Adaptation strategies to offset rising river flood risk in Europe

Supplementary Information

Summary

S1. Additional details on Methods

Table S1. Regional climate projections used in river flood impact analysis and corresponding year of exceeding 1.5, 2 and 3°C warming. Years are calculated using a 30-year moving average of surface air temperature. For the description of the climate models see Jacob et al. (2014).

RCM (R)	Driving GCM (G)	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
		1.5 °C		2 °C		3 °C	
CCLM4.8-17	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044		2067
	ICHEC-EC-EARTH	2033	2026	2056	2041		2066
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044		2067
HIRHAM5	ICHEC-EC-EARTH	2032	2028	2054	2043		2065
WRF331F	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035		2054
RACMO22E	ICHEC-EC-EARTH	2032	2026	2056	2042		2065
RCA4	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044		2067
	ICHEC-EC-EARTH	2033	2026	2056	2041		2066
	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035		2054
	MOHC-HadGEM2-ES	2021	2018	2037	2030	2069	2051
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044		2067

Table S2. Adaptation measures considered in the analysis.

Adaptation measure	Description
Strengthening of dyke systems	Strengthening of dyke systems (DS) consist of elevating river banks through permanent or temporary barriers to increase the maximum streamflow that the watercourse can fully contain and convey downstream without causing damage. Depending on the area, this measure may require building new dykes or increasing the height of existing dykes and barriers. Different typologies of dykes can be used depending on the context (e.g. urban or rural areas), ranging from earthen embankments to vertical floodwalls (Aerts, 2018). In our analysis, we consider only the construction of permanent barriers.
Retention areas	Retention areas (RA) aim at reducing flood hazard by reducing and delaying peak flows during extreme events. This is achieved by creating areas within or aside the river network that can be flooded in a controlled manner when the river stage reaches critical levels (Arrighi et al. 2018). We do not consider here retention reservoirs created by dams as they require larger investments and can have negative environmental implications (Kundzewicz, 1999). Beyond direct flood protection, this measure are used for restoration of floodplain ecosystems.

Flood-proofing measures	Flood-proofing measures (FP) represent structural and non-structural modifications of buildings in order to prevent or minimize flood damage to structures and/or their contents. Dry flood proofing aims at making a building impermeable to floodwaters up to the expected floodwater height. Conversely, wet flood proofing measures allow flooding of the structure and reduce damages by means of flood-adapted use and equipment of buildings. An example of wet flood proofing is the adaption of the interior fitting, which means that in endangered storeys only waterproofed building material and movable small interior decoration and furniture are used. Dry flood proofing measures include adjusting the building structure, e.g. via an elevated configuration or waterproof sealing of the cellar (Gersonius et al., 2008).
Relocation	Relocation (RE) reduces the exposure of people and assets at risk of flooding by moving them to areas with negligible risk (King et al. 2014). In our analysis, we assume that relocation operations include the demolishing of existing buildings, the acquisition of new land and the reconstruction of new buildings. We do not consider relocation for agricultural areas and infrastructures such as roads.

S2. Supplementary results

Table S3. Summary of the expected annual damage (EAD) in million € (2015 values) and population exposed (EAPE) in thousand people for all the countries of the study area under present conditions (base), and for the year 2100 under future socioeconomic conditions and climate scenarios (1.5°C, 2°C, 3°C warming).

	EAD				EAPE			
Country	**base**	**1.5°C**	**2°C**	**3°C**	**base**	**1.5°C**	**2°C**	**3°C**
Austria	257	687	772	1054	3.8	5.9	6.6	8.8
Belgium	209	662	945	1453	3.9	9.1	12.7	19.4
Bulgaria	81	172	219	314	2.8	1.9	2.5	3.5
Croatia	169	496	700	966	4.4	7.2	10.6	16.2
Cyprus	4	7	7	5	0.0	0.0	0.0	0.0
Czechia	396	1008	1267	1860	6.8	10.1	12.5	18.3
Denmark	14	37	50	79	0.1	0.2	0.3	0.4
Estonia	53	106	148	196	0.8	0.9	1.2	1.6
Finland	253	517	810	1069	3.7	3.7	5.5	7.8
France	1246	4299	6190	7309	21.9	51.9	76.8	87.7
Germany	895	2665	3784	5508	27.7	43.8	61.6	92.4
Greece	73	101	140	202	1.7	1.8	2.4	3.4
Hungary	252	755	1093	1937	6.5	9.7	13.7	23.3
Ireland	58	180	232	477	0.9	1.6	2.1	4.0
Italy	817	2232	2667	4179	18.2	31.0	36.6	56.2
Latvia	211	438	588	721	4.1	2.8	3.8	4.8
Lithuania	104	210	261	352	1.3	1.0	1.2	1.7
Luxembourg	19	56	84	102	0.1	0.4	0.6	0.7
Netherlands	77	257	514	670	1.6	2.9	5.8	7.6
Poland	558	1305	1665	2562	18.7	20.8	26.7	41.1
Portugal	53	78	79	76	0.8	1.1	1.1	1.1
Romania	329	795	1100	1639	12.5	12.6	16.1	22.4
Slovakia	139	390	484	704	3.1	3.8	4.8	7.0
Slovenia	55	140	195	295	1.0	1.4	1.9	2.9
Spain	449	903	938	961	11.1	17.1	17.5	17.6
Sweden	228	788	1575	2979	2.0	4.7	8.5	15.4
UK	631	1944	2629	4359	8.0	17.3	24.3	42.2
EU-27 + UK	**7631**	**21228**	**29136**	**42028**	**167.7**	**264.7**	**357.4**	**507.5**

Table S4. Differences in flood impacts under the 3°C warming scenario, assuming 2100 socio-economic conditions in respect to present-day conditions. Impacts are given at country level and for EU27+UK as expected annual damage (EAD) and population exposed (EAPE).

	Difference in impacts between 2100 and present-day society - 3.0°C scenario	
Country	**EAD**	**EAPE**
Austria	90%	9%
Belgium	94%	41%
Bulgaria	61%	-46%
Croatia	65%	0%
Cyprus	77%	207%
Czechia	70%	-1%
Denmark	72%	-1%
Estonia	59%	-11%
Finland	77%	-1%
France	77%	22%
Germany	52%	-19%
Greece	23%	-7%
Hungary	69%	-20%
Ireland	95%	15%
Italy	68%	6%
Latvia	75%	-41%
Lithuania	52%	-37%
Luxembourg	91%	142%
Netherlands	78%	1%
Poland	57%	-22%
Portugal	38%	35%
Romania	59%	-24%
Slovakia	59%	-27%
Slovenia	59%	-18%
Spain	75%	35%
Sweden	96%	64%
UK	84%	32%
EU-27 + UK	71%	-2%

Table S5. Overview of two adaptation strategies (retention areas and dikes strengthening) at country level for the 1.5°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100.

	Retention areas				Dikes strengthening			
Country	BCR	EAD red.	EAPE red.	Costs €M/y	BCR	EAD red.	EAPE red.	Costs €M/y
Austria	2.5	72%	72%	75.0	1.9	49%	47%	63.8
Belgium	3.6	81%	80%	55.8	2.5	76%	75%	72.0
Bulgaria	2.2	64%	65%	15.2	1.9	14%	17%	3.3
Croatia	2.5	90%	89%	60.4	1.5	49%	47%	49.8
Cyprus	0.0	0%	0%	0.0	0.0	0%	0%	0.0
Czechia	3.6	81%	81%	71.7	2.1	53%	53%	79.1
Denmark	2.9	81%	81%	4.3	1.2	31%	33%	3.1
Estonia	0.9	31%	31%	5.3	1.1	41%	44%	6.8
Finland	2.3	51%	42%	41.9	2.0	26%	19%	22.6
France	2.8	77%	79%	447.7	2.0	52%	58%	400.8
Germany	3.3	66%	64%	220.8	2.3	53%	52%	245.6
Greece	2.2	56%	58%	9.3	0.6	6%	8%	1.2
Hungary	2.3	73%	73%	70.7	2.0	28%	26%	26.6
Ireland	2.2	63%	62%	19.2	1.6	33%	31%	12.4
Italy	4.2	80%	83%	181.3	2.3	57%	61%	233.9
Latvia	3.5	44%	50%	22.3	1.7	49%	54%	33.7
Lithuania	2.7	25%	25%	8.7	0.8	10%	10%	3.7
Luxembourg	3.5	83%	84%	5.7	2.6	81%	80%	7.0
Netherlands	3.8	34%	31%	7.6	2.6	42%	38%	12.1
Poland	1.9	48%	48%	109.0	1.5	11%	11%	28.5
Portugal	2.7	9%	8%	0.9	1.7	6%	3%	0.7
Romania	2.1	41%	43%	44.8	1.8	17%	11%	19.4
Slovakia	2.9	76%	75%	34.2	2.8	39%	37%	19.5
Slovenia	2.0	74%	72%	16.5	1.5	33%	34%	9.2
Spain	1.9	24%	23%	43.2	1.8	8%	5%	14.9
Sweden	2.7	54%	51%	53.8	3.6	39%	34%	37.3
United Kingdom	5.4	86%	84%	122.4	2.6	74%	71%	216.3
EU+UK	**3.2**	**68%**	**67%**	**1772**	**2.3**	**46%**	**45%**	**1645**

Table S6. Overview of two adaptation strategies (flood proofing of buildings and relocation) at country level for the 1.5°C warming scenario in 2100. Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100.

	Flood proofing			Relocation			
Country	BCR	EAD red.	Costs €M/y	BCR	EAD red.	EAPE red.	Costs €M/y
Austria	6.2	0.0%	0.0	0.0	0.0%	0.0%	0.0
Belgium	29.0	0.0%	0.0	0.0	0.0%	0.0%	0.0
Bulgaria	2.0	0.2%	0.1	0.5	0.0%	0.0%	0.0
Croatia	2.1	0.3%	0.3	0.0	0.0%	0.0%	0.0
Cyprus	0.0	0.0%	0.0	0.0	0.0%	0.0%	0.0
Czechia	2.6	0.2%	0.5	3.4	0.0%	0.0%	0.0
Denmark	0.2	0.1%	0.0	0.0	0.0%	0.1%	0.0
Estonia	114.7	0.7%	0.2	186.9	0.1%	0.1%	0.0
Finland	2.9	0.3%	0.4	23.0	0.0%	0.1%	0.0
France	2.9	0.1%	1.6	4.1	0.0%	0.0%	0.1
Germany	4.2	0.1%	0.3	5.9	0.0%	0.0%	0.1
Greece	3.0	0.4%	0.1	2.8	0.1%	0.0%	0.0
Hungary	40.1	0.0%	0.0	1.4	0.0%	0.0%	0.0
Ireland	1.6	0.3%	0.2	40.5	0.0%	0.1%	0.0
Italy	2.0	0.4%	2.1	70.2	0.0%	0.0%	0.0
Latvia	2.6	0.4%	0.4	8.0	0.0%	0.0%	0.0
Lithuania	8.3	0.2%	0.1	79.0	0.1%	0.1%	0.0
Luxembourg	0.3	0.2%	0.1	0.0	0.0%	0.0%	0.0
Netherlands	0.0	0.0%	0.0	0.0	0.0%	0.0%	0.0
Poland	5.6	0.1%	0.1	4.8	0.0%	0.1%	0.0
Portugal	5.2	0.3%	0.0	5.8	0.2%	0.2%	0.0
Romania	2.7	0.6%	0.7	2.0	0.1%	0.0%	0.1
Slovakia	2.6	0.0%	0.0	0.0	0.0%	0.0%	0.0
Slovenia	3.8	0.2%	0.0	0.0	0.1%	0.1%	0.0
Spain	3.1	0.9%	1.2	3.3	0.4%	0.2%	0.4
Sweden	3.1	5.4%	9.3	5.0	0.1%	0.1%	0.1
United Kingdom	3.4	7.2%	25.7	1.9	0.2%	0.1%	0.5
EU+UK	**2.3**	1.1%	43	2.9	0.1%	0.0%	1.3

Table S7. Overview of two adaptation strategies (retention areas and dikes strengthening) at country level for the 2°C warming scenario in 2100. Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100.

	Retention areas				Dikes strengthening			
Country	BCR	EAD red.	EAPE red.	Costs €M/y	BCR	EAD red.	EAPE red.	Costs €M/y
Austria	2.5	72%	75%	75.0	1.9	49%	53%	63.8
Belgium	3.6	81%	85%	55.8	2.5	76%	77%	72.0
Bulgaria	2.2	64%	73%	15.2	1.9	14%	29%	3.3
Croatia	2.5	90%	92%	60.4	1.5	49%	64%	49.8
Cyprus	0.0	0%	0%	2.0	0.0	0%	0%	0.0
Czechia	3.6	81%	84%	71.7	2.1	53%	58%	79.1
Denmark	2.9	81%	86%	4.3	1.2	31%	46%	3.1
Estonia	0.9	31%	55%	5.3	1.1	41%	62%	6.8
Finland	2.3	51%	59%	41.9	2.0	26%	44%	22.6
France	2.8	77%	86%	447.7	2.0	52%	71%	400.8
Germany	3.3	66%	73%	220.8	2.3	53%	63%	245.6
Greece	2.2	56%	67%	9.3	0.6	6%	28%	1.2
Hungary	2.3	73%	81%	70.7	2.0	28%	43%	26.6
Ireland	2.2	63%	71%	19.2	1.6	33%	40%	12.4
Italy	4.2	80%	85%	181.3	2.3	57%	68%	233.9
Latvia	3.5	44%	63%	22.3	1.7	49%	66%	33.7
Lithuania	2.7	25%	26%	8.7	0.8	10%	23%	3.7
Luxembourg	3.5	83%	89%	5.7	2.6	81%	87%	7.0
Netherlands	3.8	34%	50%	7.6	2.6	42%	62%	12.1
Poland	1.9	48%	58%	109.0	1.5	11%	21%	28.5
Portugal	2.7	9%	8%	0.9	1.7	6%	3%	0.7
Romania	2.1	41%	52%	44.8	1.8	17%	21%	19.4
Slovakia	2.9	76%	80%	34.2	2.8	39%	44%	19.5
Slovenia	2.0	74%	77%	16.5	1.5	33%	47%	9.2
Spain	1.9	24%	28%	43.2	1.8	8%	7%	14.9
Sweden	2.7	54%	73%	53.8	3.6	39%	60%	37.3
United Kingdom	5.4	86%	88%	122.4	2.6	74%	79%	216.3
EU+UK	**3.8**	75%	74%	2155	2.8	58%	56%	**2258**

Table S8. Overview of two adaptation strategies (flood proofing of buildings and relocation) at country level for the 2°C warming scenario in 2100. Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100.

	Flood proofing			Relocation			
Country	BCR	EAD red.	Costs €M/y	BCR	EAD red.	EAPE red.	Costs €M/y
Austria	4.5	0.1%	0.3	0.1	0.0%	0.0%	0.0
Belgium	16.2	0.2%	0.6	1.3	0.0%	0.0%	0.0
Bulgaria	1.7	1.0%	0.5	0.9	0.1%	0.0%	0.0
Croatia	2.1	0.3%	0.5	0.1	0.0%	0.0%	0.0
Cyprus	0.0	0.0%	0.0	0.0	0.0%	0.0%	0.0
Czechia	2.2	2.1%	6.1	3.4	0.1%	0.0%	0.1
Denmark	0.5	0.3%	0.1	0.0	0.0%	0.1%	0.0
Estonia	11.4	13%	2.0	333.2	0.1%	0.1%	0.0
Finland	7.9	5.9%	8.6	21.7	0.2%	0.2%	0.2
France	2.3	0.6%	9.2	4.3	0.0%	0.0%	0.1
Germany	3.0	0.3%	3.1	6.2	0.0%	0.0%	0.1
Greece	3.8	0.9%	0.3	2.6	0.2%	0.0%	0.0
Hungary	29.5	0.3%	1.0	5.0	0.0%	0.0%	0.0
Ireland	1.7	0.5%	0.4	42.4	0.0%	0.1%	0.0
Italy	1.9	0.9%	6.1	52.0	0.0%	0.0%	0.1
Latvia	2.9	23%	27.7	6.4	0.1%	0.0%	0.0
Lithuania	6.8	0.7%	0.5	71.8	0.1%	0.1%	0.0
Luxembourg	0.8	0.6%	0.2	0.0	0.0%	0.0%	0.0
Netherlands	0.0	0.0%	0.0	0.0	0.0%	0.0%	0.0
Poland	4.2	0.2%	0.6	5.4	0.0%	0.1%	0.0
Portugal	6.2	0.3%	0.0	5.8	0.2%	0.3%	0.0
Romania	2.9	1.1%	1.6	2.0	0.5%	0.1%	0.7
Slovakia	3.1	0.0%	0.0	0.3	0.0%	0.0%	0.0
Slovenia	3.6	0.3%	0.1	0.5	0.1%	0.1%	0.0
Spain	3.0	2.8%	4.7	3.4	0.5%	0.4%	0.5
Sweden	2.9	45%	80.1	4.1	11%	9.3%	23.7
United Kingdom	2.9	15%	92.4	2.1	0.2%	0.1%	0.6
EU+UK	**2.6**	**5.0%**	**247**	**2.1**	**0.7%**	0.3%	**27**

S3. Database of flood protection levels

Reliable information on flood protection levels is crucial for a correct estimation of river flood risk. In Europe, detailed descriptions of protection structures (i.e. type, location, geometry, design parameters) are usually available only for limited areas, while information on the design level of protection can be found for a few countries and urban areas (Scussolini et al., 2016, Dottori et al., 2017). Recent studies tried to overcome these limitations by developing empirical functions for estimating protection levels where information is not available. Jongman et al. (2014), estimated protection levels in Europe according to modelled flood risk, assigning higher protection in areas with higher risk. Scussolini et al. (2016) combined reported protection levels (based on technical reports and policy recommendations) with modelled values, interpolated at local administrative level according to gross domestic product. In several countries in Europe, these two datasets propose substantially different protection levels, especially in Northern and Eastern Europe.

The reliability of estimating protection levels through proxy variables has been questioned. In a recent study carried out in United Stated, Wing et al., (2019) did not find any clear link between protection standards and variables such us degree of urbanization, gross domestic product, population density and land use. On the other hand, according to Jongman et al (2014) major European river watersheds such as the Rhine and the Danube maintain higher levels of protection in densely populated areas than in rural areas.

For the present study, we developed a new dataset of flood defence standards. The dataset is built combining different sources of information on protection levels, using modelled and observed flood losses to select the most plausible protection levels for each country in geographical Europe (excluding Russia, Belarus, Ukraine, and countries in the Caucasus).

The following set of rules dictate the hierarchal flood protection standards used in the dataset:

- Highest priority is given to information about design protection levels, where available from either official reports or scientific publications. To this end, we used the information collected by Scussolini et al (2016), integrated with additional reported data from literature review.
- Elsewhere, the level of flood defence is determined at country scale. We used the flood risk modelling framework described in this work to calculate multiple flood loss scenarios, using the two datasets of protection standards currently available for all Europe (Jongman

et al., 2014; Scussolini et al. 2016) and a range of uniform protection values at country scale.

- In countries where national-scale flood loss assessments are available (either from technical reports, scientific publications, or loss datasets such as EM-DAT (2019), the NatCatService (Munich-RE, 2018) and HANZE (Paprotny et al., 2018)), we selected from the multiple flood loss scenarios the protection values that provide the closest match with national-scale flood losses;
- In countries where all modelled flood loss scenarios exceed 200% of reference loss data, we used a uniform national value between 50 and 150 years. We did not use higher protection levels to avoid unrealistic values in countries where modelled losses are far from reports (e.g. Scandinavian countries), or where few reported data are available, due to the limitations of both the modelling framework and reported data (see Section S4 for a discussion).

Note that the selection of protection levels is carried out at the country scale because flood losses from observations are mostly reported at national level. The map in Figure S1 shows the distribution of protection levels across Europe, while Table S9 compares reported and modelled losses.

S4. Reliability and uncertainty of the modelling components

Modelling present and future river flood impacts at continental scale requires inevitable simplifications, which limit the accuracy of results. Furthermore, there is substantial uncertainty pertaining to models and datasets representing hazard, exposure and vulnerability, especially when used for projecting future scenarios (Dottori et al., 2018). Alfieri et al. (2016) applied a modelling framework comparable to the present work to model the impacts of major flood events that occurred in Europe since 1990, and found that recorded impacts could be adequately reproduced. However, they did not investigate in detail the skill of the single modelling components. In this Section we discuss the main sources of uncertainty of the modelling framework, we review previous validation exercises of the modelling components, and we present additional validation results regarding economic losses

The river flood hazard maps have been evaluated by Dottori et al. (2021) using official hazard maps for Hungary, Italy, Norway, Spain and the United Kingdom. Modelled maps could identify on average two-thirds of reference flood extent, however they also overestimated flood-prone areas for flood probabilities below 1-in-100-year, while for return periods equal or above 500 years the maps could correctly identify more than half of flooded areas.

Figure S1. Distribution of flood protection levels across Europe, expressed as maximum return period of the design flood (in years). Countries not included in the analysis are depicted in dark grey.

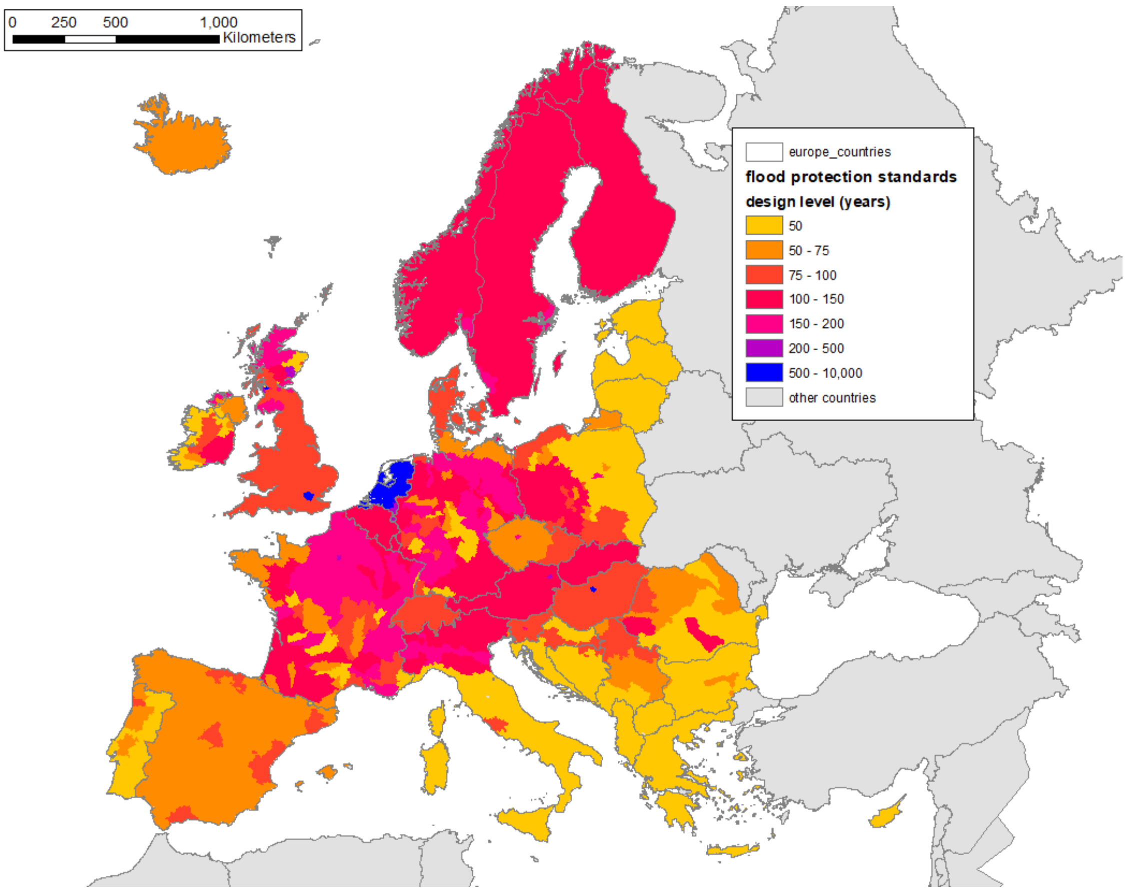

Table S9. Comparison of modelled flood losses against reported data from national reports and loss datasets (HANZE (Paprotny et al., 2018); EM-DAT (2019), the NatCatService (Munich-RE, 2018).

Country	Loss datasets (1990-2015) (million € 2015)			National loss reports (million € 2015)	Modelled losses - (million € 2015)	Notes -references for national reports
	HANZE - river	NatCat Service	EM-DAT			
Albania		5.3	1.2		31.1	

Austria	220.4	232.0	193.1		311.2	
Belgium	11.7	13.0	8.2		256.7	
Bosnia_Herzegovina		48.9	14.5		147.4	
Bulgaria	21.3	51.0	31.2		97.7	
Croatia	19.4	57.3	2.4		260.1	
Cyprus		0.2	0.0		4.1	
Czech_Republic	324.0	332.8	321.8	433-546	501.8	Puncochar 2012; Soukorova and Furova 2012
Denmark	0.0	2.5	0.0		16.5	
Estonia	0.0	0.0	0.0		54.6	
Finland	0.6	0.9	0.0	2.5	193.5	Silander et al 2012
France	262.1	270.3	265.3	664-800	1645.5	Mouncolon et al. 2014; FFA 2015; Richert et al., 2019 (all types of floods included)
North Macedonia	0.0	12.3	11.1		31.3	
Germany	859.9	1011.1	1001.4		1202.4	
Greece	1.8	29.5	59.0		76.9	
Hungary	59.7	47.1	39.5		333.6	
Iceland		0.1	0.0		11.6	
Ireland	12.4	49.0	11.6	97	73.3	OPV 2003
Italy	484.7	1250.7	1075.8		1168.2	
Latvia	0.0	0.0	0.0		218.3	
Lithuania	0.1	0.0	0.0		121.8	
Luxembourg	1.0	0.9	0.5		20.6	
Montenegro		0.5	0.0		17.7	
Netherlands	11.9	76.9	28.9		92.0	
Norway	26.6	14.3	11.2	34	120.5	Berg 2002
Poland	325.2	342.4	340.9	359	697.0	WB 2015
Portugal	0.6	0.2	0.8		55.5	
Romania	123.4	156.7	132.4	894	415.5	MMAP
Serbia		69.5	101.0		284.1	
Slovakia	17.5	34.6	16.9	81	190.6	Zeleňáková and Vranayová
Slovenia	59.1	13.3	8.0	86	76.2	Komelj 2015
Spain	28.7	70.0	60.2	1059	495.3	CCS 2004 (all type of floods)
Sweden	3.4	1.8	0.0		214.7	
Switzerland		207.1	132.8	265	316.5	WSL 2018 (floods and debris flows)
United_Kingdom	375.6	622.5	870.3	2028	863.6	OST 2004 (coastal and river floods)

The use of an ensemble with 22 climate projections aims at characterizing the overall climate uncertainty in the hydrological simulations (Mentaschi et al., 2020). However, the ensemble might still underrepresent the real uncertainty of future climate scenarios (McSweeney and Jones, 2015). Other factors such as the bias correction of climate projections and the spatial resolution of the input data may influence results though probably to a smaller degree (Alfieri et al., 2018). In this work we used a single hydrological model for all future projections, namely the Lisflood model. The skill of LISFLOOD in reproducing observed climate has been extensively validated by Arnal et al. (2019). Using an ensemble of hydrological models might better represent the uncertainty of future hydrological changes, since previous research (Dankers et al., 2014; Dottori et al., 2018) showed that future streamflow and inundation projections are significantly affected by the choice of hydrological and flooding components.

The accuracy of exposure data have been tested in previous studies (Batista e Silva et al., 2018; Rosina et al., 2018), however the 100m resolution used might be insufficient to characterize population and asset exposure in some areas (Smith et al., 2019)

Methods for evaluating economic losses due to floods are a key source of uncertainty in evaluating flood impacts (De Moel and Aerts, 2011). Huizinga et al. (2017) observed that the potential uncertainty of flood damage functions can exceed ± 50%, although this value is in line with the typical accuracy of damage models (De Moel and Aerts, 2011). This is further exemplified by previous applications of damage functions that showed mixed performances when compared with observed damages (Jongman et al., 2012; Amadio et al., 2019).

Flood protection standards are possibly the most relevant source of uncertainty in large-scale modelling exercises (Ward et al., 2013). In the present study we have developed a database combining reported and modelled protection levels from different sources (see Supplement). However, the overall confidence about flood protection estimates is highly variable across Europe, and in particular it is lower in Eastern Europe countries, due to the lack of information.

In Supplementary Table S9 we provide a further evaluation of country-scale results by comparing modelled annual average economic losses against reported losses retrieved from numerous sources. We find that in a number of countries (such as Czech Republic, Germany, Italy, and United Kingdom) the modelled losses are within 50% of maximum reported losses. In total, these countries account for more than 50% and 70% of, respectively, overall modelled and reported losses. Conversely, losses appear largely overestimated (i.e. more than 100%) in France, in Scandinavian countries (Denmark, Sweden and Finland), as well as in several medium-small countries (e.g. Belgium, Bulgaria, Croatia, Latvia, Lithuania).

While the mentioned limitations of the modelling framework can explain the gap between modelled and reported data, it is important to note the differences between loss data from different sources. On the one hand, national-scale studies report larger losses than European and global scale datasets, as observed in previous studies. A comparison of national disaster loss databases with EM-DAT loss data showed that total losses can be up to 60% higher, due to the fact that extensive losses from high-frequency, low-severity events are not accounted for (UNISDR 2015). This suggests a lower confidence of risk estimates where no national loss data are available. On the other hand, some national loss reports include impacts due to flash floods, coastal floods or dike failure events, which are not considered in our modelling framework. Where possible, we considered only reported losses attributed to river flooding. In Southern and Central European countries such as France, Greece, Italy and Spain, the contribution of flash floods to overall flood impacts is considerable and might equal the share due to river floods (Paprotny et al., 2018).

Accurate modelling of historical loss data is further complicated by the temporal and spatial variability of risk components over the period of observations (Paprotny et al., 2018), whereas modelled losses assume fixed exposure and vulnerability. In addition, reported losses refer to specific time periods, so the estimated average annual loss is influenced by the frequency of events that can vary significantly depending on the period. Finally, our modelling framework does not consider the possibility of failure of protection measures.

Uncertainty related to cost-benefit analysis

We based our cost-benefit analysis on optimizing each adaptation measure separately at NUTS2 region level (DS and RA measures) or over a 5km grid (FP and RE measures). Furthermore, On the one hand, using uniform design levels may be not ideal since exposure can be highly variable within each NUTS2 and 5km region and therefore protection measures may be needed only in certain parts of a region, such as in urban and densely populated areas. This is especially true for measures based on exposure and vulnerability reduction (i.e. relocation and damage reduction measures), for which cost/benefit analysis can be applied even at building scale. For instance, a recent analysis carried out in United States found an average BCR of 6.5 for targeted relocation of residential houses (MHMC 2019), whereas we considered for relocation all built-up areas located within the 1-in-500-year flood extent.

On the other hand, the resolution of data and models applied in this study is strongly limited by the continental scale of the analysis. For instance, additional tests considering relocation only for built-up areas located within the 1-in-50-year flood extent did not show significant changes at European and country scale in terms of cost-benefit analysis.

Moreover, having different protections standards for nearby regions may pose problems in the implementation of measures based on hazard reduction (i.e. dykes strengthening and retention areas), which require more uniform levels of protection along the river network.

The outcomes of the adaptation analysis are sensitive to the parameters used to determine costs and benefits. We used average cost values and implementation parameters (Table 2), however these vary widely among studies. For instance, studies report higher costs of raising dykes in urbanized areas (Aerts, 2018). Descriptions of flood proofing measures report variable costs according to the type of measure (e.g. wet or dry proofing, elevation), the attainable damage reduction and the level of hazard (e.g. protection up to 1m of water depth). For relocation, implementation costs are largely dependent on building parameters (e.g. number of dwellings and storeys, market value of acquired land and relocated buildings) which are not available at EU scale.

Additional simulations using increased construction and maintenance costs (not shown here) showed that all adaptation strategies bar relocation are still cost-effective in the majority of countries and NUTS regions, even though with lower impact reduction rates .

The outcomes are also sensitive to discounting, which gives more weight to present capital costs and downgrades the benefits that will mostly come later in the century. We used discount rates in line with the EC Guide to Cost-Benefit Analysis of Investment Projects (EC, 2014) that were assumed constant in time. We did not analyse the effect of higher discount values because adaptation measures must be designed for long-term effects, and thus are penalized. Using lower or time-declining social discount rates results in higher cost-effectiveness of all the measures and supports the view that we should act now to protect future generations. As such, in the article we compare impacts under present and future scenarios using undiscounted economic values, in order to highlight the impact reduction provided by the different adaptation strategies (EC 2014). Similarly, adaptation measures are optimised considering the most likely river flow projections in 2100 under the 1.5°C, 2°C and 3°C warming scenarios. Decision makers could select a more conservative criterion and aim to protect against the high-end, less probable future extreme river flows. This would require higher investments but imply less risks for future generations.

S5. SI references

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