

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.

38 1. Introduction

39 Floods are among the costliest natural hazards worldwide with estimated annual average loss of 104 billion
40 US dollar (UNISDR, 2015). The number of people affected by flood disasters has risen in most parts of the
41 world in the past about 40 years (Merz et al., 2021). In the European Union (EU), floods account the largest
42 share of about 44% of the total economic damage associated with weather- and climate-related extremes in the
43 period 1980-2023 (EEA, 2024). In this period, several flood events caused among the highest losses: 1993 and
44 1995 in the Rhine basin, 1997 in the Oder basin, 2000 in England and Wales, and 2002 in the Elbe basin
45 (Paprotny et al., 2024). the most impactful flood event in the recent past struck north-western Europe in the
46 summer of 2021, where record rainfall in parts of Germany, Belgium, and The Netherlands caused almost over
47 230 casualties and €40-50 billion in financial losses (Szönyi et al., 2022). World Weather Attribution (WWA)
48 estimated the return period of this rainfall event to be around 400 years and found that climate change has
49 increased the likelihood of such a rainfall event to occur today by a factor of 1.2–9 compared to pre-industrial
50 climate (Tradowsky et al., 2023). Another key feature of the 2021 flood event was its transboundary aspect
51 where a persistent low-pressure system and rainfall impacted multiple countries and catchments in the same
52 event (Mohr et al, 2023, Szönyi et al., 2022). This aspect highlights the need for transboundary cooperation
53 and to share expertise in addressing climate change in flood risk management practices (Heinrich & Penning-
54 Rowsell, 2020).

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

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71 Comparable to integrated water management (Loucks and van Beek, 2017), FRM can be considered by three
72 dimensions, the natural, the infrastructural and the institutional system. With regards to the natural system, we
73 are interested in the change in natural boundary conditions that determine the need and degree of adaption.
74 The infrastructural system as part of FRM includes the entire portfolio of structural measures for flood
75 protection and mitigation, e.g., 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 & Botzen, 2019) are part of the institutional system. In this work, we particularly focus on the natural dimension, i.e., assessment of future flood changes, and partly on infrastructural and institutional measures, i.e., 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). FHRM 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 the 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 the national legislation and in the 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 the approaches to account for effects of climate change in specific flood risk management measures such as e.g., 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 a 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, e.g., the federal states of Bavaria and Baden-Württemberg have implemented flood hazard maps even prior to the issuing 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

114 al., 2020; Wetzel et al., 2022) to 'storyline methods' that describe a coherent future climate narrative (Shepherd,
115 2019; Caviedes-Voullième & Shepherd, 2023). Further, more technical methods exist to assess the effect of
116 climate change on flood hazards. Non-stationary flood frequency analysis is used to fit a statistical model to
117 observed flood peaks, where distribution parameters depend either on time or climate covariates (Delgado et
118 al., 2014, Salas et al., 2018, Schlef et al., 2018). In the first case, past trends in flood peaks can be extrapolated
119 into the future. In the second case, projections of these climate covariates, such as sea surface temperature, can
120 be derived from GCMs for future climate emission scenarios. Both approaches allow for estimating design
121 floods for future periods, but they rely on strong assumptions. Consequently, the most widespread approach is
122 a modelling chain that combines hydrological-hydrodynamic models with climate scenarios (e.g., Alfieri et al.,
123 2017). This approach starts by selecting a series of representative concentration pathways (RCPs) / shared
124 socio-economic pathways (SSPs) describing different socio-economic and greenhouse gas emission scenarios.
125 Further, one or more global climate model runs associated with these RCPs/SSPs provided by the Coupled
126 Model Intercomparison Project (CMIP) (Eyring et al., 2016) are selected to obtain ensembles of future
127 meteorological boundary conditions (e.g., Hirabayashi et al., 2021). As these global climate projections are
128 relatively coarse, they need to be downscaled to finer grid resolution – for example, by dynamic downscaling
129 through regional climate models and bias correction methods (Tapiador et al., 2020) or by statistical
130 downscaling (Maraun & Widmann, 2018) including, for example, stochastic weather generators (Nguyen et
131 al., 2024). Next, these time series of downscaled future climate scenarios are used as input to combined
132 hydrological-hydrodynamic models to simulate river discharges, water levels, and inundation (e.g., Hegnauer
133 et al., 2014; Bates et al., 2021). Finally, extreme value statistics can be applied to the discharge time series to
134 estimate flood quantiles and associated return periods (Tabari, 2021) for each of the climate projections.

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136 While the modelling chain approach provides a bandwidth of possible future flood hazard values, which can
137 be used to evaluate the performance of different FRM measures under future climate conditions (Hochrainer-
138 Stigler et al., 2018), their uncertainties are often large (Lawrence, 2020; Lane et al., 2022). In addition, the
139 number of models, scenarios, and approaches is often larger than can be practically considered in management
140 practice. Moreover, new climate projections or improved statistical methods and simulation models may
141 change future design values. These issues pose a challenge for transboundary FRM when updating existing or
142 designing new FRM measures. Given this uncertainty, flexibility in flood adaptation is recommended
143 (Haasnoot et al., 2024). However, flexibility is sometimes difficult to achieve. For example, the maintenance
144 and upgrading of flood defences is expensive and time-consuming, and once investments have been made,
145 new upgrades of flood protection usually take a long time (Kind, 2012).

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

152 Depending on the country or region, the factor is named differently. Here, we use the term 'climate change
153 factor' for both rainfall or flood peak adjustment and mean a multiplicative factor indicating the difference
154 between future and historical periods. Many countries use these factors for IDF (intensity-duration-frequency)
155 rainfall curves which are then used as input to hydrological models to estimate possible future flood peaks
156 under climate change. Typically, these climate change factors are obtained from downscaled climate models
157 projections in the case of precipitation or from modelling chains consisting of climate and hydrological models
158 in the case of flood peaks. These factors may be spatially uniform across countries, like in Denmark and
159 Australia, or they may vary between regions or river basins, like in England (Wasko et al., 2021). The treatment
160 of uncertainty and whether climate change factors vary with return periods also differ widely. While some
161 guidelines use different percentiles to represent uncertainty in the climate change factors, others provide a
162 single value. Research shows that more extreme (Gründemann et al., 2022) and shorter-duration rainfall events
163 (Fowler et al., 2020) tend to intensify more in a changing climate. Consequently, some countries apply higher
164 climate change factors for more extreme and shorter events (Wasko et al., 2021). In summary, many countries
165 and regions lack policies to account for climate change in flood design, and where such policies exist, they
166 vary substantially.

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

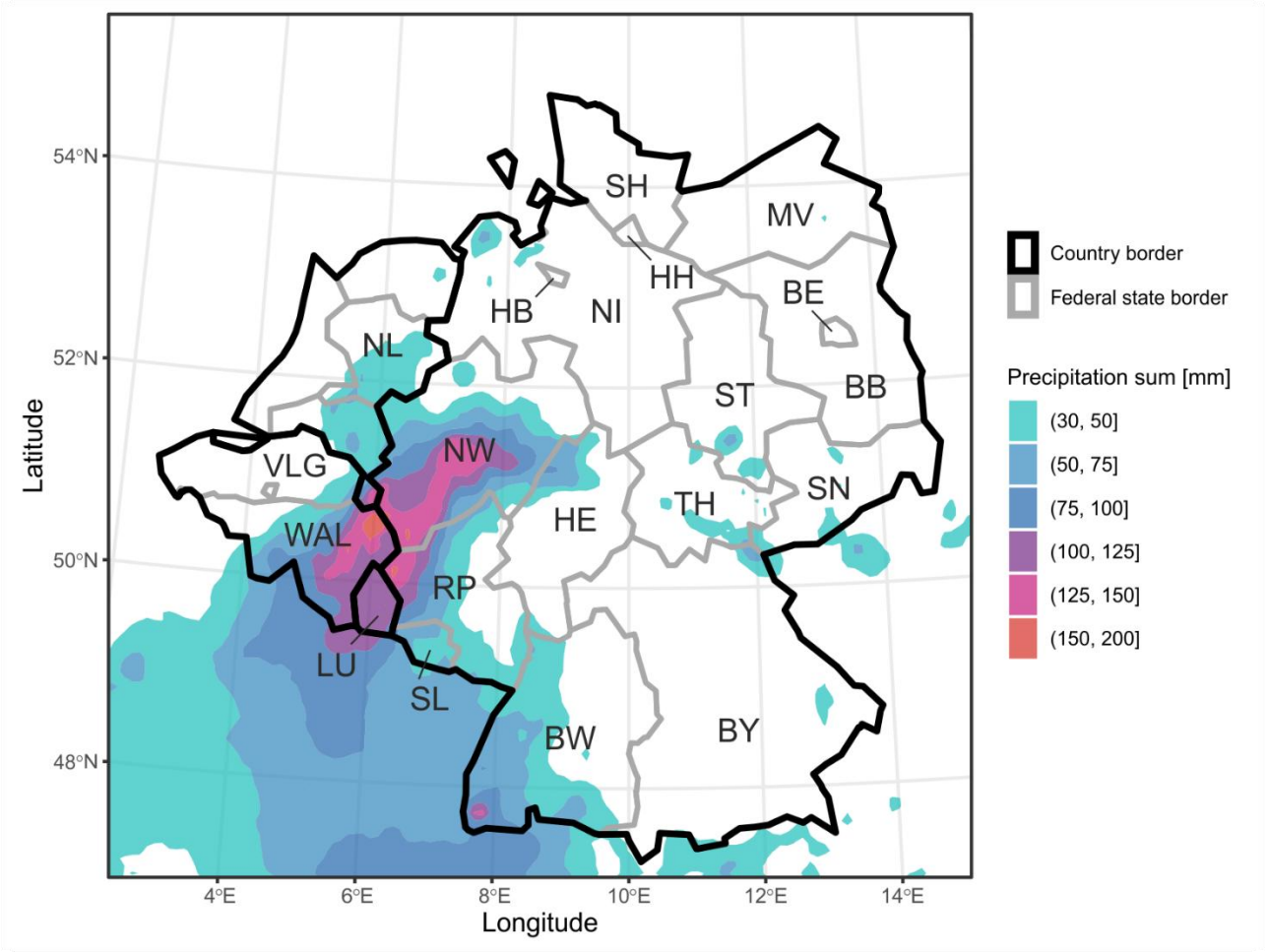
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176 **2. Case study region and approach**

177 **2.1 Case study region**

178 The flood event of summer 2021 severely hit parts of Belgium, Germany, Luxembourg, and The Netherlands
179 that share the Meuse and Rhine River basins (Figure 1). The flood disaster was caused by an atmospheric low-
180 pressure system with a total precipitation of up to 300 mm in the Ardennes-Eifel region over 48 hours in July
181 2021 (Lehmkuhl et al., 2022). Return periods for daily precipitation exceeded 500 years in some areas (Mohr
182 et al., 2023). The total estimated damage in Germany and the BeNeLux countries was €40-50 billion and over
183 230 people lost their lives (Szönyi et al., 2022; Mohr et al., 2023; Endendijk et al., 2023; Kok et al., 2023,).
184 The impacts were the largest along the smaller tributaries of the Rhine and Meuse basins: in Germany,
185 tributaries included the Ahr, Erft, Inde and Rur, with the most severe damage in the Ahr valley. Here, flood
186 inundations with water depths of several meters destructed many buildings and caused 184 fatalities
187 (Lehmkuhl et al., 2022; DKKV, 2022). In Belgium, in particular the Vesdre valley was hit and in total 39 people
188 lost their lives (Journee et al., 2023). For The Netherlands, no fatalities were reported, but damage amounted

189 to more than half a billion euro in the Geul, Rur, and Meuse River basins (ENW, 2021). Also, other countries
 190 sharing Meuse and Rhine River basins such as France, Switzerland, and Austria were affected by 2021 event,
 191 but the impacts were comparably smaller (https://en.wikipedia.org/wiki/2021_European_floods, accessed 1
 192 September 2025). We therefore focus our analysis driven by the Joint Cooperation programme for Applied
 193 scientific Research on flood and drought risk management in regional river basins (JCAR-ATRACE) on the
 194 involved countries: The Netherlands, Belgium, Luxembourg, and Germany. The study area includes in total
 195 20 regions for which the reviews are carried out: two regions in Belgium, 16 German federal states,
 196 Luxembourg and The Netherlands (Figure 1).



197
 198 **Figure 1.** Study area comprised of Belgium, Germany, Luxembourg, and The Netherlands. The four countries,
 199 regions, and federal states follow the ISO 3166-2 code: VLG – Flanders, WAL – Wallonia, SH – Schleswig-
 200 Holstein, HH – Hamburg, HB – Bremen, MV – Mecklenburg-Vorpommern, NI – Lower Saxony, NW – North
 201 Rhine-Westphalia, ST – Saxony-Anhalt, BE – Berlin, BB – Brandenburg, SN – Saxony, TH – Thuringia, HE
 202 – Hesse, RP – Rhineland-Palatinate, SL – Saarland, BW – Baden-Württemberg, BY – Bavaria, LU –
 203 Luxembourg, NL – The Netherlands. July 2021 flood event: 72-hour total precipitation above 30 mm between
 204 July 12th and 14th July 2021 based on the 0.1°x0.1° E-OBS data (Cornés et al., 2018).

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 206 Floods are a natural and recurring phenomenon in the Rhine and Meuse rivers, especially during winter and
 207 early spring (Chbab, 1995). In the smaller tributaries such as Ahr and Vesdre, floods in the summer half-year
 208 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 m³/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 m³/s has 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 sixteen 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 synthesised 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.

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 seven 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 also Hesse and Saarland are 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 its way to basin-wide syntheses of climate change impacts within international efforts such as the International Commission for the Protection of the Rhine (Görgen 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 cases, model chains as described in the Introduction were used, i.e., 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 summarised in Table 1 and compared below.

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).

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Global and Regional Climate Models

Regarding the global climate models (GCMs) and regional climate models (RCMs), there is some overlap across the regions, i.e., 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 KNMI'23 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, i.e., 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 Figure 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

358 even for low-warming scenarios. The downscaled meteorological data is intended to drive hydrological and
359 hydrodynamic models in the following step to estimate future design values and update FHRMs.

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361 In Germany, the four federal states in the KLIWA (Baden-Württemberg, Bavaria, Rhineland-Palatinate) and
362 KliBiW (Lower Saxony) consortia all use the same GCMs and almost the same RCMs with only one difference
363 (Table 1). BMVI-ExpN uses a larger ensemble of GCM-RCM combinations in part overlapping with those
364 mentioned above (Nilson et al., 2020; Hänsel et al., 2020). The model selection for all three assessments is
365 based on CMIP5, EURO-CORDEX, and ReKLiEs-De (Hübener et al., 2017), and for Lower Saxony it also
366 follows the recommendation of the “Bund-Länder Fachgespräch (BL-FG)” (BL-FG, 2024). In the ReKLiEs-
367 De project, the EURO-CORDEX simulations were systematically evaluated for Germany and supplemented
368 by selected additional simulations. The BL-FG, established in 2005, is an informal exchange between federal
369 states and national institutions on the interpretation of regional climate models. In addition, KLIWA and
370 KliBiW use the method “Klimaaudit” (BLfU, 2020; KLIWA, 2022) to check the plausibility of the selected
371 models for the respective regions. Klimaaudit uses quantitative and visual criteria to support the decision of
372 selecting or rejecting certain climate projections. In the four German federal states, the ensemble members
373 differ in the GCMs and RCMs used. Nine ensemble members are considered in Baden-Württemberg, Bavaria
374 and Rhineland-Palatinate (Iber, 2022), and eight ensemble members in Lower Saxony (NLWKN, 2021). The
375 reasoning for setting the number of ensemble members is similar in all four states: They aim to cover a wide
376 range of futures and to retain the spread of projections while having a manageable number of ensemble
377 members (NLWKN, 2021; Iber, 2022). This is achieved through a statistical ensemble reduction technique
378 which is based on monthly mean changes between a reference and a future time period for a range of key
379 climate variables (Dalelane et al., 2018). The reduced ensembles reproduce more than 90% of the spread of
380 the full ensembles (Dalelane et al., 2018; NLWKN, 2021). The same ensemble reduction approach according
381 to Dalelane et al. (2018) is taken by BMVI-ExpN for the whole of Germany, which resulted in larger ensembles
382 with 10 to 16 members depending on the emission scenario (Hänsel et al., 2020, Table 1).

383

384 *Simulated variables and future time periods*

385 The climate impact model chains can simulate different variables for various time horizons. In Flanders,
386 continuous time series of discharge are simulated until 2100 and evaluated for the time horizons 2036 – 2065
387 and 2071 – 2100 (MIRA, 2015; CIW, 2020). In Wallonia, no simulations of future discharge are yet available.
388 Transient regional climate simulations for the period from 2015 to 2100 are now available (Brajkovic et al.,
389 2015). In Lower Saxony, continuous time series are simulated for 2021 – 2050 and 2071 – 2100 (NLWKN,
390 2021). In Baden-Württemberg, Bavaria and Rhineland-Palatinate, simulations are conducted additionally for
391 a medium time horizon, namely 2041 – 2070 (Iber, 2022). BMVI-ExpN adopts two slightly different periods
392 2031 – 2060 and 2071 – 2100. In The Netherlands, simulations are carried out for three time horizons (2036 –
393 2065, 2086 – 2115, 2136 – 2165) in the large rivers (Rhine and Meuse; Buitink et al., 2023). In Flanders and
394 The Netherlands, additional flow and risk-related properties are simulated. These are, for example,
395 representative flood waves in large rivers in The Netherlands, the extent, depth, and duration of flood

396 inundation along small Dutch rivers and in Flanders. In Flanders, also economic, ecological, and social risk
397 associated with flooding are estimated (Deltares, 2024a; Beullens et al., 2021).

398

399 *Statistical downscaling and bias correction*

400 All the reviewed procedures except the one in Flanders apply bias correction to the climate model output with
401 subsequent specific regionalization of climate data for hydrological modelling (Table 1). Bias correction
402 procedures used are variants of quantile mapping. Whereas The Netherlands, Wallonia and KLiBiW use the
403 univariate methods to correct the model biases, KLIWA and BMVI-ExpN apply multivariate bias correction
404 according to Cannon (2018). BMVI-ExpN uses this method for dependent temperature and humidity variables,
405 whereas other variables, such as precipitation and wind are corrected with univariate approaches. Flanders is
406 the only region which uses a perfect prognosis approach instead of bias-corrected model output (MIRA, 2015),
407 i.e., a simulated climate change signal derived from the difference between control and projected simulations
408 is applied to observed data with additional perturbation. Perturbation is applied to wet-day frequency as well
409 as to intensity quantiles of wet-day precipitation. Additionally, perturbation of observed temperature and
410 evapotranspiration is carried out considering correlation with precipitation (MIRA, 2015).

411

412 *Hydrological and hydrodynamic models*

413 The climate variables simulated by GCMs and RCMs are used as input to hydrological and hydrodynamic
414 models to simulate future discharges and flood inundations. Many regions use the models, which are also used
415 operationally by the respective water authorities for flood forecasting or water management (CIW, 2020; Iber,
416 2022; NLWKN, 2021; Deltares, 2024a,b). In The Netherlands, the models differ slightly between large and
417 small rivers, while in Flanders different models are used for navigable and non-navigable waterways (Table
418 1).

419

420 *Purpose of future flood projections*

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

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

439 **Table 1.** Specifications of the simulations used for estimating climate change effects for flood hazards. The regions included in this table have official simulations
 440 adopted. Explanations for abbreviations are listed below the table.

Country	The Netherlands	Belgium	Belgium	Germany	Germany	Germany
<i>Region, Rivers</i>	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 ^{10,11}
<i>Emission scenarios</i>	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
<i>Global Climate Models (GCMs)</i>	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
<i>Regional Climate Models (RCMs)¹³</i>	RACMO2	EURO-CORDEX: RCAO, 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
<i>Reasoning for the selection of GCMs and RCMs</i>	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 ¹⁵ ; MAR is in- house validated RCM ^{16,17,18}	Evaluated by ReKLiEs- De; plausibility check for the region (“Klimaaudit”)	Evaluated by ReKLiEs-De and BL- FG, plausibility check for the region (“Klimaaudit”)	Evaluated by ReKLiEs-DE and ensemble reduction according to Dalelane et al. (2018)
<i>Additional scenarios</i>	Wet and dry scenario variants	Low/ mean/high rainfall and ET; low/ medium/high runoff				

<i>Number of ensemble members</i>	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
<i>Reasoning for ensemble number</i>	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
<i>Time horizon(s) projections</i>	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
<i>Statistical downscaling / Bias correction</i>	Quantile delta mapping (QDM) ¹⁴	Perfect prognosis, perturbation ²²	Equidistant quantile matching (EDCDFm) ¹⁹	Quantile delta mapping (QDM) ¹⁴	Multivariate quantile mapping ²⁰	Multivariate quantile mapping ²⁰ , Quantile delta mapping ¹⁴ , Quantile delta change mapping ²¹
<i>Hydrological (h) and hydrodynamic (hd) models</i>	Rhine and Meuse: wflow_sbm ¹ (h), SOBEK ² (hd) Regional rivers: Various (h); SOBEK (hd)	Non-navigable waterways: Probability-Distributed-Moisture (PDM) model ³ (h), Infoworks-RS ⁴ (hd) Navigable waterways: Nedbør-Afstrømnings-Model ⁵ (NAM; h), Mike11 ⁵ (hd)		LARSIM ⁶ (in BW and RP; h), WaSiM ⁷ (in BY; h)	PANTA RHEI ⁸ (h)	LARSIM-ME ¹²

<i>Reasoning for selecting the hydrological / hydrodynamic model</i>	Models are accessible and maintenance provided	Operationally used		Operationally used	Operationally used	
<i>Flood return periods</i>	T = 10a to (T = 50,000a) ⁹	Continuous simulations		Continuous simulations	Continuous simulations	Mean Annual Flood (MAF), T = 10a, 100a, 1000a (not all T are reported for all basins ¹⁰)
<i>Other simulated flow-related aspects</i>	Representative flood wave	Water level, flood inundation (extent, depth, duration)				
<i>Other simulated risks</i>		Economic, ecological and social risk				
<i>Application area</i>	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	Informing stakeholders, municipalities and the general public	FRMPs for the German parts of the Elbe, Weser, and Ems basins

CMIP – Coupled Model Intercomparison Project; EURO-CORDEX: European Coordinated Downscaling Experiment; ReKLiEs-De: Regional climate projection ensemble for Germany; BL-FG: Bund-Länder Fachgespräch (federal-state expert discussion); SSP: Shared Socio-economic Pathway; RCP: Representative Concentration Pathway; ET: evapotranspiration; KNMI: Royal Dutch Meteorological Service; T: return period. ¹ van Verseveld et al. (2024); ² Deltares (2022); ³ Moore (2007); ⁴ Infoworks-RS; ⁵ DHI (2011); ⁶ Bremicker (2000); ⁷ Schulla (2024); ⁸ NLWKN (2021); ⁹ Assessment for return periods higher than 100a is still in the research phase and not yet adopted in policies; ¹⁰ Nilson et al. (2020); ¹¹ Hänsel et al. (2020); ¹² Wolf-Schumann et al. (2013); ¹³ GCM model realization is attached to the model's name (e.g., 'r1') where known; ¹⁴ Cannon et al. (2015); ¹⁵ Sobolowski et al. (2023); ¹⁶ Doutreloup et al. (2019); ¹⁷ Doutreloup et al. (2022a); ¹⁸ Doutreloup et al. (2022b); ¹⁹ Pierce et al (2015); ²⁰ Cannon (2018); ²¹ Olsson et al. (2009); ²² MIRA(2015).

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 summarised in Table 3. In Flanders on the other hand, the discharge simulations are used to develop FHRMs. Their approach is also presented below.

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 come to determine 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 programme (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 into the national flood protection implementation programme. 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

484 periods. For the 2-year flood, the climate change factors vary between 1.25 and 1.75, and for the 100-year
 485 flood between 1.15 and 1.25 (Table 2; LfU-BW, 2005). Smaller factors are adopted for flood flows between
 486 100-year and 1000-year return periods. For return periods $T \geq 1000$ years, it is assumed that climate change
 487 will not increase flood peaks. Contrary to The Netherlands, no legally binding update cycle is implemented
 488 for the climate change factors in the two German federal states.

489

490 **Table 2.** Climate change factors for Baden-Württemberg and Bavaria. Current design standards based on past
 491 observations are multiplied with these factors to account for climate change.

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

492

493

494 In The Netherlands, climate-adjusted design values for the river branches of Rhine and Meuse are used for
 495 designing water infrastructure and levees (Deltares, 2018). For example, the discharge factors at gauge Lobith
 496 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
 497 flooding. Until a few years ago, climate-adjusted design values were estimated for return periods up to 1250
 498 years. However, the flood protection standards have been upgraded since 2017 and another perspective was
 499 taken: for people living behind a primary flood defence along the Rhine and Meuse the risk of life loss due to
 500 flooding may not exceed 1/100,000 per year. Note, the probability of life loss is different from the probability
 501 of infrastructure failure. Societal disruption should be counteracted by providing additional protection for areas
 502 which will experience a large number of casualties or large economic damage in case of flooding. Protection
 503 of vital and vulnerable infrastructure needs to be established to enhance the functioning of an area during and
 504 after a flood disaster. This needs to be achieved by 2050 at the latest (Nillisen & Kok, 2015). A large national
 505 flood protection implementation program (HWBP) is currently running to reinforce around 1500 km of
 506 primary flood defences by 2050 (Tromp et al., 2022).

507

508 The simulations of future discharges are linked to many uncertainties along the entire model chain – from
 509 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.

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

Country	Netherlands	Germany	Germany
Region	Rhine, Meuse	Baden-Württemberg	Bavaria
<i>Purpose of climate adjusted design values</i>	Design of levees and water infrastructure along large rivers	Flood protection (e.g., levees)	Flood protection (e.g., levees)
<i>Return periods for which climate-adjusted design values are estimated</i>	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
<i>Derivation of design flood values accounting for climate change</i>	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)
<i>Consideration of uncertainties</i>	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

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 judgement (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 & 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

532 representative for the future climate conditions. For rainfall, these perturbations involve seasonally varying
533 changes in the number of wet and dry days and changes in the rainfall intensities as a function of the return
534 period. Further, low, mean and high rainfall and evapotranspiration scenarios are derived based on the 5th,
535 50th and 95th percentiles of the full ensemble of climate model outputs considered (CIW, 2020). These
536 scenarios are then combined to drive a hydrological model resulting in the corresponding low, mean and high
537 runoff scenarios. The high runoff scenario is further split into a summer and winter scenario (Ntegeka et al.,
538 2014). For depicting future fluvial flood hazard and risk in the maps, the high winter flow scenario for the time
539 horizon 2036 – 2065 is considered (CIW, 2020). The maps are available online alongside the present-day flood
540 hazard and risk maps for entire Flanders (Waterinfo, 2024).

541

542 **3.3 Adaptation under uncertainty**

543 The discharge time series simulated with climate model chains can be highly uncertain. Using several
544 ensemble members and different emission scenarios results in a range of possible future developments of
545 floods. In contrast to this, deriving new design floods and adapting flood infrastructure to climate change
546 requires the specification of fixed values – a new levee will be built with one specific height and not a range
547 of heights. At the same time, infrastructure that has been adapted to climate change should not have to be re-
548 built every few years when new climate simulations are available. To deal with these challenges, some
549 regions recommend developing flexible and no-regret strategies. Flexible strategies acknowledge that the
550 future may develop in a different way than expected today and that future adjustments should then be
551 feasible (Haasnoot et al., 2024). No-regret strategies should not be regretted regardless of the extent of future
552 change (Heltberg et al., 2009). Some other regions, in contrast, argue that the uncertainties are too high and
553 are thus hesitant about publishing official guidelines in this regard yet.

554

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

562 Bavaria pursues a flexible and no-regret strategy, stating that due to the high uncertainties, any adaptations
563 should be harmless in the long run and easily adaptable (BLfU, 2005). What climate factors are applied varies
564 depending on the type of infrastructure and how easily they can be adjusted in the future. By leaving more
565 room on one side of the levee or building a stronger foundation than the current height would require, the
566 structures’ height can be easily increased later on (BLfU, 2005). Therefore, the height might be set according
567 to current design standards, while the foundations account for the climate change factor. In contrast, retrofitting
568 bridges is very costly or even impossible, so here the new climate-adjusted design standards should be fully

569 incorporated (BLfU, 2005). Baden-Württemberg focuses on cost efficiency when adapting technical flood
570 protection measures to potential climate change effects. The respective guideline (LfU-BW, 2005) states that
571 the expected consequences and additional costs of climate change should be first estimated. The assessment
572 of climate change factors for design values should be based in the scenarios developed in the KLIWA
573 consortium (Table 1; KLIWA, 2022). Based on this, flood managers should decide whether it is more cost-
574 efficient to include potential climate change effects in the planning today or retrofit later, similar to the
575 approach in Bavaria (LfU-BW, 2005).

576 The Netherlands also follows a flexible adaptive strategy coordinated by the National Delta Programme
577 (<https://dp2025.deltaprogramma.nl/en>, accessed 1 September 2025) of the central government. The main task
578 of the programme is to prepare The Netherlands for climate change and sea level rise. To do this, the
579 programme assesses future climate risk and proposes adaptation strategies to reduce those risks for different
580 regions and sectors. The KNMI climate scenarios described above serve as key input to develop adaptation
581 strategies. Since several years, the program adopted the dynamic adaptation pathway concept to deal with
582 uncertainties in future projections (Haasnoot et al., 2024) to develop the adaptive delta management approach
583 (Bloemen et al., 2019). In this context adaptive means being flexible and future-oriented. Instead of
584 implementing all solutions immediately, the approach is to adjust to new insights, developments in climate
585 change, economic growth, and technological progress. Measures are designed such that they can be adjusted
586 or extended in future. The climate scenarios are used to identify when the climate has changed that much that
587 these adjustments would be needed (Kwadijk et al., 2010). For example, if sea level rise is expected to reach
588 a critical level only decades from now, authorities already investigate which measures will be needed. But
589 instead of immediately building an expensive storm surge barrier, they might first implement smaller or
590 temporary solutions — with a plan to scale up or shift strategies as conditions change
591 (<https://www.gov.uk/guidance/managing-future-flood-risk-and-thames-barrier-thames-estuary-2100>,
592 accessed 1 September 2025).

593 *Discussion*

594 We encountered quite different viewpoints on actions to be taken in view of the uncertain future. The Flemish
595 MIRA (2015) report states that the „large uncertainties associated with climate change should not be an
596 argument for delaying impact investigations or adaptation actions”. The Netherlands develops specific
597 storylines of climate change and translates them into climate-adjusted design values with prescribed update
598 cycle. On the contrary, Saxony, clearly argues that the uncertainties of future flood projections are too high to
599 derive specific design floods based on them. According to the LfULG (2022), the available scenarios show a
600 considerable spread and therefore the respective ministry infers that they offer no reliable basis for estimating
601 future flood probabilities and adapting design values accordingly. They argue that hazard and risk maps can
602 have far-reaching impacts on risk assessments, private properties, municipal planning, the implementation of
603 measures and other aspects. Therefore, they state climate change factors must be handled very responsibly and
604 as legally secure as possible (SMEKUL, 2024). To achieve a robust basis for technical and legal enforcement,
605 Saxony suggests to specify scenarios and coordinate 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 of 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 defences to withstand potential future floods outweigh the high costs of post-flood recovery and rebuilding on the long run.

4. Synthesis and conclusions

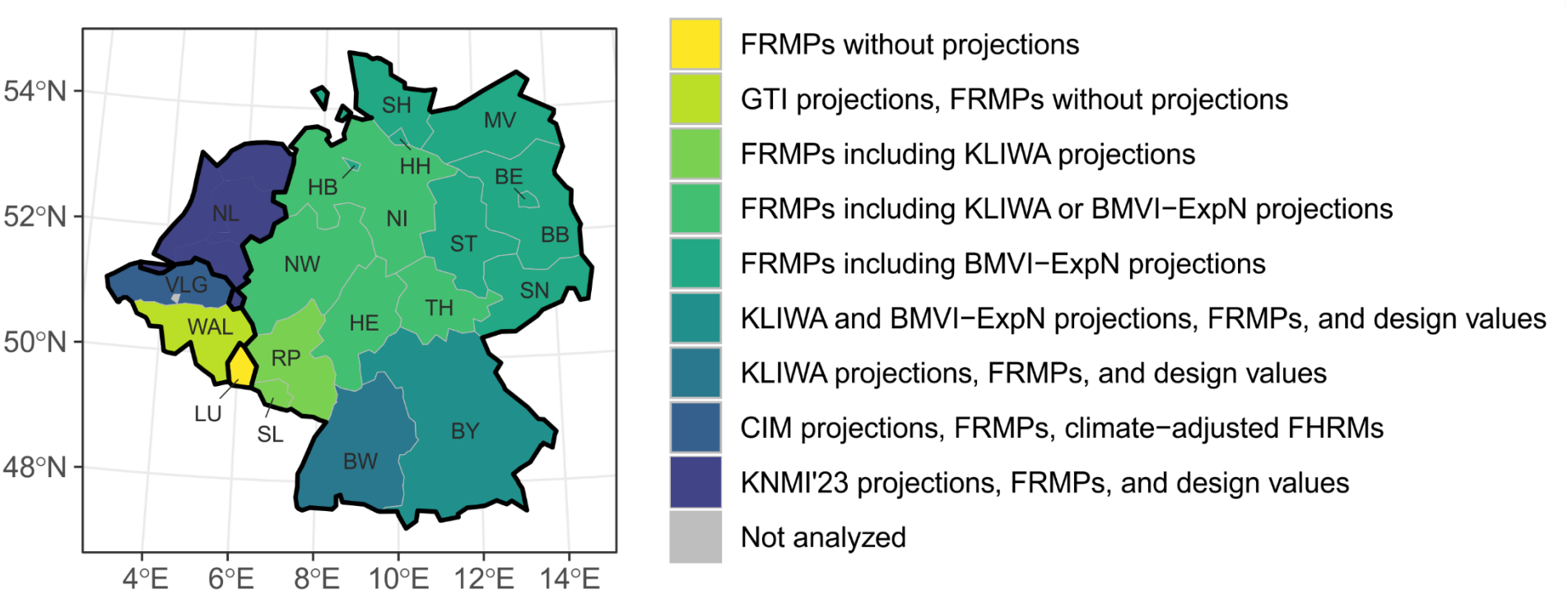
Our review shows how climate change information is derived and used in fluvial flood risk management in Germany, Belgium, The Netherlands, and Luxembourg. We assessed the current status in The Netherlands, Luxembourg, in 16 federal German states and two Belgian regions, in total 20 regions. The countries,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

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

659
660 While many of the studied regions do not have climate-adjusted design values or FHRMs yet, some regions
661 are moving towards a risk-based flood protection standard. Flanders does not only estimate flood hazard maps
662 for future scenarios, but also calculates flood risk for such projections. The Netherlands recently started using
663 risk-based protection standards. Beforehand, as in most countries, standards in The Netherlands were defined
664 by the frequency of exceedance of design water levels for levees. Now, the height of the standards is based on
665 societal disruption due to flooding and the individual risk of becoming a victim of flooding (van der Most,
666 2014).



668

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

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

685

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

699

700 At the political level, all regions show high ambitions to address climate change. This is also generally required
701 for FHRMs and FRM plans by the EU Flood Directive (EU, 2007), although without exactly specifying the
702 approaches and practices to do so. Hence, various countries and specific regions move at their own pace along
703 own trajectories. While climate information is available in different forms and degree of detail, the translation
704 of future projections into FRM practice is still sparse in many regions. The advanced practices of deriving
705 climate-adjusted design values and FHRMs can potentially be taken as examples by these regions to follow
706 suit. The Netherlands is pioneering the use of the most recent CMIP6 climate projections and uses an approach
707 to develop a limited number of storylines suitable for practical applications. The approach is especially useful
708 for communicating complex climate change scenarios to stakeholders and the general public. Also, using
709 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 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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1077

1078 **Appendix**

1079 **Summaries per region**

1080 *BE – Flanders*

1081 In Flanders, official guidelines exist for climate change simulations and for deriving flood hazard and risk
1082 maps for future scenarios (see details in the main text). So far, there is no common regional policy on how
1083 climate change impact results must be considered in flood management and climate adaptation planning. This
1084 is mainly done in an ad-hoc case-by-case way. An example is the Sigmaplan for the Scheldt and other tidal
1085 rivers where the design of actions is based on cost-benefit optimization (Willems et al., 2023). In the Weerbaar
1086 Waterland advice (Expertenpanel Hoogwaterbeveiliging, 2022), a uniform approach for defining strategic and
1087 operational goals for integrating climate change in flood risk management (FRM) in Flanders has been
1088 recommended. This advice is expected to be implemented the coming years.

1090 *BE – Wallonia*

1091 So far, climate change is not quantitatively addressed in design flood values or flood mapping in the Walloon
1092 region in Belgium. However, the methodological guidelines for the preparation of flood hazard maps (SPW,
1093 2020) state that the “probable impact of climate change on the occurrence of floods” should be taken into
1094 account in subsequent versions of flood hazard and risk maps. This should be done by accounting for “all new
1095 climate data available” such as longer statistical series, an inventory of flood episodes, and hydraulic modelling
1096 of the extreme scenario (SPW, 2020). Recently, Brajkovic et al. (2025) assessed future trends in the frequency
1097 and intensity of extreme precipitation in Belgium. A regional working group on floods (GTI) has been set up
1098 by the water management authority (SPW) to translate these climate projections into updated design discharges
1099 and FHRM.

1101 *DE – Baden-Württemberg*

1102 In Baden-Württemberg, official simulations for the estimation of climate change effects for flood hazards based
1103 on KLIWA projections exist as well as climate change factors for design standards (see details in the main
1104 text). In the future, the projections might be updated by using SSPs instead of RCPs as emission scenarios
1105 (KLIWA, 2022). As part of the Rhine and Danube basin communities, Baden-Württemberg contributes to the
1106 FRMP Rhine (FGG Rhein, 2021) and FRMP Danube (FGG Donau, 2021), which consider KLIWA projections.

1108 *DE – Bavaria*

1109 In Bavaria, official simulations for the estimation of climate change effects on flood hazards exist based on
1110 KLIWA projections (KLIWA, 2022) as well as climate change factors for design standards (see details in the
1111 main text). It should be added, that the guidelines state that in “justified individual cases” it may be appropriate
1112 not to apply the climate change factor. As an example, transboundary rivers are mentioned where design flood
1113 values “should not be changed unilaterally” (BLfU, 2005). In FRMPs for the Elbe (FGG Elbe, 2021) and Weser
1114 (FGG Weser, 2021), where Bavaria contributes to, climate change projections based on BMVI-ExpN are
1115 considered. As part of the Rhine and Danube basin communities, Bavaria contributes to the FRMP Rhine (FGG
1116 Rhein, 2021) and FRMP Danube (FGG Donau, 2021), which consider KLIWA projections.

1117

1118 *DE – Berlin*

1119 Berlin as part of the Elbe basin community contributes to the FRMP Elbe, in which BMVI-ExpN projections
1120 are considered (FGG Elbe, 2021). No design values and climate-adjusted flood mapping is adopted.

1121

1122 *DE – Brandenburg*

1123 So far, climate change is not quantitatively addressed in design flood values or flood mapping in Brandenburg.
1124 With regards to designing levees at the large rivers Elbe, Oder and Neiße, Brandenburg is dependent on
1125 agreements with the neighbouring federal states and countries. In the FRMP for the Elbe basin (FGG Elbe,
1126 2021) BMVI-ExpN projections are considered. In the FGG Elbe, the focus in dealing with climate change is
1127 currently on the creation of additional retention areas, e.g., through relocations of levees or by creating polders
1128 (FGG Elbe, 2021). In addition, design floods are estimated based on time series where retention effects of
1129 dams have been excluded (Hatz et al., 2018). This can be considered as a “buffer” for climate change effects,
1130 even though no quantification of such “climate buffer” has been conducted.

1131

1132 *DE – Bremen*

1133 Bremen as part of the Weser basin community contributes to the FRMP Weser, in which BMVI-ExpN
1134 projections are considered (FGG Weser, 2021). No design values and climate-adjusted flood mapping is
1135 adopted.

1136

1137 *DE – Hamburg*

1138 Hamburg as part of the Elbe basin community contributes to the FRMP Elbe, in which BMVI-ExpN projections
1139 are considered (FGG Elbe, 2021). No design values and climate-adjusted flood mapping is adopted.

1140

1141 *DE – Hesse*

1142 In Hesse, climate change is not quantitatively addressed in design flood values or flood mapping yet. Since 2024,
1143 Hesse is part of the KLIWA consortium, and even before has been evaluating climate projections in cooperation
1144 with KLIWA (HMuKLV, 2024). Hesse is using the same climate models, analysing the same time horizons,
1145 and considering the same emission scenarios as done in Baden-Württemberg and Bavaria (see details in the
1146 main text). While these analyses are not as far advanced yet for Hesse, the aim is to derive climate change

1147 factors for flood discharges of different return periods as is done in the other two federal states (HMUKLV,
1148 2017). Work on this is ongoing (HMUKLV, 2024). As part of the Rhine and Weser basin communities, Hesse
1149 contributes to the respective FRMPs (FGG Rhein, 2021; FGG Weser, 2021), which consider KLIWA and
1150 BMVI-ExpN projections, respectively.

1151

1152 *DE – Lower Saxony*

1153 While official simulations for the estimation of climate change effects for flood hazards exist for Lower Saxony
1154 (KliBiW) (see details in the main text), climate change is not yet accounted for in design standards. So far,
1155 only rather vague statements can be found, saying that climate change should be considered in this context
1156 without detailing how to do this. For example, in a final report of the project KliBiW, the following is stated
1157 (translated by the authors): “The combination of increasing peak flows and flood durations means an increase
1158 in flood risk and the associated potential damage in the future. These more severe flood situations should be
1159 taken into account in planning processes in a forward-looking and preventive manner. The development of
1160 adaptation strategies should also be promoted” (NLWKN, 2021). Regarding adaptation strategies, the ministry
1161 of environment states that new technical flood protection measures should be planned farsighted and should
1162 be adaptable (MU, 2022). As part of the Rhine, Elbe, Weser, and Ems basin communities, Lower Saxony
1163 contributes to the respective FRMPs (FGG Rhein, 2021; FGG Elbe, 2021; FGG Weser, 2021; FGG Ems, 2021).
1164 While the FRMP for the Rhine considers KLIWA projections, the latter three FRMPs mention BMVI-ExpN
1165 projections.

1166

1167 *DE – Mecklenburg-Vorpommern*

1168 So far, climate change is not quantitatively addressed in design flood values or flood mapping in Mecklenburg-
1169 Vorpommern. However, currently a climate office is being established in the respective ministry, which will
1170 work on these issues. As part of the Elbe basin community Mecklenburg-Vorpommern contributes to the FRMP
1171 Elbe, in which BMVI-ExpN projections are considered (FGG Elbe, 2021).

1172

1173 *DE – North Rhine-Westphalia*

1174 Up to now climate change is not quantitatively addressed in design standards or flood mapping in North Rhine-
1175 Westphalia. However, this is supposed to change. Following the flood in 2021, a “10-point plan for flood
1176 protection in times of climate change” was issued by the respective ministry (MULNV, 2022). It includes
1177 aspects such as improving flood warning systems or enhancing cooperation between municipalities for cross-
1178 municipal flood protection concepts, and also addresses new design floods and FHRMs. In this regard, it states
1179 that flood hazard and risk maps might be updated in advance of the next cycle required by the European Flood
1180 Directive as the 2021 event has changed the discharge statistics on which the FHRMs are based (MULNV,
1181 2022). Further, it will be checked whether flood-prone areas beyond the inundation areas of an extreme event
1182 (HQextreme) can be included in the maps. For the delineation of official floodplains the integration of a climate
1183 change factor will be assessed (MULNV, 2022). As part of the Rhine and Weser basin communities, North

1184 Rhine-Westphalia contributes to the respective FRMPs (FGG Rhein, 2021; FGG Weser, 2021), which consider
1185 KLIWA and BMVI-ExpN projections, respectively.

1186
1187 *DE – Rhineland-Palatinate*

1188 In Rhineland-Palatinate, official simulations for the estimation of climate change effects for flood hazards exist
1189 based on KLIWA projections (see details in the main text) (KLIWA, 2022), but climate change is not yet
1190 accounted for in design values. The simulations are used for informing stakeholders and the general public. In
1191 general, i.e., independent of climate change, the design of flood protection measures is based on the boundary
1192 conditions of the individual case in Rhineland-Palatinate. This is based on the population at risk, the potential
1193 for flood damage and the economic viability (KLIWA, 2022). As part of the Rhine basin community,
1194 Rhineland-Palatinate contributes to the FRMP Rhine (FGG Rhein, 2021), which considers KLIWA projections.

1195
1196 *DE – Saarland*

1197 So far, climate change is not quantitatively addressed in design standards or flood mapping in the federal state
1198 Saarland. Saarland has been a guest in the KLIWA cooperation since 2019 and officially joined the consortium
1199 in 2024 (KLIWA, 2022). In 2024, a “Future plan flood protection” has been presented by the respective
1200 ministry. However, it does not contain any statements about using climate simulations or estimating climate-
1201 adjusted design standards or FHRMs (MUKMAV, 2024). Instead, the 4-page document touches on aspects
1202 such as helping municipalities with funding, building new gauges or improving warning procedures
1203 (MUKMAV, 2024). As part of the Rhine basin community, Rhineland-Palatinate contributes to the FRMP
1204 Rhine (FGG Rhein, 2021), which considers KLIWA projections.

1205
1206 *DE – Saxony*

1207 In Saxony, climate change is not quantitatively addressed in design flood values or flood mapping yet. The
1208 reasoning is that the uncertainties in climate simulations are too high, but reliable quantitative assessments
1209 would be required to justify measures and increase design values. For details see in the main text. As part of
1210 the Elbe basin community Saxony contributes to the FRMP Elbe, in which BMVI-ExpN projections are
1211 considered (FGG Elbe, 2021).

1212
1213 *DE – Saxony-Anhalt*

1214 So far, climate change is not quantitatively addressed in design flood values or flood mapping in Saxony-Anhalt.
1215 In 2022, the respective ministry published the report “Stable in climate change – State strategy for flood
1216 protection in Saxony-Anhalt” (MWU, 2022). The report contains a large list of measures such as the restoration
1217 of levees, creating retention areas, improving early warning, helping municipalities with measures for flood
1218 protection, and increasing outreach on this topic (MWU, 2022). However, there is no mentioning of increasing
1219 design values, despite stating that (translated by the authors) “climate models predict a significant increase in
1220 risk potential in the climate-sensitive areas of action in flood risk management by 2050 and beyond” (MWU,

1221 2022). As part of the Elbe and Weser basin communities Saxony-Anhalt contributes to the FRMPs Elbe and
1222 Weser, in which BMVI-ExpN projections are considered (FGG Elbe, 2021; FGG Weser, 2021).

1224 *DE – Schleswig-Holstein*

1225 So far, climate change is not quantitatively addressed in design flood values or flood mapping in Schleswig-
1226 Holstein. Studies of the long-term behaviour of meteorological and hydrological time series have shown that
1227 trends in rainfall and runoff can vary greatly between different catchments in this federal state (MELUND,
1228 2017). Therefore, the respective ministry states that more detailed regional studies at the river basin level are
1229 necessary before climate-adjusted design standards can be derived (MELUND, 2017). As part of the Elbe basin
1230 community Schleswig-Holstein contributes to the FRMP Elbe, in which BMVI-ExpN projections are
1231 considered (FGG Elbe, 2021).

1233 *DE – Thuringia*

1234 Up to now, climate change is not quantitatively addressed in design flood values or flood mapping in Thuringia.
1235 A report by the respective ministry states that data analyses show no clear trend in floods in the federal state,
1236 but that climate projections still suggest that action is needed (TMUEN, 2019; TMUEN, 2023). While no
1237 climate-adjusted design standards have been derived, the report still classifies measures which are taken
1238 “primarily due to increasing flood risks” as being closely linked to climate change. In contrast, the maintenance
1239 or renovation of existing flood protection facilities cannot be considered as climate adaptation measures
1240 (TMUEN, 2019). With regards to flood risk management plans, the report states that if the annual frequency
1241 of flood events changes due to climate change, this should be taken into account in an update of the plans
1242 (TMUEN, 2019). However, “as a rule, there will be no increase in safety margins due to climate change” in
1243 Thuringia (translated by the authors; TMUEN, 2019). As part of the Rhine, Elbe, and Weser basin communities
1244 Thuringia contributes to the FRMP Rhine, in which KLIWA projections are considered (FGG Rhein, 2021),
1245 and to the FRMPs Elbe and Weser, in which BMVI-ExpN projections are considered (FGG Elbe, 2021; FGG
1246 Weser, 2021).

1248 *Luxembourg*

1249 So far, climate change is not quantitatively addressed in design flood values or flood mapping in Luxembourg.
1250 The respective administration acknowledges the importance of climate change, and cites relevant projects,
1251 such as for example FLOW MS, where climate change simulations are used (IKSMS, 2013). However, these
1252 projects focus on simulating future water balance, and no estimation of extreme discharges is conducted.
1253 Currently, Luxembourg considers engagement in the German KLIWA consortium to advance its assessments
1254 of climate change on hydrologic extremes (LGDGDL, 2023).

1256 *The Netherlands*

1257 In The Netherlands, official guidelines exist for climate simulations for small and large rivers and for climate-
1258 adjusted design standards for large rivers (see details in the main text). In addition to what has been described

1259 in the main text, The Netherlands also uses a weather generator for the construction of 50,000-year time-series,
1260 based on which discharge extremes for high return periods for the rivers Rhine and Meuse are estimated
1261 (Beersma & Buishand, 2003; Hegnauer et al., 2014).

1262

1263 **References in the Appendix**

1264

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1338 **Supplement**

1339

1340 JCAR-RAT: Climate change effects in flood estimation and design

1341 **Question catalogue for the approach in** _

1342 _____ [*country, region*]

1343 Filled in by: _____

1344

	Question	Answer
General	Country	
	Region (e.g. Flanders, Bavaria or national)	
	Flood type (e.g. riverine, pluvial, coastal)	
	First integration of CC into flood estimation and/or design	
	Latest update	
Estimation	Authority and guidelines	
	Authority (or similar) responsible for the estimation of climate change effects	
	Guidelines/reports/publications in which the consideration of climate change in flood estimation is described and on which the responses below are based	
	Ensembles	
	Which emission scenarios (RCPs) are considered?	
	Are any other scenarios considered, and if yes, which? (e.g. dry vs. wet future)	

	Why are those (emission) scenarios considered?	
	Which global climate models (GCMs) are used?	
	Which regional climate models (RCMs) are used?	
	Why are those climate models (GCMs and RCMs) used?	
	Which hydrological and/or hydrodynamic models are used?	
	Why are those hydrological and/or hydrodynamic models used?	
	Reference or website with a description of the hydrological/hydrodynamic models (if available)	
	How many ensemble members are considered?	
	Why is this number of ensemble members used?	
	Are any other steps (not mentioned above yet) included in the model chain?	
	Target values	
	Which flood return periods are considered in the estimation? (see below for RPs considered in design)	
	Are other flow-related aspects estimated in addition to discharge, and if yes, which aspects? (e.g. water levels, water depth exceedance probabilities, inundation patterns)	

	Are other risk-related aspects estimated in addition to flood hazard, and if yes, which aspects? (e.g. number of affected people, economic damage)	
	For which time horizon(s) are future flood projections estimated?	
	For which purpose are future flood projections estimated? (e.g. planning/adaptation of levees/dams, hazard maps, ...)	
	Uncertainty	
	Which sources of uncertainty are considered in the estimation (i.e. along the model chain)?	
	How is uncertainty expressed in the results? (e.g. probabilistic, scenarios)	

Design, management, adaptation	Authority and guidelines	
	Authority (or similar) responsible for considering climate change in flood design, management and adaptation	
	Guidelines/reports/publications in which the consideration of climate change in flood design, management and adaptation is described and on which the responses below are based	
	Design	
	How are future flood projections that include the estimated effects of climate change transferred to design values?	
	What are those design values used for? (e.g. levees, dams)	
	Target values	
	For which return periods are climate change effects considered in the design?	
	Uncertainty	
	Which sources of uncertainty are considered in the design?	
	How is uncertainty considered for design values? (e.g. probabilistic, scenarios)	
	Management	
	In which flood risk management practices is climate change considered? How?	

	(e.g. preparation of hazard and risk maps)	
	Adaptation	
	How are future flood projections and design values that include climate change effects transferred to adaptation measures?	
Additions	Are any other aspects relevant to the reviewed approach which have not been covered by the questions above? Please list any additions here.	