

Review

How Is Climate Change Included in the Implementation of the European Flood Directive? Analysis of the Methodological Approaches of Different Countries

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Abstract: Climate change has major effects on the planet, and its consequences on today's society are undeniable. Climate change is the cause of the increased frequency and intensity of extreme weather events including floods. Flood management in Europe has experienced a significant change due to the emergence of the Flood Directive and its implementation in national regulations. The Flood Directive requires the inclusion of the effects of climate change. With multiple factors such as governmental and administrative diversity, and various management tools, each country uses a different methodology. This research conducts a bibliographic review to analyze the methodological approaches applied by four different countries—the United Kingdom, the Netherlands, Germany, and Spain—showing their differences and the causes of such differences and examining the common weaknesses and strengths in the countries' approach. To this end, it analyzes how to include climate change in the implementation of the Flood Directive in the four countries studied throughout the two cycles. Developing a uniform approach to FD implementation has been hampered by (1) different starting points in the technology of flood prediction, (2) widely varying “traditional” approaches to flood and risk management, and (3) differing levels of the integration of local, regional, and national agencies. Development under the FD has, however, led to increased awareness of the common uncertainty associated with the different current methodologies and the need to deepen the knowledge of climate change as well as the need to develop the technology to reduce said uncertainty.

Keywords: climate change; flood prevention; flood risks; flood directive; preliminary flood risk assessment; flood hazard; uncertainty



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1. Introduction

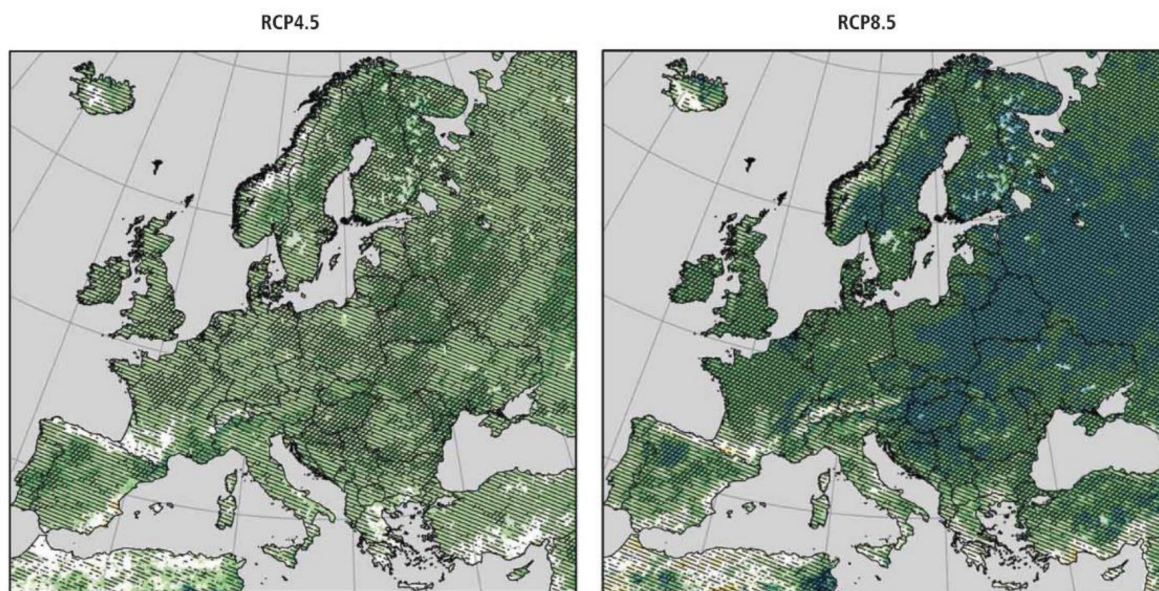
The frequency and intensity of extreme flood episodes have been increasing, and their relationship with climate change is undeniable [1–3]. In particular, flood episodes set human lives at risk and have significant social and economic consequences [4–7]. Environmental consequences can also be substantial because the integrity of facilities containing hazardous substances can be compromised, in turn damaging ecosystems [8]. Euro-Cordex researchers [9] have mapped projected seasonal changes in Europe under different IPCC scenarios (Figure 1). It can be observed that the risk of river flooding is expected to increase in many parts of Europe [10,11].

Climate change is only one of the main causes of the increase in extreme floods and their associated risks. Other factors such as changes in land use (that increase its impermeability [12,13]) or the intensification of soil erosion (which increases the erosivity of rainfall and runoff [14]) aggravate these risks. However, this study only focused on flood impacts that are most clearly linked to climate change.

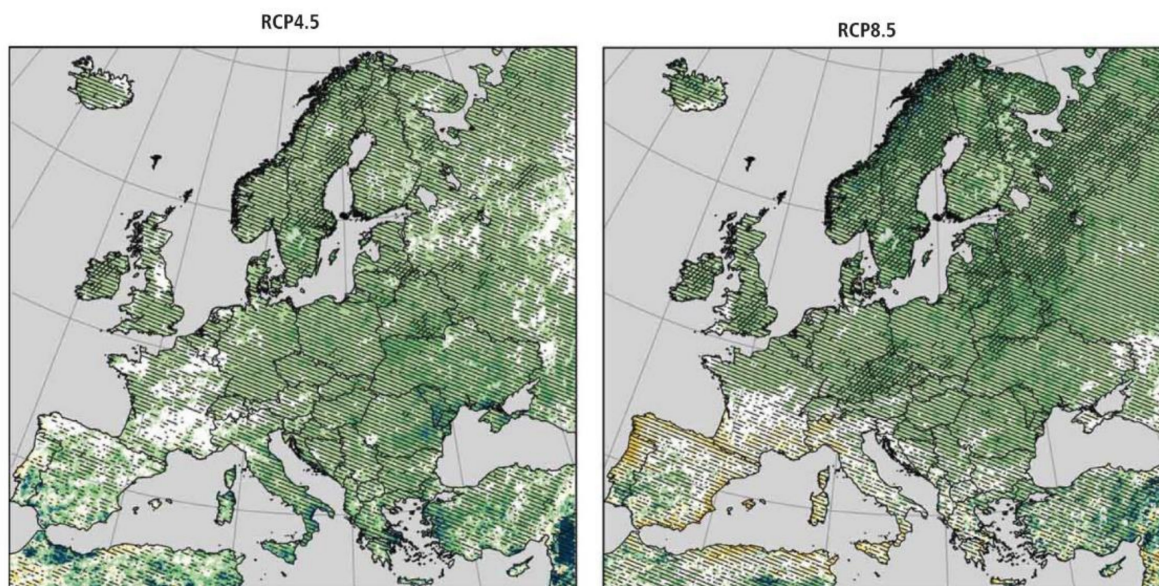
In summer, a decrease in heavy precipitation is expected in some parts of the Iberian Peninsula and southern France, accompanied by regional increases in other parts of Spain and Portugal. These effects are shown in Figure 1. Additionally, in central and eastern

Europe, heavy precipitation increases moderately in this season. For winter, significant increases in heavy rains are expected in most parts of Europe. The EuroCordex RCMs forecast that the spatial patterns of precipitation change are the same for IPCC scenarios RCP 4.5 and RCP 8.5, just increased in magnitude with the higher emissions pathway.

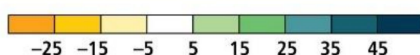
(a) DJF seasonal changes in heavy precipitation (%), 2071–2100 compared to 1971–2000



(b) JJA seasonal changes in heavy precipitation (%), 2071–2100 compared to 1971–2000



Seasonal changes in heavy
precipitation in percent



//// Significant change
\\\\ Robust change

Figure 1. Projected seasonal changes in heavy precipitation in the months from December to February (DJF) (a) and June to August (JJA) (b) for RCP 4.5 and RCP 8.5. (Modified from [9]).

Traditionally, most European countries had based their flood management (FM) strategies on prevention and defense against floods [1]. However, the increase in extreme flood

events due to climate change has led to an understanding that more diversified strategies should be considered for adaptation to the new situation [1–3,15–17].

The European Flood Directive (FD) [18] was developed in response to the major floods in Europe in the last decades of the twentieth century and the first decades of the twenty-first century [19–22]. In this way, the main objective of the FD has been to establish a framework for the assessment and management of flood risks to reduce the adverse consequences for human health, the environment, cultural heritage, and economic activity associated with floods in the community [15–17,23]. This action must be coordinated between the different public administrations and society as a whole. To this end, a three-stage process has been established, which must be updated cyclically every six years in coordination with the cycle of the Water Framework Directive (WFD) [24].

The first phase is the preliminary flood risk assessment (PFRA), in which areas of potentially significant flood risk (APSFR) for each river basin district are identified. In the second phase, flood hazard and flood risk maps (FHRM) are drawn, showing the possible consequences of these flood results for different scenarios [5]. Finally, in the flood risk management plans (FRMP), specific measures have been established according to the characteristics of hazard and risk of each area identified in the previous stages. These are the measures required to achieve the FM objectives.

According to the *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC), climate change will produce changes in flood patterns [4]. Therefore, despite the great associated uncertainty, the essential steps that must be taken are to deepen our knowledge of its possible influence and consequences as well as to manage the risks that may arise from this situation [25]. In some regions, this influence is already evident [2,20].

Member countries should consider the identification of the areas with the highest risk of flooding when carrying out PFRAs [20,26]. Likewise, the FD advocates broadening of flood risk management (FRM) strategies to increase the territory's resilience and facilitate faster recoveries [1,20,27]. In any case, the member states have incorporated the influence of climate change into their implementation of FD in variable ways in different stages and with very different methodologies.

This article aims to analyze the distinctive features of the methodologies used by four different countries—the United Kingdom, the Netherlands, Germany, and Spain—showing their differences and the causes of such differences and examining the common weaknesses and strengths in the country's approaches. The selected countries share a long tradition in the field of FM and view flood risk as a critical issue since floods and massive damage are frequent. Most remarkable are the floods in Germany in 2013 and 2002, the United Kingdom in 2015 and 2007, Spain in 2018 and 1983, and the Netherlands from 2017 to 2020 and 1953.

On the other hand, the methodology developed by each country follows a different tradition because each one has its own administrative organization system (centralized, federal, regionalized) and legal system, diverse orography and climatology, and different population development and technological progress. As a result, the country's responses to flood risk are diverse, with different patterns and development processes over time [19,23]. Therefore, the selected countries differed significantly, both in their tradition of flood studies procurement and in the instruments and institutions to implement the FD [28].

2. Methodology

In this article, there was a semi-systematic literature review. Although this method does not have an accurate and rigorous approach to collecting literature as a systematic review, it is considered as a highly effective way of covering broader research questions not achievable with systematic approaches. This type of review is commonly used to analyze topics conceptualized in a different way and studied by different groups and organizations, making a complete systematic review process difficult [29]. This semi-systematic analysis identifies common strengths and weaknesses within a research methodology and can contribute to the synthesis of the state of knowledge and a historical description of a

specific topic [30]. In this regard, a combined review of legal, political, and technical literature will be performed to conduct this multidisciplinary research.

First, a review of the legal framework for flood management was conducted including an analysis of the FD [18] and the WFD [24].

Next, the official documentation of the implementation of both directives was assessed by analyzing the implementation reports transmitted by the European Commission to the European Parliament of the WFD (currently, the second river basin management plan) and to the FD (presently the first FRMP). This documentation is published within the *“The fifth WFD Implementation Report-assessment of the second River Basin Management Plans and the first Floods Directive Implementation Report-assessment of the first FRMP (2019)”*, which can be found on the website of the European Commission [31]. In this regard, particular importance has been given to *“A European overview of the implementation of the first FRMP”* [32] and specific assessments carried out by the European Commission for each of the studied countries [33–36]. Furthermore, the technical recommendations of the European Working Group on Floods within the Common Implementation Strategy [37] and other documentation available on the information exchange platform Communication and Information Resource Center for Administrations Businesses and Citizens (CIRCABAC) [38] were analyzed in detail.

Third, reports from public authorities, recommendations, and experiences from both the first and the second cycles of FD implementation were consulted to obtain the methodologies applied by each country. PFRA, FHRM, and FRMP of the first cycle of the regulation and the PFRA of the second cycle, were also examined:

In the case of the United Kingdom, the reports of the Environment Agency (EA) describing the FD implementation on the first cycle and the PRFA on the second cycle were analyzed. These reports can be found on the UK Environment Agency website [39]. Moreover, reports of climate projections used for the study of climate change on floods in both the first and second cycles of FD implementation were consulted, which can be found on the website of the UK Climate Projections 2018 [40].

For Germany, the authors consulted the reports of the German Working Group on water issues of the Federal States, Länder-Arbeitsgemeinschaft Wasser, on the implementation of the first cycle of the FD and of the PRFA of the second cycle, which can be found on its website [41]. This same website contains reports about the climate projections used to include climate change in the study.

In the case of the Netherlands, the website of the Executive Agency of Ministry of Infrastructure and Water Management *“Rijkswaterstaat Water, Traffic, and Environment”* [42] contains the reports used in this work on the implementation of the first and second FD cycles. All the information about new scenarios, climate projections, and climate change in general were obtained from reports on the website of The Royal Netherlands Meteorological Institute *“Koninklijk Nederlands Meteorologisch Instituut”* (KNMI) [43] and the Delta Program [44]. Relevant information on flood risk prevention was obtained from documents published on the Foundation for Applied Research Water Management website, Stichting Toegepast Onderzoek Waterbeheer [45].

In the case of the Spanish system, the documentation regarding the implementation of the first cycle of the FD and the PRFA of the second cycle was obtained from official publications of *“Ministerio para la transición ecológica y reto demográfico”* (MITECO). For this paper, publications of basin organizations of the different hydrographic confederations and documentation on research lines on flood issues were consulted. All these documents can be found on the MITECO website [46].

For greater clarity, Figure 2 summarizes the regulation and “gray literature” used in this article. Furthermore, this work is complemented by a review of research articles on the subject matter to provide an overview and new avenues in terms of the new proposed methodologies. Forty-two research articles were included. To transmit as possible transparency of the investigation [29], Figure 2 also describes the selection criteria of the academic research literature followed.

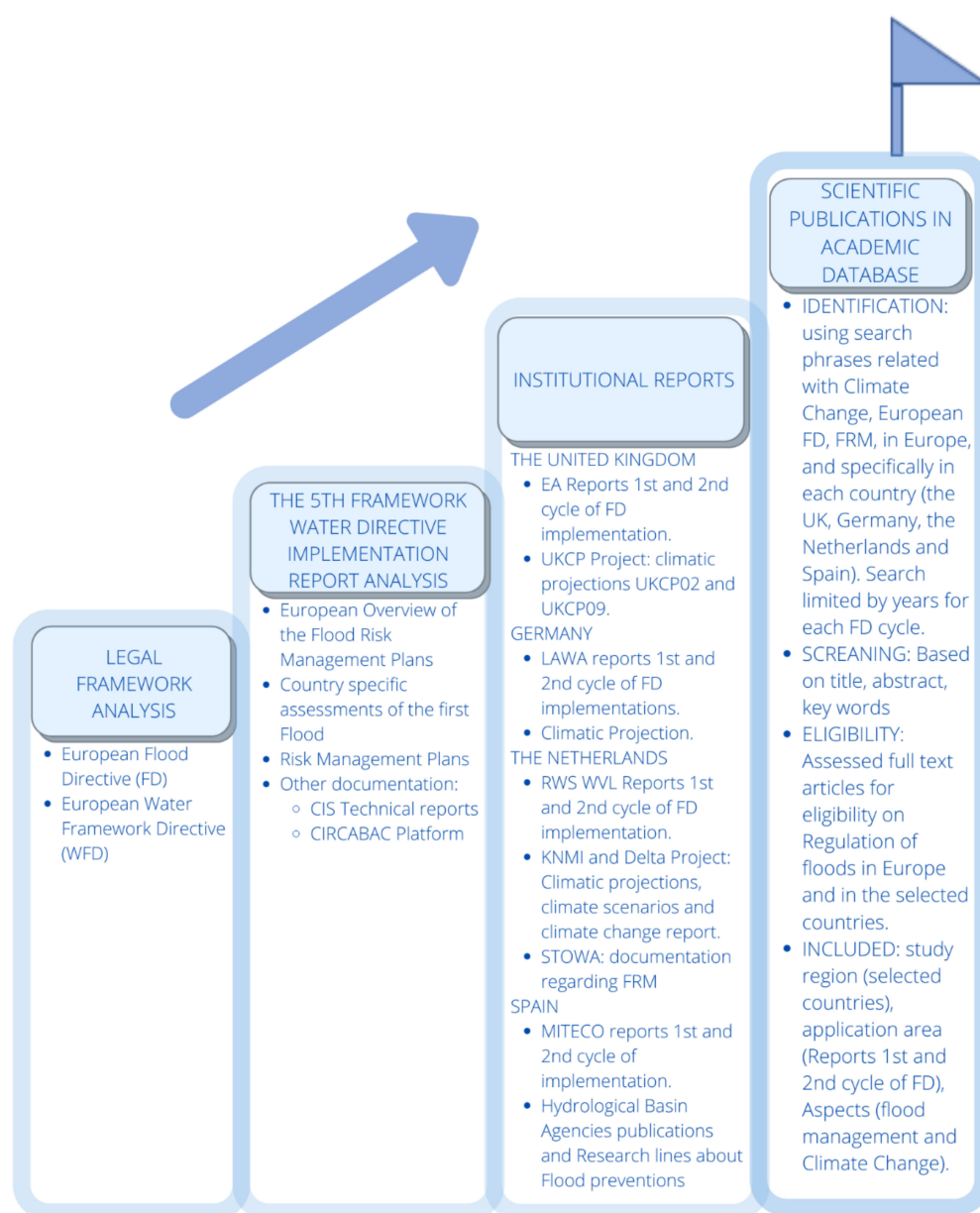


Figure 2. Bibliographic research process.

After the examination and analysis of the documentation, the conclusions derived from the process were summarized to examine the common weaknesses and strengths in the countries' approaches.

3. Analysis of the Implementation of Flood Directive

The EU member states included the effects of climate change in flood risk prevention in various ways in different phases and with very different methodologies.

According to FD, the influence of climate change must be included in the first stages of its implementation (PFRA and FHRM) [18]. This section presents the different approaches used by the studied countries for the inclusion of climate change studies in their implementation of the flood directive. Furthermore, the evolution of this implementation can be shown due to the incorporation of new data and knowledge. Thereby, the work was organized according to the two implementation cycles of the FD. Before comparing the implementation of FD in the FRM of the countries being studied, this paper presents the preceding situation of the FRM approach of each country.

3.1. *Prior Approaches from the FM to the Implementation of the Flood Directive*

The essential characteristics of the determining factors in FRM in each of the countries studied are described below such as government organization, experience with floods, and traditional approaches to FM.

3.1.1. The United Kingdom

Water management in the UK has been highly centralized with different institutional levels responsible for land and water management [14,18,47]. Coordination between the central and the local government has traditionally had considerable difficulties [1].

Until the mid-2000s, the UK followed an FRM policy focused on prevention and protection. After the great floods of 2007, it reconsidered its strategy and is pursuing a more diversified and balanced approach in terms of prevention, defense, and mitigation [48]. Different studies have highly recommended this position [3,49,50] to achieve greater flood resilience of the territory.

At the time of this research, the United Kingdom was still a member of the European Union, which is the reason why it was considered in this study.

3.1.2. Germany

Germany has an entirely decentralized federal government system, and each federal state is responsible for the river basin districts of its territory. Despite the creation of working groups among the local, federal, and national administration to implement the FD's recommendations, the complex distributions of responsibilities make such implementation difficult [19,51]. The FM has traditionally focused on prevention and defense. Since the severe floods of 2012, studies have focused mainly on risk and mitigation [9].

3.1.3. The Netherlands

The Netherlands is especially vulnerable to floods due to its geographical location: a delta area through which four major international rivers flow [5]. Much of the settlement of its population is below sea level. Therefore, the Netherlands has vast experience in FM.

FM has been an essential aspect of the country's governance, and its legislation related to water is entirely centralized. Thus, uniform guidelines for the subsequent implementation of the FD are available [19].

FM has been traditionally based on flood defense. However, in recent years, different studies have been developed to improve resilience through the diversification of strategies with a focus on risk. The Netherlands was included in the comparison due to its remarkable tradition of studying floods. Its importance is undeniable; 25% of its area is below sea level [9], 60% of its area is in a frequently flooded area [10], and 35% of its inhabitants are protected by the ring system of dikes [52].

3.1.4. Spain

Floods are considered the most important natural hazard in Spain. The country has one of the highest European indices in terms of the number of episodes and fatalities caused by floods per year [6,21].

The FM has focused on prevention and defense [53] as in other European countries, although the trend has been shifting toward different and more diversified approaches that increase the territory's resilience as a result of FD implementation.

3.2. *First Cycle of Implementation of the FD*

This section describes the general aspects of the implementation of the first cycle of the FD in its three phases (PFRA, FHRM, and FRMP) for each of the four selected countries, with December 2015 being the deadline for delivering the first FRMPs. Thereby, in this stage, experiences varied [54]. Some member states did not incorporate climate change in their FRMP. Of the four countries compared, only the United Kingdom and Germany took climate change into account in their PFRA and FHRM, both in the case of fluvial, pluvial,

and seawater floods. Although the Netherlands has conducted detailed studies on the implementation of FRMPs, they have not reported on the study of climate change until this stage [55]. Table 1 summarizes the most significant aspects of the methodology followed for the implementation of the first cycle of the FD.

Table 1. Methodologies in the first cycle of implementation of the FD. Own elaboration based on documents: “EU overview of methodologies used in the preparation of Flood Hazard and Flood Risk Maps” [55] and “European Overview-Flood Risk Management Plans” [32].

	The UK	Germany	The Netherlands	Spain
Types of flooding sources reported in FRMPs assessed per member state	Fluvial Seawater, AWB structures	Fluvial Seawater, Multiple sources	Fluvial Seawater	Fluvial Seawater, Groundwater
Approaches used in the calculation of return periods and probabilities for fluvial floods	Historical data modeling	Historical data modeling	Expert judgment, Historical data, Statistical analysis Modeling, Hydrological rainfall–runoff models, Hydrological studies	Modeling Hydrological rainfall–runoff models, Hydrological studies
Time frame of climate scenarios discussed in FRMP	Northern Ireland: 2030 and 2100 England 2025 and 2100 Scotland 2080	2050 and 2100	2050 and 2100	No information
Elements included in the hazard maps of seawater flooding	Flood extent, Water depth level, Water flood velocity	Flood extent, Water depth level	Flood extent, Water depth level, Water flood velocity (only low-probability scenario)	Flood extent (not in high scenario), Water depth level (not in high scenario)
Elements included in the hazard maps of fluvial flooding	Flood extent, Water depth level Flow velocity or the relevant water flow	Flood extent, Water depth level	Flood extent, Water depth level Flow velocity or relevant water flow	Flood extent, Water depth level
Scenarios mapped for fluvial flooding with associated expressions of probabilities and return period (years)	HP ¹ 10 to 30 or 1% Main river and sea floods in England and Wales MP ² 100 to 200 LP ³ 1000	HP 10,20,25,30 MP 100 LP 200, 1000	HP 10 MP 100 LP 1000	HP 10 MP 100 HP 500
Scenarios mapped for sea water floods with associated expressions of probabilities and return period (years)	HP 10 and 10% MP 200 and 0.5%, 1% LP 1000 and 0.1%	HP 20 MP 100,200 LP 200	LP 1000 MP 100 HP 10	HP not mapped LP 500 MP 100

Notes: ¹ HP: high probability; ² MP: medium probability; ³ LP: low probability.

3.2.1. The United Kingdom

In the United Kingdom, different climate change assessment reports on floods have been published [56], showing percentages of change in extreme rains according to the different hydrographic basins. Overall, climate change projections show warmer and rainier winters, hotter and drier summers, and an increase in extreme precipitation events. At the same time, it describes how the sea level gradually rises as the water in the oceans warms and the ice melts. Different scenarios and return periods have been considered. Maximum rainfall and temperatures were estimated from the UK regional climate projections 2009 (UKCP09 DATA) [57] from global projections (IPCC). River flows were determined through hydrological models. Precipitation intensities and sea level rises were also evaluated.

Despite the uncertainties, the FHRM elaboration indicates a 20% increase in the peak river flow for the year 2100 due to climate change and other considerations that also generate uncertainty despite significant seasonal and geographical variations [58]. The rise in sea level also increases according to location along the country’s coast [59] for the different periods considered (2080 and 2100).

Moreover, the importance of spatial planning policies for the study of flood risks is noted [58]. Each UK territory has developed its FHRMs with pluvial, coastal, fluvial, and coastal flooding taken into consideration (major rivers only) and artificial water-bearing infrastructure concerning climate change [55].

3.2.2. Germany

In the case of Germany, climate change in the first cycle of FD implementation has also been considered based on global and regional climate projections. However, the prediction of the effects of climate change is different in each river basin district. While the Weser area estimated an increase in floods, no significant changes were expected in the Rhine area [33]. The sea level is also expected to increase throughout the entire German territory.

In this case, each river basin district conducts an individual study following the guidelines considered above, thus providing variety in the FD implementation. A significant effort has been made to link current national climate models and FM.

Despite the existing studies, only a few river basin districts (Danube and Schley) have introduced specific flood defense measures. An example is the climate change factor (CCF) as a precautionary instrument for technical protection against floods. The CCF is designed as a surcharge value (in terms of a percentage margin) to consider in the flood calculations of all new protection measures such as dikes, retention basins, flood protection walls, or dams [7].

Germany's main objectives in its first-cycle FRMPs were general and strategic and can be summed up as reducing the adverse consequences of floods and the probability of occurrence (defense). The measures for achieving these objectives were also very general, and their implementation lacked detail. They did not have measurable indicators, their planning was undeveloped, and budgets or assigned financing were not detailed. In the FRMP, the implemented measures focused on no structural flood mitigation techniques. The FRMP indicates that the general measures to reduce the impact of floods also include the effects of climate change. However, with some exceptions such as the application of the CCF, no specific measures regarding climate change were given.

3.2.3. The Netherlands

Despite general climate change projections showing a higher frequency of extreme weather events, the Netherlands did not include climate change in the first two stages of FD implementation [36]. In contrast, FRMP describes the expected effects of climate change in detail and specific measures to address it. They also indicate that climate change is considered in the general approach to FM. Thereby, following the emergence of the European FD, the Netherlands did not develop a new policy in this context but instead sought to be as close as possible to the existing plans and programs [16]. They have a long tradition in flood management and have conducted comprehensive studies.

In the first stage of the FD, the Netherlands did not designate areas of potential significant flood risk (APsFR). Rather, they considered that this risk exists throughout the country due to its unique geographical situation. In the same way, FHRMs presented updated versions of previous plans under a national or regional context and are used to prioritize the measures included in the FRMP. In the case of the FRMPs, it included all the previously established objectives and measures [60]. These objectives are general and vague, and focus on flood protection, consequence prevention, and crisis management. Each measure established in the FRMP is associated with a specific objective and some specific measures that include climate change.

In addition to the above, the Netherlands continues with investigations already initiated related to flood risk management. An example of this is the VNK2 Project [61], which is a large-scale quantitative project that analyzes the flood risks for major levee systems in the Netherlands by combining the probability and the consequences of flooding for different scenarios. It allows for informing and improving flood risk management by prioritizing interventions.

3.2.4. Spain

In the case of Spain, the influence of climate change was not considered in the first cycle of FD implementation because of contradictions among the findings of the IPCC [62] and other national [63] and regional [64] studies. Additionally, the associated uncertainties

were significant. According to these studies, forecast tendencies of the global decrease in precipitation and unclear or diverse trends in terms of maximum daily precipitation were observed. As a result of this uncertainty, all FRMPs included a specific measure to address climate change by conducting further studies on the effects of climate change on flood risk because of the insufficient information at that time. Other incorporated measures are related to improvement in meteorological predictions.

The calculated APSFRs are based on the threshold of significant risk. This threshold is based on the efficiency of applying flood mitigation measures per unit length of the study section. Thereby, flood episodes with a medium risk (return period of 100 years) were first modeled through hydrological–hydraulic studies using 1D or 2D simulations. Thus, the flood extent maps for the 100-year avenue were obtained. Next, the vulnerability of the territory was studied by using geographic information system (GIS) processes, crossing the flood extent areas with the affected areas' vulnerability. A statistical calculation of the expected impacts was carried out considering the probability of the occurrence of each flood episode, thus finding a quantitative value of the area's risk. Then, the areas with the highest unit risk were obtained. These areas had the most significant amount of hazard in the shortest possible time. Thus, efforts were directed to these areas where the maximum mitigation of global risk occurred. These APSFRs are considered high risk, corresponding to a variable percentage according to the river basin considered of the expected total risk.

In the case of a seawater flood, for a low-occurrence risk scenario (a return period of 500 years), the flood extent area is calculated as the tidal and wave flood surface envelope [65]. The risk assessment procedure, the definition of a significant risk threshold, and the specification of coastal APSFR are performed in a similar way as river flood assessments.

3.2.5. First Cycle Summary

Table 2 details the considerations and others related to the methodology followed for the inclusion of climate change in the different phases of the first implementation cycle.

Table 2. Summary of how climate change is included in the first cycle of FD implementation. Own elaboration based on documents: “EU Overview of Methodologies Used in the Preparation of Flood Hazard and Flood Risk Maps” [55] and “EU Overview of Assessment of Member States’ Reports on PFRA and Identification of Areas of Potentially Significant Flood Risk” [66].

	The UK	Germany	The Netherlands	Spain
Climate change was taken into account in preparing maps	Yes	Yes	No	No
Climate change trend scenarios were obtained from national research programs	Yes	No	No	No
Flood hazard scenarios included trend analysis of historical data of hydrological and meteorological observations	Yes	Yes	Yes	No
Flood hazard scenarios included a statistical assessment of historical climate data	No	Yes	Yes	No
Information provided in FRMPs regarding climate impacts on flood risks	Increase in heavy rain and other weather extremes	Increased flooding expected in Weser; no change in Rhine; increased seawater flooding expected due to sea level rise	Increase in frequency of extreme weather events	Measures designed to investigate impacts of climate change and associated uncertainty

In sum, the effects of climate change in each of the stages of the first cycle of implementation of the FD are taken into account in varied ways and under diverse considerations both in scenarios (climatic and temporal) and in the sample of results (FHRM).

3.3. Second Cycle of Implementation of the FD

After studying the first FRMPs and analyzing the European Commission working group's recommendations for the second cycle of implementation of the directive [67], the member countries have made some changes to their considerations, as explained below.

The deadline for submitting the first two stages of the second implementation cycle of the FD has already passed. Each country submitted its PFRA and FHRM reviews in December 2018 and December 2019, respectively. The anticipated date for the review of the FRMP is December 2021.

As in the case of the first cycle, the main characteristics of the inclusion of climate change in the implementation of the FD for the second cycle were analyzed in the case of fluvial, pluvial, and seawater floods in the United Kingdom, Germany, the Netherlands, and Spain. The four countries already included the effects of climate change with more elaborate methodologies than in the first cycle of the FD, with the most notable characteristics shown below.

3.3.1. The United Kingdom

In the United Kingdom, the inclusion of climate change in the first cycle of the directive was developed fully. Only certain aspects were modified and/or updated to improve its implementation for the second cycle.

Generally, the first-cycle studies were based on the UK Climate Projections, 2009 (UKCP09). Since then, some river basin districts have conducted local studies that included climate change assessments on flood risk [40]. These studies used climate projections with a cell width of approximately 2.2 km.

Other flooding sources were included for the study such as those coming from groundwater, ordinary waterways, or the combined impact of multiple sources.

Data on increases in rainfall and flows and sea level rise were provided by the EA for the river basin districts. This organization prepared tables [68] that show the increase in the peak river flow in the main river basin districts. Variable percentages were assigned, which vary between 60% and 120% for the year 2100. Therefore, the 20% increase considered in the first cycle of the FD implementation has become particularized for each river basin district. With regard to the rise in sea level, a total increase of +1.90 m was considered throughout the territory in the year 2100.

Once the increases in peak river flows and sea level were specified, the models used to determine the APSFR exposed to the risk of fluvial, pluvial, and coastal floods became similar to those in the first cycle (although other scenarios were taken into account [69]). Similarly, the FHRMs were based on the APSFR and the flood risk vulnerability classifications obtained from the tables prepared by the EA [59].

3.3.2. Germany

The main changes made in the first two stages of FD implementation, concerning the first cycle, focused on the attempt to standardize the methodology at the country level. An example of this fact can be seen in the river modeling strategy: in most cases, the Federal Institute of Hydrology (BfG) is in charge of simulating the main streams (Danube, Elbe, and Rhine) as well as federal waterways whereas the federal states take on responsibility for the modeling of most tributaries, partly reaching far into the upper catchment. This fact is reflected in the applied modeling techniques, which are different depending on the administration in charge [70].

General guidelines were set from the central government for all federal states to follow when implementing PFRA and FHRM. Thereby, the climate scenarios used were based on the emission scenarios of the fifth report of the IPCC [71], which are the Representative

Concentration Pathways (RCP) RCP 2.6 and RCP 8.5, through projections generated from global and regional climate models of the European project EURO-CORDEX [72] and the German projects [73]. Moreover, an acceleration in sea level rise is considered. The central government and the states agreed to use the RCP 8.5 scenario, in which the probable range of global mean rise in sea level in this century is between 0.61 and 1.10 m. This increase in sea level is considered for the entire coast of Germany.

The most significant change concerning the first cycle of the implementation of the FD will occur in 2021 in the FRMP. More detailed and measurable prevention measures are currently being prepared, as recommended by the commission to Germany in the first cycle [33].

Together with the federal states, the German government decided on the joint elaboration of the “German National Flood Protection Program” (NHWSP). Within the frame of this program, the government supports the realization of large-scale retention measures for the improvement of supra-regional flood prevention [70] and the increase of the territory’s resilience. One particular case is the “Bavarian Polder Program”. This program accounts for 12 potential sites for the construction of controlled polders along the Danube. The Polder Program intends to increase the resilience of flood protection infrastructure by expanding retention volume and reducing flood risk for downstream cities in the case of overload.

3.3.3. The Netherlands

Due to the vast experience of the Netherlands with flooding, it has devoted significant efforts to the research. Aside from river and rain floods, coastal floods were included in the creation of a methodological guide [74].

The essential aspects of the consequences of climate change for flood defense are sea level rise and changes in rainfall patterns reflected in extreme levels of peak river flows in the main system and regional water systems.

A hydrodynamic model is used to represent flood zones. Even so, uncertainties are inherent in the process, although new studies on the matter are expected to possibly reduce the influence of such uncertainties in the coming years [75].

The climate scenarios used were based on observed climate change and recent calculations with IPCC global climate models [71], complemented by different calculations based on the KNMI Europe project climate model [76]. These scenarios are related to two variables: the increase in temperature and the change in atmospheric circulation. Table 3 shows the values of the considered climatic variables.

Table 3. Values of the climatic variables that give rise to the KNMI14 climate scenarios [73].

	Scenarios	Time Frame of Climate Scenarios		Based on
		2050	2085	
Global temperature change	G	+1 °C	+1 °C	RCP 4.5
	W	+1.5 °C	+3.5 °C	RCP 8.5
Change pattern airflow	L	Minimal changes		
	H	Strong changes		

Notes: G1: moderate increase of the global temperature; W2: strong increase of the global temperature; L3: low value; H4: high value.

The Delta Program [44] is an integrated FRM approach with a combination of measures that reduce flood probability (determined by hydraulic load and defense strength/height) and measures that reduce flood consequences (damage and casualties, determined by flood characteristics, buildings, and evacuation success).

A long-term perspective introduces uncertainty (about the future conditions of climate, population, economy, and society). These measures have to be designed, which are to be tackled in an adaptive way that involves planning, maximizing flexibility, keeping options open, and avoiding lock-in.

Four non-climate scenarios based on socioeconomic development models—so-called delta scenarios—have also been used to handle this uncertainty. Such scenarios are given particular importance because they completely change the focus of FRM. Each scenario describes a plausible future in which climate change (rapid or moderate) is combined with socioeconomic development such as continued economic and demographic growth or low economic growth and demographic decline. Figure 3 presents the combination of variables that give rise to the four delta scenarios.

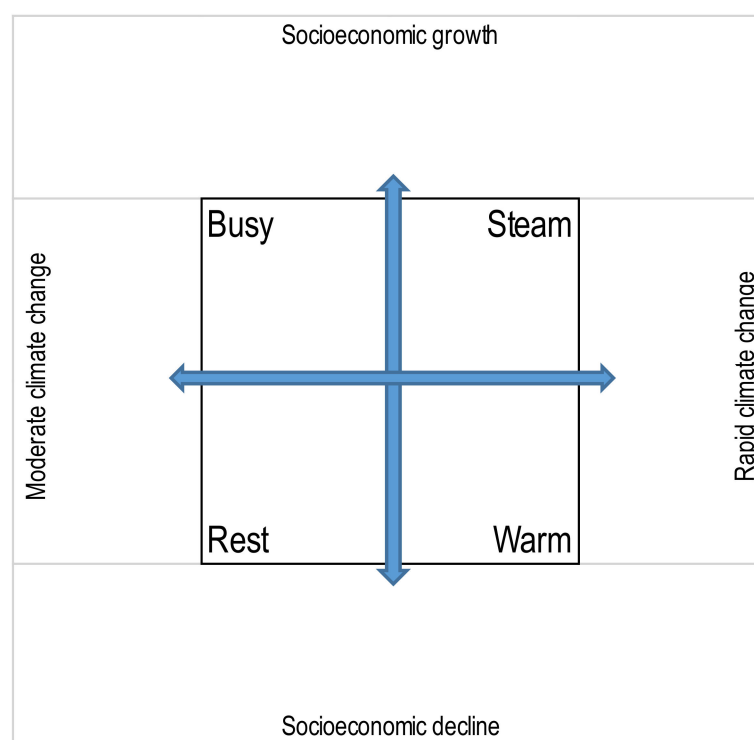


Figure 3. Graphical representation of delta scenarios [77].

The scenarios were performed for two-time horizons, namely, 2050 and 2085, and provide qualitative (maps and arguments) and quantitative (key figures) information on climate, water systems, water use, and land use. Under this perspective, the Netherlands model predicts a sea level rise between 0.25 and 0.80 m until the end of the century and a global temperature rise between +2 °C and +4 °C.

The scenarios act as an inspiration for strategy development and present a framework for checking the strategies' performance under different future conditions.

3.3.4. Spain

In the first cycle of FD implementation, Spain did not consider the effects of climate change in floods due to the significant uncertainties of the studied models. These effects were included in the second cycle.

In the framework of the program “Plan to Promote the Environment for Adaptation to Climate Change in Spain” (PIMA Adapta Plan), a methodology was developed, which incorporates the assessment of the possible influence of climate change on the risk of fluvial and pluvial flooding to obtain APSFRs [78]. The methodology is based on a comparison, for the same return period (the average probability of 100 years is used), of the daily time series of maximum annual precipitation and the associated river streamflow in two different scenarios; the first includes the effect of the climate change, whereas the second does not. If the differences are significant by applying statistical methods (Monte Carlo method [78]), then these areas will become new APSFRs. The climatic projections used are twelve combinations of global and regional climate models (GCM-RCM) from the EURO-

CORDEX project [72], which were used for the study (with a cell width of approximately 12.5 km). The river streamflow function in the projected current climate situation and in the climate change implementation scenario was calculated according to the regulation “5.2-IC Drenaje superficial en la Instrucción de carreteras” [79] in steady state.

With regard to FHRM, variations concerning the first cycle of FD implementation were limited to some adjustments to the valuation of damages and facilities included in the Spanish transposition of Integrated Pollution Prevention and Control Directive (IPPC) [80] on account of its revision. The FHRM corresponding to the return periods of a low and a high probability of occurrence (10 and 500 years), respectively, was also included. Therefore, in the case of river basin districts that include coastal zones, climate change from seawater flooding is included, according to the C3E project [81]. Table 4 shows a summary of the climatic and non-climatic scenarios considered for this case.

Table 4. Climatic and non-climatic scenarios considered in the C3E project for the Spanish coast [82].

		Based on:	Horizon Year:
Climatic scenarios	C1 (GMSL ¹ rise 0.50 m)	RCP 4.5	2100
	C2 (GMSL rise 0.85 m)	RCP 8.5	2100
	C3 (GMSL rise 2 m)	Based on semi-empirical models	2100
		Variables considered	Horizon Year:
Non-climatic scenarios	v0: Current society vulnerability	Current conditions	2100
	v1: Society vulnerability 2040	GDP ² , GVA ³ , GDHI ⁴ , and capital stock	2040

Notes: ¹ GMSL: global mean sea level; ² GDP: gross domestic product; ³ GVA: gross value added; ⁴ GDHI: gross disposable household income.

Non-climatic scenarios were used to assess the flood risk analysis and are related to the vulnerability and resilience of natural assets [83].

In the case of Spain, flood extent zones were found by applying a simple model based on the crossing of georeferenced layers. The digital terrain model (DTM) coastline and the water depth level were defined for each scenario and, with the crossing of the two layers, the flood extent area was obtained.

3.3.5. Final Considerations

The essential characteristics of the determining factors in FRM and the FD implementation in each of the countries studied are the government organization, experience with floods, and traditional approaches. Thus, in Germany, despite creating working groups among the local, federal, and national administrations to implement the FD’s recommendations, the complex distributions of responsibilities make such implementation difficult. In the UK, with an FRM highly centralized and with different institutional levels of responsibility for water management, the coordination between the central and the local government has traditionally had considerable difficulties. In the Netherlands, however, FRM regulation is entirely centralized. Thus, uniform guidelines for the subsequent implementation of the FD are available.

Different countries have had a traditional approach to flood management based on prevention and defense. An example of this was the application of the 20% increase in the peak river flow for FHRM elaboration in the UK in the first cycle of FD implementation. This coefficient was changed into a variable percentage increase in the second cycle. Another example was the application of the CCF in Germany, like a surcharge value (a percentage margin) to be considered in the flood calculations of all new protection measures.

It can be observed that the countries that have varied their methodology the most markedly between the first and second cycles of the FD are those that performed the implementation in the first place more incompletely, as in the case of Spain. On the other hand, the countries that have developed the methodology the most have focused their modifications on improvements in climate model reviews or new technological resources.

An essential detail to bear in mind is that the deadline to submit the FRMPs for the second cycle has not been met yet. Therefore, further variations are expected in terms of the measures applied to reduce the risk of floods.

Table 5 summarizes the hypotheses used in the methodologies in the second cycle of FD implementation (PFRA and FHRM phases) to find the maximum accumulated rainfall and accumulated streamflow in the case of climate change implementation in different countries.

Table 5. Starting hypotheses for maximum rainfall and accumulated streamflow.

		The UK	Germany	The Netherlands	Spain
CURRENT CLIMATE	Return period of maximum daily rainfall	Different return periods considered	100 years	Different return periods considered (10, 100, and 1000)	100 years
	Greenhouse gas emission scenario	Scenario +2 °C and +4 °C (Regionalized RCP to the UK)	RCP 8.5, RCP 4.5, and RCP2.5	RCP 8.5 and RCP 4.5	RCP 8.5 and RCP 4.5
	Control period interval	1961–1990 or 1981–2001	1971–2000	1981–2010	1951–2005 or 1971–2005 (depending on model)
	Source of information	Projections UKCP09	Regional projections of the EURO-CORDEX project in the control period	IPCC 2013; global projections and own studies of KNMI	12 regional projections of the EURO-CORDEX project in the control period
FUTURE CLIMATE	Future horizon to place projections	2020–2050–2080	2021–2050 and 2071–2100	2050–2085 or 2100	2041–2070
	Projections to simulate climate dynamics	Projections UKCP09	Regional projections of the EURO-CORDEX project in the control period	IPCC 2013; global projections and own studies of KNMI	12 regional projections of the EURO-CORDEX project in the control period to the future

As stated in this report, the uncertainty of the process is essential due to the uncertainty inherent in climate change scenarios and the limitations of available databases [84]. Thereby, the climate projections on which the studies are based are different due to the regionalization considered by each country. There are significant variations in the precision of these regionalizations: In Spain, twelve combinations of global and regional climate models (GCM-RCM) from the EURO-CORDEX project [72] were used for the study with a cell width of approximately 12.5 km; in the UK, local studies used 2.2 km cell climate projections. The uncertainty generated in this regard will therefore depend on this accuracy. Countries with significant climatic variations within their territory such as Spain are significantly influenced by this parameter. As technology advances and new regionalizations and local studies are carried out with higher precision, this type of uncertainty will decrease.

Other significant sources of uncertainty are the accuracy of the DTM model used and the hydrologic–hydraulic model used. For instance, despite using adequate DTM model precision in Spain, another significant source of uncertainty is the use of a simplified hydrological model (streamflow in a steady state), instead of a hydrodynamic model with a higher accuracy, as in other countries (the Netherlands, for example).

The increases in river flows and sea level rise calculated for the return periods considered were calculated for the RCP scenarios in Table 5 by the studied countries. However, Spain uses these levels to identify APSFRs, and not for the preparation of the FHRM. The use of these parameters would lead to a better characterization of the areas exposed to flood risk. Other countries such as England or Germany have already considered the influence of climate change on FHRM from the first cycle of FD implementation.

Currently, to reduce global uncertainty, new strategies are being contemplated that consider different scenarios (climatic and non-climatic). An example can be found in the Netherlands. In Spain, these scenarios are also considered, but only to analyze the flood risk and the territory's vulnerability due to coastal flooding. These strategies suggest changes toward flood management focused on risks (Project VNK2 in the Netherlands)

and increasing the territory's resilience (large-scale retention measures to improve the supra-regional flood prevention in Germany).

4. Discussion and Conclusions

Although climate change is a critical factor in flood patterns, the approach used to include it in the FD implementation varies for each European Member State. One of the main causes of this is the different tradition due to (1) different orography and climatology, (2) organization through different institutions and instruments of government, and (3) different population development and technological progress. Therefore, the evolution of the methodology followed by each country is a complex process that depends on the factors above-mentioned. At present, this fact complicates the implementation of common methodological aspects in the different countries.

In this bibliographic research work, the authors carried out a semi-systematic analysis of regulation and “gray” and academic literature related to how CC is included in FD implementation by four European Member States. Thereby, the research shows how the different countries have had a traditional approach to flood management based on prevention and defense. This approach involves predicting the extent of future floods by considering the effects of climate change as accurately as possible.

The analysis of the implementation of the Flood Directive every six years implies a continuous review of the knowledge of climate change and a long-term trend. The global uncertainty associated with these predictions is high and is caused by various sources presented in the article, among which are:

The starting point for developing the different methodologies are the IPCC's climatic scenarios and the global climatic projections. The uncertainty associated is hard to quantify.

Each country develops its methodology based on its own regional climate projections, DTMs, and hydrological–hydraulic models that differ from one country to another and, even within each country, from a basin organization to another. In these aspects, a reduction in uncertainty could be achieved through current and future technological development (higher precision of projections, DTM, and hydrological–hydraulic models).

In the last years, each of the studied countries have developed an own flood management strategy based on reducing risk and decreasing the territory's vulnerability, thus achieving greater resilience.

Therefore, it can be concluded that, although climate change consequences are still not known enough, it is necessary to develop some climate change prediction models to reduce the uncertainty and to improve the accuracy of the hydrological–hydraulic models. To this effect, a key factor is the dissemination of current research findings. The implementation of the FD has achieved some transfer of knowledge and technology, for example, urging the countries to coordinate their risk planning for international basins. Other ways of performing this diffusion of knowledge could be the financing of joint European projects such as the EUROCORDEX Project, the implementation of open information platforms such as CIRCABAC, or the financing of the transnational mobility of researchers. In this way, an effective exchange of research findings would be achieved, jointly advancing knowledge about climate change.

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Abbreviations

The following acronyms are used in this manuscript:

APSFR	Areas of Potential Significant Flood Risk
BfG	Federal Institute of Hydrology of Germany
CC	Climate Change
CCF	Climate Change Factor
CEDEX	Center for Public Works Experimentation Studies
CIRCABAC	Communication and Information Resource Center for Administrations Businesses and Citizens
CIS	Common Implementation Strategy
DTM	Digital Terrain Model
EA	The Environment Agency (UK)
FD	Flood Directive
FHRM	Flood Hazard and Flood Risk Maps
FM	Flood Management
FRM	Flood Risk Management
FRMP	Flood Risk Management Plans
GCM	Global climate models
GDHI	Gross disposable household income
GDP	Gross domestic product
GIS	Geographic Information System
GMSL	Global mean sea level
GVA	Gross value added
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control Directive
KNMI	The Royal Netherlands Meteorological Institute, “Koninklijk Nederlands Meteorologisch Instituut”
LAWA	German Working Group on water issues of the Federal States, “Länder-Arbeitsgemeinschaft Wasser”
MITECO	Ministry to the ecological transition and demographic challenge, “Ministerio para la transición ecológica y reto demográfico”
NHWSP	German National Flood Protection Program
PFRA	Preliminary Flood Risk Assessments
RCM	Regional climate models
RCP	Representative Concentration Pathways
RWS WVL	Ministry of infrastructure and Water Management “Rijkswaterstaat Water, Traffic and Environment”
STOWA	Foundation for Applied Research Water Management, “Stichting Toegepast Onderzoek Waterbeheer”
UKCP09	UK regional climate projections 2009
UKCP18	UK Climate Projections 2018
WFD	Water Framework Directive

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