologic extremes (LGDGDL 2023), but to date, it has no established procedure for assessment of future flood changes. Since 2008, the federal state of Lower Saxony assesses flood changes in future climates within the project “KliBiW—Global climate change: Water management impact assessment for inland areas.” Finally, in the research program “KLIWAS” (www.kliwas.de, accessed 1 September 2025), a comprehensive climate impact assessment studies on navigable reaches of rivers in Germany were carried out between 2009 and 2013, covering entire Germany. These assessments were further methodologically enhanced and updated in a subsequent work of the Expert Network of the German Federal Ministry of Transportation and Infrastructure (BMVI-ExpN) in 2016–2019 (Nilson et al. 2020). The KLIWA and BMVI-ExpN projections contribute to specific FRMPs at the level of the German parts of the international river basins (FGG Rhein 2021; FGG Donau 2021; FGG Elbe 2021; FGG Weser 2021; FGG Ems 2021). Further, some assessments find their way to basin-wide syntheses of climate change impacts within international efforts such as the International Commission for the Protection of the Rhine (Görge et al. 2010, ICPR 2024, <https://www.chr-khr.org/en/news/chr-launches-project-rheinblick2027-2024-2027>, accessed 9 November 2025). In all above-mentioned

TABLE 1 | Specifications of the simulations used for estimating climate change effects for flood hazards.

Country	The Netherlands	Belgium	Belgium	Germany	Germany	Germany
Region, Rivers	Rhine, Meuse, Regional rivers	Flanders	Wallonia	Baden-Württemberg (BW), Bavaria (BY), Rhineland-Palatinate (RP)	Lower Saxony (NI)	Navigable reaches of the Rhine, Danube Elbe, Weser, and Ems rivers ^{k,l}
Emission scenarios	SSP1-2.6 SSP2-4.5 SSP5-8.5	RCP2.6 RCP4.5 RCP6.0 RCP8.5	SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5	RCP8.5	RCP8.5	RCP8.5 RCP4.5 RCP2.6
Global Climate Models (GCMs)	CMIP6 models, EC-EARTH3	CMIP5 models	MIROC6r1 NorESM2-MMr1 MPI-ESM-2-HR EC-Earth3-Veg-HRr1 CMCC-CM2-SR5r1 IPSL-CM6A-LRr1	EC-EARTHr12 EC-EARTHr1 MIROC5r1 MPI-ESM-LRr1 HadGEM2-ESr1	EC-EARTHr12 EC-EARTHr1 MIROC5r1 MPI-ESM-LRr1 HadGEM2-ESr1	CanESM2r1 EC-EARTHr12 HadGEM2-ESr1 IPSL-CMA5A-MRr1 MIROC5r1 MPI-ESM-LRr1r2
Regional Climate Models (RCMs) ^m	RACMO2	EURO-CORDEX: RAO, RACMO HIRHAM, CHRM, HadRM3P, REMO, ARPEGE, CLM, PROMES CORDEX.be: ALARO, COSMO-CLM, MAR	MAR	CCLM4-8-17 RACMO22E SMHI-RCA4 WRF361H	CCLM4-8-17 RACMO22E WETTREG2013 WRF361H	REMO RACMO CCLM RCA4
Reasoning for the selection of GCMs and RCMs	Well established GCMs, in-house GCM/RCM	Well established models + high-resolution RCMs; satisfactory projections for the region	GCM selection is recommended by the EURO-CORDEX community ^o ; MAR is in-house validated RCM ^{p,q,r}	Evaluated by ReKLieEs-De; plausibility check for the region (“Klimaaudit”)	Evaluated by ReKLieEs-De and BL-FG, plausibility check for the region (“Klimaaudit”)	Evaluated by ReKLieEs-DE and ensemble reduction according to Dalelane et al. (2018)
Additional scenarios	Wet and dry scenario variants	Low/mean/high rainfall and ET; low/medium/high runoff				

(Continues)

TABLE 1 | (Continued)

Country	The Netherlands	Belgium	Belgium	Germany	Germany	Germany
Number of ensemble members	8 per SSP and per wet/dry variant	Full set of available CMIP5 and EURO-CORDEX runs. In total more than 200 GCM-RCM combinations for all scenarios. Various numbers of runs per model (historical control run, and RCP based scenario runs for RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios).	6 GCM-RCM(MAR) per SSP	9	8	RCP 8.5: 16 (13 used for extreme value statistics) RCP4.5: 11 RCP2.6: 10
Reasoning for ensemble number	Realistic representation of natural variability, number chosen by KNMI	All available simulations for Belgium to cover the entire spread		Manageable number, representative, cover a wide range of futures	Manageable number, retain maximum spread of projections	Maximum spread in change signal of key variables retained with minimum number of ensemble members
Time horizon(s) projections	2036–2065 2086–2115 2136–2165	2036–2065 2071–2100	2015–2100	2021–2050 2041–2070 2071–2100	2021–2050 2071–2100	2031–2060 2071–2100
Statistical downscaling/Bias correction	Quantile delta mapping (QDM) ⁿ	Perfect prognosis, perturbation ^v	Equidistant quantile matching (EDCDFm) ^s	Quantile delta mapping (QDM) ⁿ	Multivariate quantile mapping ^t	Multivariate quantile mapping, Quantile delta mapping ⁿ , Quantile delta change mapping ^u
Hydrological (h) and hydrodynamic (hd) models	Rhine and Meuse: wflow_sbm ^a (h), SOBEK ^b (hd) Regional rivers: Various (h); SOBEK (hd)	Non-navigable waterways: Probability-Distributed-Moisture (PDM) model ^c (h), Infoworks-RS ^d (hd) Navigable waterways: Nedbør-Afstrømnings-Model ^e (NAM; h), Mike11 ^f (hd)		LARSIM ^g (in BW and RP; h), WaSIM ^h (in BY; h)	PANTA RHEI ⁱ (h)	LARSIM-ME ^l

(Continues)

TABLE 1 | (Continued)

Country	The Netherlands	Belgium	Belgium	Germany	Germany	Germany
Reasoning for selecting the hydrological/hydrodynamic model	Models are accessible and maintenance provided	Operationally used	Operationally used	Operationally used	Operationally used	Operationally used
Flood return periods	$T = 10a$ to ($T = 50,000a$) ^j	Continuous simulations	Continuous simulations	Continuous simulations	Continuous simulations	Mean Annual Flood (MAF), $T = 10a$, 100a, 1000a (not all T are reported for all basins ^k)
Other simulated flow-related aspects	Representative flood wave	Water level, flood inundation (extent, depth, duration)	Economic, ecological and social risk			
Other simulated risks						
Application area	Rhine and Meuse: planning/adaptation of levees/dams and other water infrastructure Regional rivers: Design for drainage, awareness raising	Hazard and risk maps		Wallonia	Design floods for technical flood protection (e.g., levees, embankments), FRMP for the German parts of the Rhine and Danube basins	FRMPs for the German parts of the Elbe, Weser, and Ems basins

Note: The regions included in this table have official simulations adopted.

Abbreviations: BL-FG, Bund-Länder Fachgespräch (federal-state expert discussion); CMIP, coupled model intercomparison project; ET, evapotranspiration; EURO-CORDEX, European Coordinated Downscaling Experiment; KNMI, royal Dutch meteorological service; RCP, representative concentration pathway; ReKLiEs-De, regional climate projection ensemble for Germany; SSP, shared socio-economic pathway; T, return period.

^avan Verseveld et al. (2024).

^bDellares (2022).

^cMoore (2007).

^dInfoworks ICM (2023).

^eDHI (2011).

^fBremicker (2000).

^gSchulla (2024).

^hNLWKN (2021).

ⁱAssessment for return periods higher than 100a is still in the research phase and not yet adopted in policies.

^jNilson et al. (2020).

^kHänsel et al. (2020).

^lWolf-Schumann et al. (2013).

^mGCM model realization is attached to the model's name (e.g., "r1") where known.

ⁿCannon et al. (2015).

^oSobolowski et al. (2023).

^pDoutreloup et al. (2019).

^qDoutreloup, Bois, et al. (2022).

^rDoutreloup, Fettweis, et al. (2022).

^sPierce et al. (2015).

^tCannon (2018).

^uOjsson et al. (2009).

^vMIRA (2015).

cases, model chains, as described in the Introduction, were used, that is, global and regional climate simulations were fed into hydrological and hydrodynamic models. The exact setup of the model chains, such as the emission scenarios or climate models used, differs between the regions. The setups are summarized in Table 1 and compared below.

3.1.1 | Emission Scenarios

Climate change simulations are driven by the selection of RCPs or SSPs, which characterize the future concentrations of greenhouse gases in the atmosphere. RCPs and SSPs are used in the Coupled Model Intercomparison Project (CMIP) 5 and 6, respectively. Simulated discharges can differ strongly depending on the selected emission scenarios. All regions include at least a high-emission scenario in their simulations, sometimes referred to as a “business-as-usual” scenario. The members of the KLIWA consortium (Bavaria, Baden-Württemberg, Rhineland-Palatinate) as well as Lower Saxony consider only this high-emission scenario, namely RCP8.5 (Iber 2022; KLIWA 2022; NLWKN 2021). BMVI-ExpN uses three emission scenarios: RCP2.6, RCP4.5, and RCP8.5 (Nilson et al. 2020). Flanders adopts the entire range of CMIP5 scenarios including RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Tabari et al. 2015). Climate projections currently considered in the Walloon region are also based on four CMIP6 SSP scenarios ranging from low-end (SSP1-2.6) to high end (SSP5-8.5) emissions (Brajkovic et al. 2025). In The Netherlands, a wide range of CMIP6 scenarios, namely SSP1-2.6, SSP2-4.5, and SSP5-8.5, are used for climate model simulations (van der Wiel et al. 2024).

3.1.2 | Global and Regional Climate Models

Regarding the global climate models (GCMs) and regional climate models (RCMs), there is some overlap across the regions, that is, some models are used in several regions. However, the number of models used by different regions varies substantially (Table 1). In The Netherlands, the most recent generation, referred to as KNMI23 climate scenarios, includes four scenarios described below (van der Wiel et al. 2024). Selecting these four scenarios is a pragmatic approach. It is expected to cover most of the potential hydrological changes due to climate change. Furthermore, dealing with only four scenarios is manageable for most users. These scenarios apply not only to The Netherlands, but also to the upstream parts of the river basins of Rhine and Meuse as these rivers largely determine the flood and drought risk downstream in The Netherlands. These scenarios are derived from 33 CMIP6 GCM models split into two groups reflecting a wet and dry trending group of model results and reflecting uncertainty in the precipitation response (van der Wiel et al. 2024; van Dorland et al. 2024). The groups are formed based on the normalized projected change in annual, winter, and summer precipitation. Focusing on the wet and dry scenario variants allows for specific analyses of flood and drought hazard (van der Wiel et al. 2024). Median CMIP6 responses in terms of temperature, precipitation, and cumulative water balance deficit, that is, difference between potential evapotranspiration and total monthly precipitation, between April and September were derived for the period of interest. To downscale the GCM data,

these responses were first used as constraints to resample years from a 16-member ensemble of the EC-EARTH3 GCM model. In this way, scenarios consisting of EC-EARTH3 output were produced that are consistent with the responses of other CMIP6 GCMs. In the second step, the resampled EC-EARTH3 climate data were substituted with the bias-corrected 12-km climate downscaled with the RACMO RCM (van der Wiel et al. 2024). For summary of the workflow, the reader may refer to fig. 1 in van der Wiel et al. (2024).

Flanders uses a 12-member GCM ensemble from CMIP5 (CIW 2020; Tabari et al. 2015) and the respective RCMs downscaling from EURO-CORDEX (Jacob et al. 2014) and CORDEX.be (Termonia et al. 2018). CMIP5 and EURO-CORDEX are well-established simulations which are then further downscaled with region-specific high-resolution (4 km) RCMs. Based on a broad range of emission scenarios, scenarios with low, mean and high rainfall and evapotranspiration are developed. An evaluation for central Belgium showed that the RCMs are satisfactory in representing historical statistics for the region. In Flanders, the number of ensemble members is not reduced to a more manageable set and a great number of meteorological scenarios in hydrological models results in low, medium and high runoff projections (Ntegeka et al. 2014). Here, the focus is on considering the entire width of future projections and therefore all CMIP5 and EURO-CORDEX simulations available for Belgium are taken into account (MIRA 2015; CIW 2020).

In Wallonia, Brajkovic et al. (2025) recently carried out dynamical downscaling of six CMIP6 GCMs using the MAR regional climate model with the resolution of 5 km. The so-downscaled precipitation for four CMIP6 SSPs shows a considerable increase for the period 2015–2100 compared to the historical period 1951–2021 even for low-warming scenarios. The downscaled meteorological data is intended to drive hydrological and hydrodynamic models in the following step to estimate future design values and update FHRMs.

In Germany, the four federal states in the KLIWA (Baden-Württemberg, Bavaria, Rhineland-Palatinate) and KliBiW (Lower Saxony) consortia all use the same GCMs and almost the same RCMs with only one difference (Table 1). BMVI-ExpN uses a larger ensemble of GCM-RCM combinations in part overlapping with those mentioned above (Nilson et al. 2020; Hänsel et al. 2020). The model selection for all three assessments is based on CMIP5, EURO-CORDEX, and ReKLiEs-De (Hübener et al. 2017), and for Lower Saxony it also follows the recommendation of the “Bund-Länder Fachgespräch (BL-FG)” (BL-FG 2014). In the ReKLiEs-De project, the EURO-CORDEX simulations were systematically evaluated for Germany and supplemented by selected additional simulations. The BL-FG, established in 2005, is an informal exchange between federal states and national institutions on the interpretation of regional climate models. In addition, KLIWA and KliBiW use the method “Klimaaudit” (BLfU 2020; KLIWA 2022) to check the plausibility of the selected models for the respective regions. Klimaaudit uses quantitative and visual criteria to support the decision of selecting or rejecting certain climate projections. In the four German federal states, the ensemble members differ in the GCMs and RCMs used. Nine ensemble members are

considered in Baden-Württemberg, Bavaria and Rhineland-Palatinate (Iber 2022), and eight ensemble members in Lower Saxony (NLWKN 2021). The reasoning for setting the number of ensemble members is similar in all four states: They aim to cover a wide range of futures and to retain the spread of projections while having a manageable number of ensemble members (NLWKN 2021; Iber 2022). This is achieved through a statistical ensemble reduction technique which is based on monthly mean changes between a reference and a future time period for a range of key climate variables (Dalelane et al. 2018). The reduced ensembles reproduce more than 90% of the spread of the full ensembles (Dalelane et al. 2018; NLWKN 2021). The same ensemble reduction approach according to Dalelane et al. (2018) is taken by BMVI-ExpN for the whole of Germany, which resulted in larger ensembles with 10–16 members depending on the emission scenario (Hänsel et al. 2020, Table 1).

3.1.3 | Simulated Variables and Future Time Periods

The climate impact model chains can simulate different variables for various time horizons. In Flanders, continuous time series of discharge are simulated until 2100 and evaluated for the time horizons 2036–2065 and 2071–2100 (MIRA 2015; CIW 2020). In Wallonia, no simulations of future discharge are yet available. Transient regional climate simulations for the period from 2015 to 2100 are now available (Brajkovic et al. 2015). In Lower Saxony, continuous time series are simulated for 2021–2050 and 2071–2100 (NLWKN 2021). In Baden-Württemberg, Bavaria and Rhineland-Palatinate, simulations are conducted additionally for a medium time horizon, namely 2041–2070 (Iber 2022). BMVI-ExpN adopts two slightly different periods: 2031–2060 and 2071–2100. In The Netherlands, simulations are carried out for three time horizons (2036–2065, 2086–2115, 2136–2165) in the large rivers (Rhine and Meuse; Buitink et al. 2023). In Flanders and The Netherlands, additional flow and risk-related properties are simulated. These are, for example, representative flood waves in large rivers in The Netherlands, the extent, depth, and duration of flood inundation along small Dutch rivers and in Flanders. In Flanders, also economic, ecological, and social risk associated with flooding are estimated (Deltares 2024a; Beullens et al. 2021).

3.1.4 | Statistical Downscaling and Bias Correction

All the reviewed procedures except the one in Flanders apply bias correction to the climate model output with subsequent specific regionalization of climate data for hydrological modeling (Table 1). Bias correction procedures used are variants of quantile mapping. Whereas The Netherlands, Wallonia and KliBiW use the univariate methods to correct the model biases, KLIWA and BMVI-ExpN apply multivariate bias correction according to Cannon (2018). BMVI-ExpN uses this method for dependent temperature and humidity variables, whereas other variables, such as precipitation and wind are corrected with univariate approaches. Flanders is the only region which uses a perfect prognosis approach instead of bias-corrected model output (MIRA 2015), that is, a simulated climate change signal derived from the difference between control and projected simulations is applied to observed data with additional

perturbation. Perturbation is applied to wet-day frequency as well as to intensity quantiles of wet-day precipitation. Additionally, perturbation of observed temperature and evapotranspiration is carried out considering correlation with precipitation (MIRA 2015).

3.1.5 | Hydrological and Hydrodynamic Models

The climate variables simulated by GCMs and RCMs are used as input to hydrological and hydrodynamic models to simulate future discharges and flood inundations. Many regions use the models, which are also used operationally by the respective water authorities for flood forecasting or water management (CIW 2020; Iber 2022; NLWKN 2021; Deltares 2024a, 2024b). In The Netherlands, the models differ slightly between large and small rivers, while in Flanders, different models are used for navigable and non-navigable waterways (Table 1).

3.1.6 | Purpose of Future Flood Projections

The simulated future flood projections resulting from the modeling chains are used differently in the regions. In Baden-Württemberg, Bavaria, and Rhineland-Palatinate, the main aim is to derive design values for technical flood protection measures such as levees and embankments (KLIWA 2022). The assessments are also considered in the FRMPs for the German parts of the Rhine and Danube basins (FGG Rhein 2021; FGG Donau 2021). The main objective of the Germany-wide climate impact assessments by BMVI-ExpN is to comprehensively assess the effects of climate change on navigable rivers and associated infrastructure and include low and flood flows, sea level rise, soil erosion and sediment transport as well as water temperature and ecological state (Nilson et al. 2020). The BMVI-ExpN assessments for flood changes are further included in FRMPs for the German parts of the major river basins Elbe, Weser, and Ems (FGG Elbe 2021; FGG Weser 2021; FGG Ems 2021). Also in The Netherlands, the simulations are used for planning and adaptation of levees, dams, and other water infrastructure (Deltares 2024a, 2024b). However, the way in which design values are derived from the flood projections differs considerably between The Netherlands and the German federal states (Section 3.2).

In Flanders, the simulations are used to derive flood hazard, exposure, and risk maps representing potential future conditions (CIW 2020; Section 3.2). In Lower Saxony and incidentally for small rivers in The Netherlands, the future simulations are only used to inform regional decision-makers or the general public about future flood hazards. They are not (yet) used quantitatively to set design standards or derive flood hazard and risk maps (NLWKN 2021; STOWA 2021).

3.2 | Transfer of Future Flood Projections to Design Values and Flood Hazard and Risk Maps

Based on simulated discharge time series for the future, climate-adjusted design values and flood hazard and risk maps can be derived. Official guidelines for the derivation of

climate-adjusted design floods only exist for the large rivers (Rhine, Meuse) in The Netherlands and two federal states in Germany—Bavaria and Baden-Württemberg. For regional rivers in The Netherlands there is some optional national guidance, but in practice climate change information is not reflected in official design values. The approaches used in these two countries are quite different. They are presented below and summarized in Table 3. In Flanders, on the other hand, the discharge simulations are used to develop FHRMs. Their approach is also presented below.

3.2.1 | Design Values

For the large rivers in The Netherlands, an extreme value analysis of the discharge time series simulated with the climate model chain is conducted (Buitink et al. 2024). Based on this, discharge and water level values for certain return periods corresponding to flood protection standards or design standards are derived and provided as design values. To come to final design values there is a lot of attention for uncertainties (hydrological and hydraulic). In order to determine the design value for each location, uncertainties are mathematically integrated. Importantly, each primary levee along the large rivers is evaluated to assess its compliance with the flood protection standard. This procedure is anchored in legal regulations and is binding. When a primary levee is not approved, it is identified to be upgraded in the national flood protection implementation program (HWBP). When primary levees are prioritized to be upgraded, flood protection designs will be robust and based on national levee design guidelines including future climate change scenarios. The new design standards are applied to only those levees included in the national flood protection implementation program. The national levee design guidelines are evaluated roughly every 7 years when new scenarios with design values become available; in fact, they are not always immediately updated according to the new available information for practical reasons. New protection standards came into force for all primary levees in 2017. According to law, every levee will have to meet the new standards (ranging from 1/300 to 1/100,000 per year failure probabilities) in 2050 the latest.

In the two German federal states Baden-Württemberg and Bavaria, present-day design values are taken as the starting point and then multiplied by a climate change factor (LfU-BW 2005; BLfU 2005). This means that present-day design values are increased by a certain percentage to account for future changes. The climate change factors were derived in 2005, based on future flood projections from the model chain approach combined with extreme value statistics. In Bavaria, a uniform climate change factor of 1.15 is used in the entire federal state and for all return periods between 2 and 100 years (BLfU 2005). For a return period flow of 200 years, the factor is set to 1.075. If desired, the climate change factor can be adjusted regionally (BLfU 2005). In Baden-Württemberg on the other hand, climate change factors differ not only with return period but also by region (LfU-BW 2005). Here, five regions were identified where floods are expected to change in a similar way within each region. The changes are expected to be larger for small return periods than for large return periods. For the 2-year flood, the climate change factors vary between 1.25 and 1.75, and for the 100-year flood between 1.15 and 1.25 (Table 2; LfU-BW 2005). Smaller factors are adopted for flood flows between 100- and 1000-year return periods. For return periods $T \geq 1000$ years, it is assumed that climate change will not increase flood peaks. Contrary to The Netherlands, no legally binding update cycle is implemented for the climate change factors in the two German federal states.

In The Netherlands, climate-adjusted design values for the river branches of Rhine and Meuse are used for designing water infrastructure and levees (Deltares 2018). For example, the discharge factors at gauge Lobith for the worst climate scenario in 2085 range between 1.4 for 1/10 per year to 1.15 for 1/10,000 per year flooding. Until a few years ago, climate-adjusted design values were estimated for return periods up to 1250 years. However, the flood protection standards have been upgraded since 2017 and another perspective was taken: for people living behind a primary flood defense along the Rhine and Meuse the risk of life loss due to flooding may not exceed 1/100,000 per year. Note, the probability of life loss is different from the probability of infrastructure failure. Societal disruption should be counteracted by providing additional protection for areas which will experience a large number of casualties or

TABLE 2 | Climate change factors for Baden-Württemberg and Bavaria.

Return period (T) (years)	Baden-Württemberg					Bavaria
	Southeast	Central North	Central	Central South	Rest	
2	1.25	1.75	1.75	1.50	1.50	1.15
5	1.24	1.65	1.67	1.45	1.45	1.15
10	1.23	1.55	1.60	1.43	1.40	1.15
20	1.21	1.42	1.50	1.40	1.33	1.15
50	1.18	1.25	1.35	1.31	1.23	1.15
100	1.15	1.15	1.25	1.25	1.15	1.15
200	1.12	1.07	1.15	1.18	1.08	1.075
500	1.06	1.00	1.05	1.08	1.03	1.00
1000	1.00	1.00	1.00	1.00	1.00	1.00

Note: Current design standards based on past observations are multiplied with these factors to account for climate change.

TABLE 3 | Derivation of climate-adjusted design floods in three regions.

Country	Netherlands	Germany	Germany
Region	Rhine, Meuse	Baden-Württemberg	Bavaria
Purpose of climate adjusted design values	Design of levees and water infrastructure along large rivers	Flood protection (e.g., levees)	Flood protection (e.g., levees)
Return periods for which climate-adjusted design values are estimated	Design standards for $T = 10a$ to $T = 100,000a$	Climate change factors for $T = 2a$ to $T = 1000a$	Climate change factors for $T = 2a$ to $T = 1000a$
Derivation of design flood values accounting for climate change	Extreme value analysis of streamflow time series simulated by climate model chains; discharge extremes for certain return periods taken as design values	Multiply present-day design values with different climate change factors for 5 regions and different return periods; no change in design values for retention basins and dams ($T > 1000a$) (Table 2)	Multiply present-day design values with different climate change factors for different return periods ($T > 500a$); no change in design values for retention basins and dams (Table 2)
Consideration of uncertainties	Statistical and model uncertainties are accounted for through a probabilistic approach with illustration points and percentiles	Model uncertainties should be accounted for by updating climate change factors in due time	Model uncertainties should be accounted for by updating climate change factors in due time

large economic damage in case of flooding. Protection of vital and vulnerable infrastructure needs to be established to enhance the functioning of an area during and after a flood disaster. This needs to be achieved by 2050 at the latest (Nillesen and Kok 2015). A large national flood protection implementation program (HWBP) is currently running to reinforce around 1500 km of primary flood defenses by 2050 (Tromp et al. 2022).

The simulations of future discharges are linked to many uncertainties along the entire model chain—from uncertainties in the used climate and hydrological models to uncertainties about how emissions will develop in the future and uncertainties in applying extreme value statistics (KNMI 2014; KLIWA 2022). This needs to be accounted for when defining design values. The guidelines of Baden-Württemberg and Bavaria mention that model uncertainties should be accounted for by updating climate change factors in due time (LfU-BW 2005; BLfU 2005). The KLIWA consortium is currently reassessing the procedure by which the climate factors for design values are determined and whether the previous values (Table 2) are confirmed using CMIP5-based projections (Table 1). For the time being, the earlier values are still active.

3.2.2 | Flood Hazard and Risk Maps

In Germany, FHRMs are currently developed for the present climate only. The same applies to The Netherlands, both for flooding from the Rhine and Meuse and for the regional rivers (Slager 2019). Developing such maps is challenging since they depend not only on the flood water levels and their return period but also on the probability of a levee failure. This latter is estimated in The Netherlands through expert judgment (Deltares 2017), while levee failure is not considered in the other regions. Official FHRMs that account for climate change and depict potential future flood-prone areas have only been derived in Flanders so far. These maps are

derived based on climate projections for the time horizons 2036–2065 and 2071–2100 (CIW 2020). FHRMs are derived for future fluvial, pluvial, and coastal flooding, but in this study the focus is on fluvial flood hazard only. After considering the full ensemble of GCMs and RCMs available for Belgium (Table 1), statistical downscaling based on the quantile perturbation method (Willems and Vrac 2011; Willems et al. 2012) is applied. This means that the changes between current and future climate rainfall and potential evapotranspiration are analyzed and applied to perturb historical time series to time series that are statistically representative for the future climate conditions. For rainfall, these perturbations involve seasonally varying changes in the number of wet and dry days and changes in the rainfall intensities as a function of the return period. Further, low, mean, and high rainfall and evapotranspiration scenarios are derived based on the 5th, 50th, and 95th percentiles of the full ensemble of climate model outputs considered (CIW 2020). These scenarios are then combined to drive a hydrological model resulting in the corresponding low, mean, and high runoff scenarios. The high runoff scenario is further split into a summer and winter scenario (Ntegeka et al. 2014). For depicting future fluvial flood hazard and risk in the maps, the high winter flow scenario for the time horizon 2036–2065 is considered (CIW 2020). The maps are available online alongside the present-day flood hazard and risk maps for entire Flanders (Waterinfo 2024).

3.3 | Adaptation Under Uncertainty

The discharge time series simulated with climate model chains can be highly uncertain. Using several ensemble members and different emission scenarios results in a range of possible future developments of floods. In contrast to this, deriving new design floods and adapting flood infrastructure to climate change requires the specification of fixed values—a new levee will be built with one specific height and not a range of heights. At the same

time, infrastructure that has been adapted to climate change should not have to be re-built every few years when new climate simulations are available. To deal with these challenges, some regions recommend developing flexible and no-regret strategies. Flexible strategies acknowledge that the future may develop in a different way than expected today and that future adjustments should then be feasible (Haasnoot et al. 2024). No-regret strategies should not be regretted regardless of the extent of future change (Heltberg et al. 2009). Some other regions, in contrast, argue that the uncertainties are too high and are thus hesitant about publishing official guidelines in this regard yet.

In Flanders, the “precautionary principle” is pursued, therefore applying high-impact scenarios (MIRA 2015). Several emission scenarios as well as scenarios of rainfall and potential evapotranspiration are considered to identify the scenarios with high impact discharges (CIW 2020). The guidelines state the importance to consider especially such scenarios with significant consequences in policymaking and management, and that this should be done in a way which allows for adjustments as climate knowledge increases (CIW 2020; MIRA 2015). In particular, decision-making should avoid creating irreversible conditions that limit future adaptation options (MIRA 2015).

Bavaria pursues a flexible and no-regret strategy, stating that due to the high uncertainties, any adaptations should be harmless in the long run and easily adaptable (BLfU 2005). What climate factors are applied varies depending on the type of infrastructure and how easily they can be adjusted in the future. By leaving more room on one side of the levee or building a stronger foundation than the current height would require, the structures' height can be easily increased later on (BLfU 2005). Therefore, the height might be set according to current design standards, while the foundations account for the climate change factor. In contrast, retrofitting bridges is very costly or even impossible, so here the new climate-adjusted design standards should be fully incorporated (BLfU 2005). Baden-Württemberg focuses on cost efficiency when adapting technical flood protection measures to potential climate change effects. The respective guideline (LfU-BW 2005) states that the expected consequences and additional costs of climate change should be first estimated. The assessment of climate change factors for design values should be based in the scenarios developed in the KLIWA consortium (Table 1; KLIWA 2022). Based on this, flood managers should decide whether it is more cost-efficient to include potential climate change effects in the planning today or retrofit later, similar to the approach in Bavaria (LfU-BW 2005).

The Netherlands also follows a flexible adaptive strategy coordinated by the National Delta Programme (<https://dp2025.deltaprogramma.nl/en>, accessed 1 September 2025) of the central government. The main task of the program is to prepare The Netherlands for climate change and sea level rise. To do this, the program assesses future climate risk and proposes adaptation strategies to reduce those risks for different regions and sectors. The KNMI climate scenarios described above serve as key input to develop adaptation strategies. Since several years, the program adopted the dynamic adaptation pathway concept to deal with uncertainties in future projections (Haasnoot et al. 2024) to develop the adaptive delta management approach (Bloemen et al. 2019). In this context adaptive means being flexible and

future-oriented. Instead of implementing all solutions immediately, the approach is to adjust to new insights, developments in climate change, economic growth, and technological progress. Measures are designed such that they can be adjusted or extended in future. The climate scenarios are used to identify when the climate has changed that much that these adjustments would be needed (Kwadijk et al. 2010). For example, if sea level rise is expected to reach a critical level only decades from now, authorities already investigate which measures will be needed. But instead of immediately building an expensive storm surge barrier, they might first implement smaller or temporary solutions—with a plan to scale up or shift strategies as conditions change (<https://www.gov.uk/guidance/managing-future-flood-risk-and-thames-barrier-thames-estuary-2100>, accessed 1 September 2025).

3.3.1 | Discussion

We encountered quite different viewpoints on actions to be taken in view of the uncertain future. The Flemish MIRA (2015) report states that the “large uncertainties associated with climate change should not be an argument for delaying impact investigations or adaptation actions.” The Netherlands develops specific storylines of climate change and translates them into climate-adjusted design values with prescribed update cycle. On the contrary, Saxony clearly argues that the uncertainties of future flood projections are too high to derive specific design floods based on them. According to the LfULG (2022), the available scenarios show a considerable spread and therefore the respective ministry infers that they offer no reliable basis for estimating future flood probabilities and adapting design values accordingly. They argue that hazard and risk maps can have far-reaching impacts on risk assessments, private properties, municipal planning, the implementation of measures and other aspects. Therefore, they state climate change factors must be handled very responsibly and as legally secure as possible (SMEKUL 2024). To achieve a robust basis for technical and legal enforcement, Saxony suggests specifying scenarios and coordinating methods across Germany (SMEKUL 2024). This should also help with achieving higher acceptance of the adopted measures. They point out that increasing design standards would mean that more land and more financial resources are required to build flood protection measures according to the new standards. This, however, could increase opposition to such measures and could thus impede the implementation of adaptation measures (SMEKUL 2024). A recent study by Swiss Re Institute (2024) suggests, however, that the benefits of investing in adaptation and of updating flood defenses to withstand potential future floods outweigh the high costs of post-flood recovery and rebuilding in the long run.

4 | Synthesis and Conclusions

Our review shows how climate change information is derived and used in fluvial flood risk management in Germany, Belgium, The Netherlands, and Luxembourg. We assessed the current status in The Netherlands, Luxembourg, in 16 federal German states and two Belgian regions, in total 20 regions. The countries where this study is conducted in the frame of the

Joint Cooperation programme for Applied scientific Research on flood and drought risk management in regional river basins (JCAR-ATRACE) have been significantly affected by the 2021 flood disaster. This event can be considered as a manifestation of the flood hazard that might be unfolding in central and north-western Europe more often due to climate change (Tradowsky et al. 2023). Our assessment focused on regional practices and guidelines with focus on flood design standards and FHRMs that account for climate change.

Our findings reveal that the current integration of climate change information into FRM practices and its progress differ significantly between the regions. All regions have FRMPs in place as prescribed by the EU Flood Directive (EU 2007). In Germany, for example, these plans are developed at the level of river basin communities (“Flussgebietsgemeinschaften”) and include all the riparian federal states: FRMP Rhine (FGG Rhein 2021), FRMP Danube (FGG Donau 2021), FRMP Elbe (FGG Elbe 2021), FRMP Weser (FGG Weser 2021), FRMP Ems (FGG Ems 2021), and further FRMPs for smaller basins. In Luxembourg, FRMP encompasses the entire country integrating the plans for the tributaries of the Rhine and Meuse basins.

However, only 4 of the 20 regions have derived design values or FHRMs adjusted for projected future climate (Figure 2). FHRMs depicting future flood hazard have been developed in Flanders in Belgium, while climate-adjusted design standards are available in The Netherlands and the two German federal states of Bavaria and Baden-Württemberg (Figure 2). The remaining 14 German federal states include climate change projections either from KLIWA or from BMVI-ExpN into FRMPs (Table 1, Figure 2) depending on the basin and respective FRMPs. However, these projections are not purposefully used to adopt specific measures or design values. FGG Elbe (2021), FGG Weser (2021), and FGG Ems (2021) using BMVI-ExpN projections state that currently no robust assessment of flood flows relevant for flood design purposes ($T \geq 100a$) is possible among others due to open questions related to (1) suitability and bias correction of climate models with regard to extreme precipitation; (2) differences in extreme value statistics for observed and simulated values; (3) future changes of water resources management (flood retention and reservoir flood

control) as well as consideration of dike failure scenarios. These FRMPs list measures for adaptation to climate change without specifically quantifying their contribution to offsetting it. These measures include restoration of levees, creation of retention areas, improving early warning, helping municipalities with funding and implementation of flood protection, or enhancing outreach and information of the general public. Two German federal states Hesse and Saarland have indicated that they plan to derive future flood projections, or have already started working in this direction. They have recently joined the KLIWA consortium, which helped deriving climate change factors in Bavaria and Baden-Württemberg, with the aim of following suit. Luxembourg recently announced to join the KLIWA consortium (LGDGD 2023), but to date it does not have an established procedure for assessment of future flood changes. The Walloon region in Belgium is updating its procedure for developing FHRMs in the light of climate change. In the past, only scenarios up to a 100-year flood were considered in flood mapping and for the design of flood protection measures. Currently, the flood frequency analysis is updated by including the estimated discharges of 2021 flood in the time series and the scenario of a 1000-year flood is additionally considered in the analyses. Also, for other rivers, including 1000-year inundation areas in future hazard maps is under consideration. Recently, a regional working group has been set up to define how to translate new climate projections for the Walloon region conducted by Brajkovic et al. (2025) into design discharges and FHRM. Further details about the current practices in all studied regions can be found in the Appendix A.

While many of the studied regions do not have climate-adjusted design values or FHRMs yet, some regions are moving toward a risk-based flood protection standard. Flanders does not only estimate flood hazard maps for future scenarios, but also calculates flood risk for such projections. The Netherlands recently started using risk-based protection standards. Beforehand, as in most countries, standards in The Netherlands were defined by the frequency of exceedance of design water levels for levees. Now, the height of the standards is based on societal disruption due to flooding and the individual risk of becoming a victim of flooding (van der Most et al. 2014).

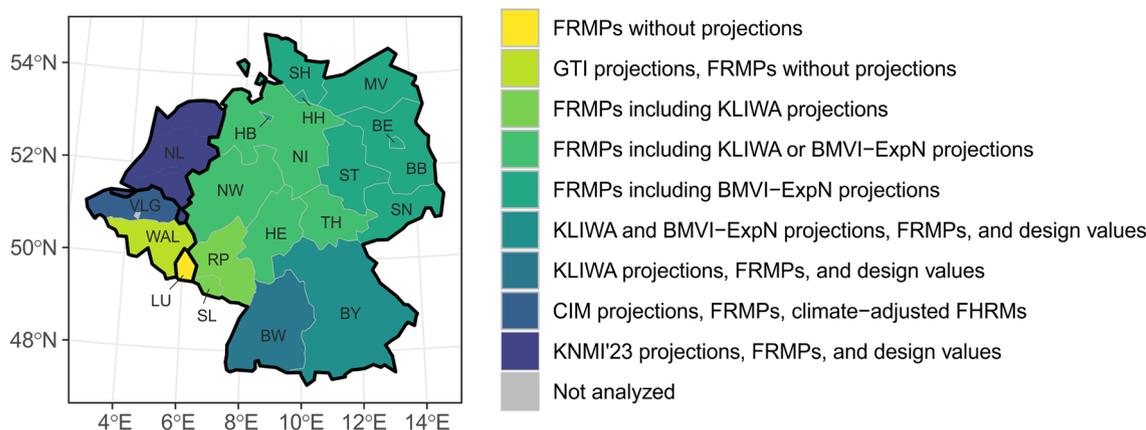


FIGURE 2 | Synthesis of the current practices of integrating climate change into flood risk management in the study area (Germany, Belgium, The Netherlands, Luxembourg). The focus is on whether regions use future flood projections in planning adaptation measures and specifically to derive design standards and FHRMs. The region notations follow the ISO 3166-2 code. Practices in the City of Brussels are not analyzed.

In the regions with official future flood projections, some commonalities as well as differences in the procedures exist. All regions use a model chain consisting of GCMs and downscaling RCM simulations. These GCM-RCM projections are used as input to hydrological models to simulate time series of current and future discharges. In The Netherlands and Flanders, hydrodynamic models are used additionally to estimate water levels and flood extent. The numbers and sets of models used differ between regions: in Flanders and The Netherlands, the entire sets of CMIP5 and CMIP6 GCM simulations are considered, respectively, while the German regions only use subsets of CMIP5 GCMs which passed regional validation and ensemble reduction procedures. Wallonia selected 6 GCMs following EURO-CORDEX community recommendation and downscaled them with a single RCM. In general, the number of considered emission scenarios is lowest in the German regions using KLIWA and KliBiW projections. Bavaria, Baden-Württemberg, Rhineland-Palatinate and Lower Saxony only take the highest CMIP5 emission scenario RCP8.5 into account. In contrast, Flanders, Wallonia, and The Netherlands use a range of emission scenarios and consider a large spread of possible futures.

The high uncertainties of future flood projections present challenges for agencies and governments in upgrading existing flood protection measures or designing new ones. The German federal state of Saxony as well as Luxembourg argue that the uncertainties are so high that they do not allow reliably estimating climate-adjusted design standards. They prefer to wait for an improved knowledge base before adapting design values and FHRMs. Bavaria and Baden-Württemberg, on the other hand, have derived climate change factors to adjust design standards and aim for cost-efficient, flexible and no-regret measures when applying them. Further, they reduce the uncertainty by only considering the high emission scenario. In contrast, Flanders and The Netherlands consider a wide range of emission scenarios and then reduce uncertainty by deriving a limited number of scenario variants for practical applications. The Netherlands uses a storyline approach, where simulations are grouped to represent dry-trending and wet-trending futures. In Flanders, simulations are classified based on the impact into scenarios with low, medium and high runoff. Further, Flanders follows the precautionary principle, taking especially those flood projections into account that would have significant consequences.

At the political level, all regions show high ambitions to address climate change. This is also generally required for FHRMs and FRM plans by the EU Flood Directive (EU 2007), although without exactly specifying the approaches and practices to do so. Hence, various countries and specific regions move at their own pace along their own trajectories. While climate information is available in different forms and degrees of detail, the translation of future projections into FRM practice is still sparse in many regions. The advanced practices of deriving climate-adjusted design values and FHRMs can potentially be taken as examples by these regions to follow suit. The Netherlands is pioneering the use of the most recent CMIP6 climate projections and uses an approach to develop a limited number of storylines suitable for practical applications. The approach is especially useful for communicating complex climate change scenarios to stakeholders and the general public. Also, using reduced sets of model ensembles and emission scenarios, as for instance done in

some German federal states, can be implemented even when resources are scarce. When the selection of models and scenarios is well founded, the flood projections can still provide valuable information and help with climate-proofing flood protection. For example, the information can be used to stress-test certain measures and make them more robust. In summary, our review highlights that climate-proofing flood risk management is in its infancy. Large variations across regions in approaches and degrees of implementation, due to their organic growth over the past years, is evident. Developing climate information for FRM needs a tailored approach since both the geographical and policy context in each region varies significantly. We believe more cross-border learning, to which the presented review will hopefully contribute, will enhance coordination and effectiveness of climate-informed transboundary FRM, while countries and regions steadily move forward at their own pace.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** jfr370173-sup-0001-supplement.docx.

Appendix A

Summaries Per Region

BE—Flanders

In Flanders, official guidelines exist for climate change simulations and for deriving flood hazard and risk maps for future scenarios (see details in the main text). So far, there is no common regional policy on how climate change impact results must be considered in flood management and climate adaptation planning. This is mainly done in an ad-hoc case-by-case way. An example is the Sigmaphan for the Scheldt and other tidal rivers where the design of actions is based on cost–benefit optimization (Willems et al. 2023). In the Weerbaar Waterland advice (Expertenpanel Hoogwaterbeveiliging 2022), a uniform approach for defining strategic and operational goals for integrating climate change in flood risk management (FRM) in Flanders has been recommended. This advice is expected to be implemented in the coming years.

BE—Wallonia

So far, climate change is not quantitatively addressed in design flood values or flood mapping in the Walloon region in Belgium. However, the methodological guidelines for the preparation of flood hazard maps (SPW 2020) state that the "probable impact of climate change on the occurrence of floods" should be taken into account in subsequent versions of flood hazard and risk maps. This should be done by accounting for "all new climate data available" such as longer statistical series, an inventory of flood episodes, and hydraulic modeling of the extreme scenario (SPW, 2020). Recently, Brajkovic et al. (2025) assessed future trends in the frequency and intensity of extreme precipitation in Belgium. A regional working group on floods (GTI) has been set up by the water management authority (SPW) to translate these climate projections into updated design discharges and FHRM.

DE—Baden-Württemberg

In Baden-Württemberg, official simulations for the estimation of climate change effects for flood hazards based on KLIWA projections exist as well as climate change factors for design standards (see details in the main text). In the future, the projections might be updated by using SSPs instead of RCPs as emission scenarios (KLIWA 2022). As part of the Rhine and Danube basin communities, Baden-Württemberg contributes to the FRMP Rhine (FGG Rhein 2021) and FRMP Danube (FGG Donau 2021), which consider KLIWA projections.

DE—Bavaria

In Bavaria, official simulations for the estimation of climate change effects on flood hazards exist based on KLIWA projections (KLIWA 2022) as well as climate change factors for design standards (see details in the main text). It should be added that the guidelines state that in "justified individual cases" it may be appropriate not to apply the climate change factor. As an example, transboundary rivers are mentioned where design flood values "should not be changed unilaterally" (BLFU 2005). In FRMPs for the Elbe (FGG Elbe 2021) and Weser (FGG

Weser 2021), which Bavaria contributes to, climate change projections based on BMVI-ExpN are considered. As part of the Rhine and Danube basin communities, Bavaria contributes to the FRMP Rhine (FGG Rhein 2021) and FRMP Danube (FGG Donau 2021), which consider KLIWA projections.

DE—Berlin

Berlin as part of the Elbe basin community contributes to the FRMP Elbe, in which BMVI-ExpN projections are considered (FGG Elbe 2021). No design values and climate-adjusted flood mapping are adopted.

DE—Brandenburg

So far, climate change is not quantitatively addressed in design flood values or flood mapping in Brandenburg. With regards to designing levees at the large rivers Elbe, Oder and Neiße, Brandenburg is dependent on agreements with the neighboring federal states and countries. In the FRMP for the Elbe basin (FGG Elbe 2021) BMVI-ExpN projections are considered. In the FGG Elbe, the focus in dealing with climate change is currently on the creation of additional retention areas, for example, through relocations of levees or by creating polders (FGG Elbe 2021). In addition, design floods are estimated based on time series where retention effects of dams have been excluded (Hatz et al. 2018). This can be considered as a “buffer” for climate change effects, even though no quantification of such “climate buffer” has been conducted.

DE—Bremen

Bremen as part of the Weser basin community contributes to the FRMP Weser, in which BMVI-ExpN projections are considered (FGG Weser 2021). No design values and climate-adjusted flood mapping are adopted.

DE—Hamburg

Hamburg as part of the Elbe basin community contributes to the FRMP Elbe, in which BMVI-ExpN projections are considered (FGG Elbe 2021). No design values and climate-adjusted flood mapping are adopted.

DE—Hesse

In Hesse, climate change is not quantitatively addressed in design flood values or flood mapping yet. Since 2024, Hesse is part of the KLIWA consortium, and even before has been evaluating climate projections in cooperation with KLIWA (HMUKLV 2024). Hesse is using the same climate models, analysing the same time horizons, and considering the same emission scenarios as done in Baden-Württemberg and Bavaria (see details in the main text). While these analyses are not as far advanced yet for Hesse, the aim is to derive climate change factors for flood discharges of different return periods as is done in the other two federal states (HMUKLV 2017). Work on this is ongoing (HMUKLV 2024). As part of the Rhine and Weser basin communities, Hesse contributes to the respective FRMPs (FGG Rhein 2021; FGG Weser 2021), which consider KLIWA and BMVI-ExpN projections, respectively.

DE—Lower Saxony

While official simulations for the estimation of climate change effects for flood hazards exist for Lower Saxony (KliBiW) (see details in the main text), climate change is not yet accounted for in design standards. So far, only rather vague statements can be found, saying that climate change should be considered in this context without detailing how to do this. For example, in a final report of the project KliBiW, the following is stated (translated by the authors): “The combination of increasing peak flows and flood durations means an increase in flood risk and the associated potential damage in the future. These more severe flood situations should be taken into account

in planning processes in a forward-looking and preventive manner. The development of adaptation strategies should also be promoted” (NLWKN 2021). Regarding adaptation strategies, the ministry of environment states that new technical flood protection measures should be planned farsighted and should be adaptable (MU 2022). As part of the Rhine, Elbe, Weser, and Ems basin communities, Lower Saxony contributes to the respective FRMPs (FGG Rhein 2021; FGG Elbe 2021; FGG Weser 2021; FGG Ems 2021). While the FRMP for the Rhine considers KLIWA projections, the latter three FRMPs mention BMVI-ExpN projections.

DE—Mecklenburg-Vorpommern

So far, climate change is not quantitatively addressed in design flood values or flood mapping in Mecklenburg-Vorpommern. However, currently, a climate office is being established in the respective ministry, which will work on these issues. As part of the Elbe basin community, Mecklenburg-Vorpommern contributes to the FRMP Elbe, in which BMVI-ExpN projections are considered (FGG Elbe 2021).

DE—North Rhine-Westphalia

Up to now, climate change is not quantitatively addressed in design standards or flood mapping in North Rhine-Westphalia. However, this is supposed to change. Following the flood in 2021, a “10-point plan for flood protection in times of climate change” was issued by the respective ministry (MULNV 2022). It includes aspects such as improving flood warning systems or enhancing cooperation between municipalities for cross-municipal flood protection concepts and also addresses new design floods and FHRMs. In this regard, it states that flood hazard and risk maps might be updated in advance of the next cycle required by the European Flood Directive as the 2021 event has changed the discharge statistics on which the FHRMs are based (MULNV 2022). Further, it will be checked whether flood-prone areas beyond the inundation areas of an extreme event (HQextreme) can be included in the maps. For the delineation of official floodplains, the integration of a climate change factor will be assessed (MULNV 2022). As part of the Rhine and Weser basin communities, North Rhine-Westphalia contributes to the respective FRMPs (FGG Rhein 2021; FGG Weser 2021), which consider KLIWA and BMVI-ExpN projections, respectively.

DE—Rhineland-Palatinate

In Rhineland-Palatinate, official simulations for the estimation of climate change effects for flood hazards exist based on KLIWA projections (see details in the main text) (KLIWA 2022), but climate change is not yet accounted for in design values. The simulations are used for informing stakeholders and the general public. In general, that is, independent of climate change, the design of flood protection measures is based on the boundary conditions of the individual case in Rhineland-Palatinate. This is based on the population at risk, the potential for flood damage, and the economic viability (KLIWA 2022). As part of the Rhine basin community, Rhineland-Palatinate contributes to the FRMP Rhine (FGG Rhein 2021), which considers KLIWA projections.

DE—Saarland

So far, climate change is not quantitatively addressed in design standards or flood mapping in the federal state Saarland. Saarland has been a guest in the KLIWA cooperation since 2019 and officially joined the consortium in 2024 (KLIWA 2022). In 2024, a “Future plan flood protection” has been presented by the respective ministry. However, it does not contain any statements about using climate simulations or estimating climate-adjusted design standards or FHRMs (MUKMAV 2024). Instead, the 4-page document touches on aspects such as helping municipalities with funding, building new gauges or improving warning procedures (MUKMAV 2024). As part of the Rhine basin community, Rhineland-Palatinate contributes to the FRMP Rhine (FGG Rhein 2021), which considers KLIWA projections.

DE—Saxony

In Saxony, climate change is not quantitatively addressed in design flood values or flood mapping yet. The reasoning is that the uncertainties in climate simulations are too high, but reliable quantitative assessments would be required to justify measures and increase design values. For details see in the main text. As part of the Elbe basin community, Saxony contributes to the FRMP Elbe, in which BMVI-ExpN projections are considered (FGG Elbe 2021).

DE—Saxony-Anhalt

So far, climate change is not quantitatively addressed in design flood values or flood mapping in Saxony-Anhalt. In 2022, the respective ministry published the report “Stable in climate change – State strategy for flood protection in Saxony-Anhalt” (MWU 2022). The report contains a large list of measures such as the restoration of levees, creating retention areas, improving early warning, helping municipalities with measures for flood protection, and increasing outreach on this topic (MWU 2022). However, there is no mention of increasing design values, despite stating that (translated by the authors) “climate models predict a significant increase in risk potential in the climate-sensitive areas of action in flood risk management by 2050 and beyond” (MWU 2022). As part of the Elbe and Weser basin communities, Saxony-Anhalt contributes to the FRMPs Elbe and Weser, in which BMVI-ExpN projections are considered (FGG Elbe 2021; FGG Weser 2021).

DE—Schleswig-Holstein

So far, climate change is not quantitatively addressed in design flood values or flood mapping in Schleswig-Holstein. Studies of the long-term behavior of meteorological and hydrological time series have shown that trends in rainfall and runoff can vary greatly between different catchments in this federal state (MELUND 2017). Therefore, the respective ministry states that more detailed regional studies at the river basin level are necessary before climate-adjusted design standards can be derived (MELUND 2017). As part of the Elbe basin community, Schleswig-Holstein contributes to the FRMP Elbe, in which BMVI-ExpN projections are considered (FGG Elbe 2021).

DE—Thuringia

Up to now, climate change is not quantitatively addressed in design flood values or flood mapping in Thuringia. A report by the respective ministry states that data analyses show no clear trend in floods in the federal state, but that climate projections still suggest that action is needed (TMUEN 2019, 2023). While no climate-adjusted design standards have been derived, the report still classifies measures which are taken “primarily due to increasing flood risks” as being closely linked to climate change. In contrast, the maintenance or renovation of existing flood protection facilities cannot be considered as climate adaptation measures (TMUEN 2019). With regard to flood risk management plans, the report states that if the annual frequency of flood events changes due to climate change, this should be taken into account in an update of the plans (TMUEN 2019). However, “as a rule, there will be no increase in safety margins due to climate change” in Thuringia (translated by the authors; TMUEN 2019). As part of the Rhine, Elbe, and Weser basin communities, Thuringia contributes to the FRMP Rhine, in which KLIWA projections are considered (FGG Rhein 2021), and to the FRMPs Elbe and Weser, in which BMVI-ExpN projections are considered (FGG Elbe 2021; FGG Weser 2021).

Luxembourg

So far, climate change is not quantitatively addressed in design flood values or flood mapping in Luxembourg. The respective administration acknowledges the importance of climate change and cites relevant projects, such as for example FLOW MS, where climate change simulations are used (IKSMS 2013). However, these projects focus on simulating future water balance, and no estimation of extreme discharges

is conducted. Currently, Luxembourg considers engagement in the German KLIWA consortium to advance its assessments of climate change on hydrologic extremes (LGDGDL 2023).

The Netherlands

In The Netherlands, official guidelines exist for climate simulations for small and large rivers and for climate-adjusted design standards for large rivers (see details in the main text). In addition to what has been described in the main text, The Netherlands also uses a weather generator for the construction of 50,000-year time-series, based on which discharge extremes for high return periods for the rivers Rhine and Meuse are estimated (Beersma and Buishand 2003; Hegnauer et al. 2014).