

Cost-effective adaptation strategies to rising river flood risk in Europe

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River flood risk in Europe could rise to unprecedented levels due to global warming and continued development in flood-prone areas. Here, we appraise the potential of four key adaptation strategies to reduce flood risk across Europe based on flood risk modelling and cost–benefit analysis. We find that reducing flood peaks using detention areas is economically the most attractive option. In a scenario without climate mitigation (3 °C global warming), they can lower projected flood losses in Europe by 2100 from €44(30–61) billion to €8.1(5.5–10.7) billion per year and lower population exposed by 84% (75–90%) or achieve a risk level comparable to today. The economic investment required over 2020–2100 would provide a return of €4(3.5–6.3) for each €1 invested. The risk reduction potential of strengthening of dykes is somewhat lower, at 70% (59–83%) for a comparable annual investment. Implementing building-based flood proofing and relocation measures is less cost-effective but can reduce impacts in localized areas.

River floods are a major cause of damage in Europe¹. Absolute losses have increased over time mainly due to human encroachment and economic development on flood-prone land that resulted in a strong rise in exposure and loss of natural storage capacity^{2,3}. The numbers of fatalities and economic losses expressed relative to the exposed value and size of the economy, however, have dropped in Europe⁴ as well as other regions of the world⁵. Hence, improved protection against floods has counter-balanced the effects of increasing exposure on risk and resulted in a strong reduction in vulnerability⁶.

It is less clear if, and how, climate change has affected the trend in flood risk. There is no consistent continental-scale climatic change signal in flood discharge observations in Europe⁷, despite a trend towards increasing floods in northwestern Europe and decreasing flood hazard in southern and eastern Europe⁸. However, there is growing consensus that climate change will intensify the hydrological cycle^{9,10} and amplify the intensity and probability of floods in most parts of Europe^{11,12}. Fuelled with continued development and urbanization in floodplains this could give rise to an unprecedented increase in flood risk^{13,14}.

European societies will therefore need to implement effective adaptation strategies to reduce flood hazard, vulnerability or exposure

or to manage the consequences. Considering a range of adaptation measures is essential to find the most effective strategy, limit potential negative environmental effects and avoid maladaptation¹⁵. Among those measures, nature-based solutions have recently gained attention as more environmentally sustainable ways to reduce flood risk¹⁶.

Despite the wide literature on flood risk reduction, relatively few studies have quantified costs and benefits of different measures, typically at local scale^{17–20}. Others analysed the flood risk reduction potential attainable in Europe with different adaptation strategies under future scenarios but they did not quantify implementation costs²¹. Other continental- and global-scale studies focused on increasing dyke height²², considered a generic vulnerability reduction²³ or evaluated residual flood damage for the feasible maximum adaptation level using hardware measures²⁴. However, the effectiveness of nature-based solutions needs to be appraised in large-scale studies.

Here, we present an assessment of the costs and benefits across Europe of four key flood adaptation options: raising dykes, detention areas, flood proofing and relocation. First, flood hazard and risk were projected up to the end of the century for different global warming levels (GWL, 1.5, 2 and 3 °C) assuming present flood protection based on

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a large ensemble of climate projections and long-term socioeconomic projections for the European Union (EU). Each adaptation strategy was appraised using a cost–benefit analysis (CBA) that optimizes the net present value (NPV), which integrates the discounted overall costs of implementation and avoided economic damages over the lifetime of the measure. The costs were calculated as the sum of capital investments and maintenance costs, taken from a database of risk reduction measures based on literature review (Methods). The benefits are the economic damages avoided by implementing the measure, calculated as the difference between future direct damages with and without adaptation, respectively. Compared to ref. ²¹, we propose a realistic framework to simulate costs and physical constraints of implementing each measure (for example, location and dimensioning of detention areas required to reduce flood peaks, as explained in the Methods). Flood losses, costs and benefits are presented undiscounted in general, so that present and future scenarios with and without adaptation can be compared while giving equal weight to each of them. We present the median estimate and interquartile range derived from all the model simulations to represent the uncertainty of flood risk modelling and cost–benefit estimates. More details of the sensitivity analysis are presented in the Methods, with an evaluation of the skill of the modelling components in the Supplementary information.

Future flood risk scenarios

We estimate that at present in the EU and United Kingdom (hereafter, EU + UK), river flooding causes annual damage of €7.6 (5.6–11.2) billion per year and exposes around 166,000 (124,000–276,000) people per year to inundation (Supplementary Tables 3 and 4). In the absence of further climate mitigation (3 °C in 2100) and adaptation (assuming present vulnerability), flood damage would rise to €44 (30–61) billion per year by the end of the century, while annually nearly half-a-million Europeans (370,000–675,000) would be exposed to river flooding (Fig. 1a,b). Climate change is the main driver of the risk increase in most European countries (Supplementary Table 5) with few exceptions in the Mediterranean region (Cyprus, Portugal and Spain), where changes in exposure dominate future flood impacts. Stringent climate mitigation would roughly halve the risk (Supplementary Tables 3 and 4), yet the likelihood that global warming be stabilized at well below 2 °C above pre-industrial levels is low²⁵. This means that adaptation will be needed to offset the projected rise in flood risk.

Adaptation through river dykes

Strengthening protection through dyke systems consists of elevating the river banks, through permanent or temporary barriers, to increase the maximum streamflow that the watercourse can fully contain and convey downstream without causing damage. Investments in dykes is found to be economically convenient to reduce the projected flood impacts on economy and society (Fig. 1 and Table 1). The implementation of the optimal design in the whole study area (EU + UK) for the 3 °C warming scenario would require an annual investment of €3.1 (2.1–4.5) billion per year (average of undiscounted costs over 2020–2100). The corresponding increased levels of protection would lower annual flood damages by 70% (59–83%), a reduction of €30 (23–43) billion per year by the end of the century. Also 350,000 (290,000–530,000) fewer people would be exposed to flooding (Fig. 1 and Table 1). The overall discounted benefit-to-cost ratio (BCR) of the dyke investments ranges from 2.7 to 4.5 with a median value of 3.3. The BCR and impact reduction capacity grow with GWL (Supplementary Tables 7 and 11), showing that adaptation measures targeted at reducing flood hazard become more relevant as global temperature rises.

Strengthening existing dyke systems is cost-effective in most countries of Europe but with considerable variation between countries in risk reduction potential and BCR (Table 1). The median damage reduction potential for single countries ranges from <10% in Cyprus, Greece and Portugal and Spain to 88% in Belgium and the United

Kingdom (Supplementary Table 15 provides IQRs). The large regional differences in risk reduction rate (Fig. 2) is due to the variability in local optimal design option (the degree of implementation locally providing the highest NPV), with no change in design and consequently no damage reduction effect in regions with BCR < 1. In regions with limited projected increase in impacts (for example, in Southern and Eastern Europe; Extended Data Fig. 1), the costs of adaptation are not compensated by avoided impacts. In other regions in Central and Western Europe (for example, the Netherlands), protection standards are already high (Extended Data Fig. 1) and the reduction in residual risk is not enough to make additional dyke heightening economically efficient. Reduction rates in population exposed are broadly similar to those in damages (Supplementary Table 15).

Despite the favourable CBA in most regions of Europe and the fact that limited implementation space is required, an extensive reliance on dyke systems can have socioeconomic and environmental drawbacks. Raising river dykes generally increases the magnitude of peak flows and hence flood risk downstream²⁶. If CBA is based solely on economic values, this can lead to inequality in the spatial distribution of flood risk, prioritizing adaptation in wealthier areas over less developed and rural areas²⁷. The reduction in flood frequency and sense of safety favours further development in flood-prone areas and can paradoxically increase flood risk in the long term^{28,29}. Dykes further distort the natural functioning of wetlands and riparian floodplains due to the lost hydraulic connectivity with the river channel³⁰.

Adaptation through detention areas

We consider here the creation of detention areas within or beside the river network that can be flooded in a controlled manner to store excess water temporarily to reduce peak flows during extreme events^{18,31}. Note that we do not consider here flood control reservoirs and dams for reasons detailed in the Methods. The CBA shows that detention areas can be highly effective to reduce flood risk in Europe. At the EU + UK level, implementing the optimal design for 3 °C warming would require an annual investment of €2.6 (1.9–3.8) billion per year over the period 2020–2100 (undiscounted values), with a BCR of 4.2 (3.5–6.3) (Fig. 1). The resulting storage capacity would reduce flood economic damages by 83% (74–89%) and population exposed by 84% (75–90%) at the end of the century, hence to a risk level that is comparable in absolute terms to that of today. Because detention areas reduce the hazard by attenuating the flood hydrograph they become increasingly effective when flood hazard rises with global warming.

Natural detention areas are economically convenient practically everywhere except for some regions (Fig. 2, regions defined according to the Nomenclature of Territorial Units for Statistics level 2) where projected increases in flood impacts are small (for example, in Portugal, Spain and Greece), where protection standards are high (for example, the Netherlands) and where floodplains are too narrow to accommodate detention areas (for example, Portugal). In general, detention areas show higher BCR values compared with river dykes and their optimal implementation results in a stronger reduction in socioeconomic impacts (Supplementary Tables 1–14). The higher efficacy in reducing flood hazard at regional level occurs because detention areas reduce flood peaks for all downstream river reaches, rather than locally containing it with river dykes. Furthermore, detention areas offer additional benefits not considered in the economic optimization. Reconnecting with rivers restores the natural functioning of floodplains, which improves aquatic and riparian ecosystem quality and provides a range of additional services, such as the reduction of pollutants, regulation of sediment fluxes and recreational opportunities^{32,33}. The monetary evaluation and inclusion of environmental services would further increase the cost-effectiveness of detention areas.

On the other hand, detention areas require the occupation of large portions of land (according to our calculations, the largest areas can exceed 100 km²), which would no longer be available for some land uses

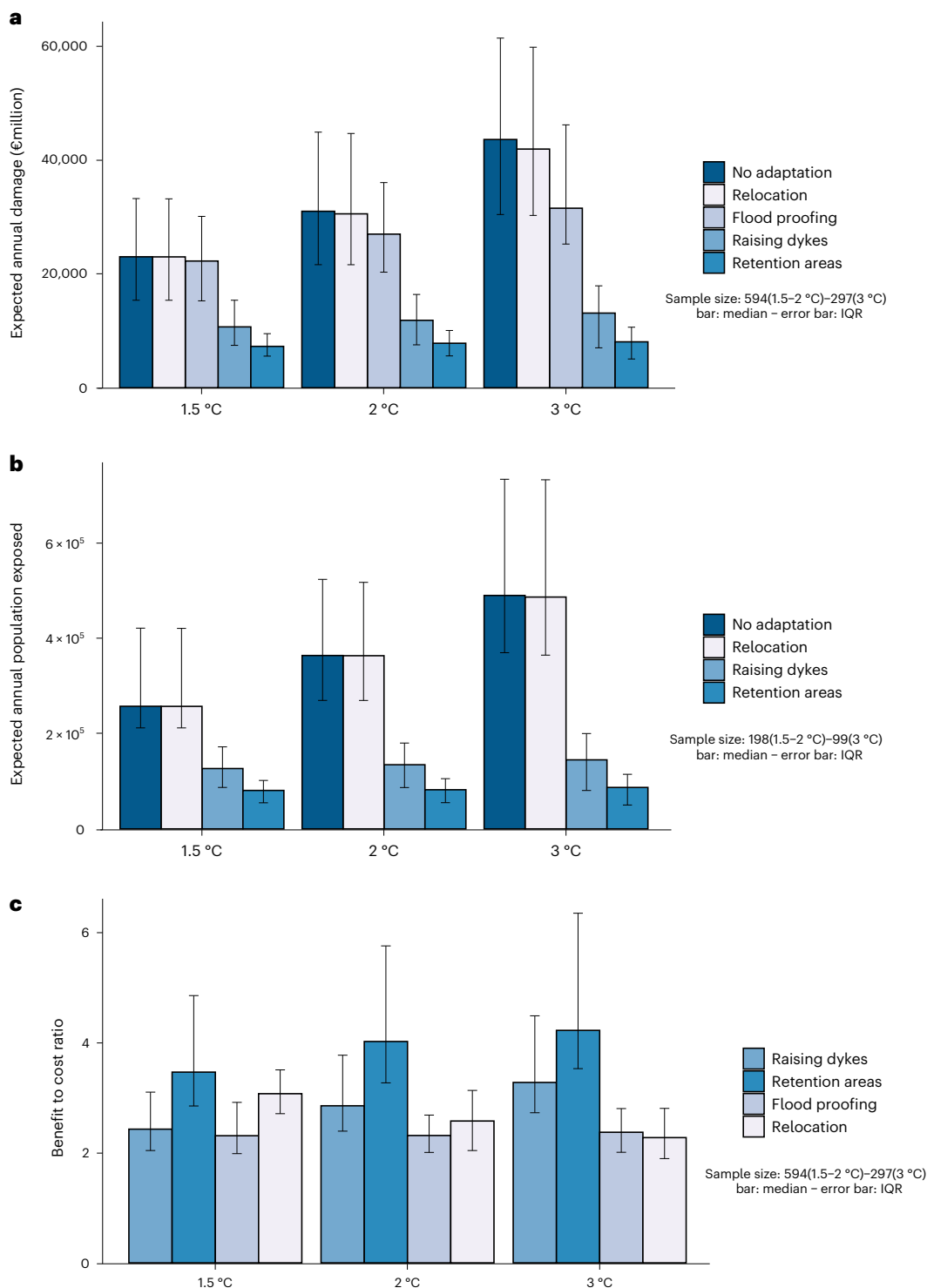


Fig. 1 | Summary of the outcomes for the four adaptation strategies considered under 1.5, 2 and 3 °C warming scenario. a, b, Future undiscounted economic damages (a) and population exposed (b) for the year 2100, calculated under a no-adaptation scenario and optimizing each of the four adaptation

strategies. **c,** The benefit-to-cost ratio calculated from total discounted benefits and costs over the period 2020–2100. Coloured bars and error bars indicate, respectively, the median and the 75th–25th percentiles of the model ensemble. All results are based on averages at EU + UK level. IQR, interquartile range.

(for example, intensive agriculture and urbanization). However, we estimate that even in the most demanding scenario the overall flood-plain area required would be <2% of the overall cropland area in Europe.

It is worth noting that the spatial attribution of costs and benefits of detention areas is more complex than for other measures because the design has to be carried out considering the entire river basin.

This has to be considered when evaluating BCR results at NUTS2 level because areas located downstream benefit from upstream detention areas and hence reduce local implementation costs. Ideally, implementation costs should be shared among all regions within a river basin. Planning in transboundary rivers, such as the Danube, may be complex, although some projects have already been successfully carried out³⁴.

Table 1 | Overview of the four adaptation strategies for the 3°C warming scenario in 2100 at country levels and EU+UK level

Country	Detention areas			Dyke strengthening			Flood proofing			Relocation		
	BCR	EAD reduction	Costs €millionyr ⁻¹	BCR	EAD reduction	Costs €millionyr ⁻¹	BCR	EAD reduction	Costs €millionyr ⁻¹	BCR	EAD reduction	Costs €millionyr ⁻¹
Austria	3.3	83%	88	2.6	70%	104	1.6	0.4%	1.4	0.0	0.0%	0.0
Belgium	4.8	89%	82	3.9	88%	91	1.8	0.3%	1.2	0.0	0.0%	0.0
Bulgaria	3.5	80%	19	2.4	35%	11	1.8	1.5%	1.0	1.3	0.0%	0.0
Croatia	4.0	96%	74	2.1	79%	81	1.8	0.4%	0.6	0.0	0.0%	0.0
Cyprus	0.0	0%	3	0.0	0%	0	0.0	0.0%	0.0	0.0	0.0%	0.0
Czechia	4.9	87%	88	2.9	72%	131	1.9	1.7%	9.1	2.8	0.1%	0.1
Denmark	4.1	92%	6	1.8	64%	8	1.4	1.6%	0.4	0.0	0.0%	0.0
Estonia	1.3	59%	11	2.2	74%	12	2.7	0.6%	0.2	144	0.1%	0.0
Finland	3.7	79%	78	3.2	65%	83	2.4	2.0%	5.3	5.3	0.0%	0.0
France	3.5	86%	544	2.8	74%	634	1.7	0.5%	11.7	4.3	0.0%	0.1
Germany	3.8	80%	383	3.2	74%	454	2.0	0.3%	4.7	4.3	0.0%	0.3
Greece	2.7	69%	13	1.1	2%	1	3.0	0.4%	0.0	2.1	0.2%	0.0
Hungary	3.8	92%	105	3.0	69%	108	1.6	0.3%	1.6	0.0	0.0%	0.0
Ireland	3.5	87%	31	2.7	74%	37	1.7	2.3%	3.2	2.8	0.0%	0.0
Italy	5.3	88%	227	2.9	76%	373	1.9	1.2%	16.2	1.7	0.0%	0.1
Latvia	2.8	56%	39	2.2	71%	50	2.1	0.7%	0.9	3.4	0.0%	0.0
Lithuania	1.8	34%	10	1.6	20%	9	2.1	0.9%	0.5	7.3	0.1%	0.0
Luxembourg	4.0	88%	7	3.4	90%	8	1.2	0.0%	0.0	0.0	0.0%	0.0
the Netherlands	4.5	44%	18	3.7	57%	25	0.0	0.0%	0.0	0.0	0.0%	0.0
Poland	2.6	72%	184	1.8	34%	127	2.1	0.3%	2.2	5.7	0.1%	0.1
Portugal	1.8	7%	1	1.4	5%	1	4.6	0.4%	0.0	5.4	0.2%	0.0
Romania	2.6	63%	91	2.4	44%	77	2.8	1.3%	2.9	2.1	0.6%	1.3
Slovakia	3.9	87%	43	2.6	63%	49	1.8	0.0%	0.0	0.0	0.0%	0.0
Slovenia	2.6	82%	20	1.7	57%	22	2.4	0.4%	0.1	1.8	0.1%	0.0
Spain	2.1	33%	70	1.7	11%	26	3.1	1.3%	2.5	3.3	0.5%	0.6
Sweden	5.7	85%	113	7.6	79%	85	3.5	67%	170	2.4	0.3%	0.6
United Kingdom	9.0	93%	174	4.0	88%	296	2.1	37%	394	2.2	0.2%	1.0
EU+UK	4.2	83%	2,567	3.3	70%	3,093	2.4	16%	1,110	2.3	0.2%	1.0

BCR calculated as ratio of discounted benefits and costs over period 2020–2100. Reduction (in %) in expected annual damage (EAD) calculated as difference in undiscounted damage in 2100 with and without adaptation. Cost of implementation (in €million per year) reflect average of undiscounted costs over period 2020–2100. For each variable, the ensemble median is provided. The IQRs for each variable are provided in Supplementary Tables 14–17.

Adaptation through flood proofing of buildings

A large share of flood losses relates to damage to buildings and their content³⁵. Structural and non-structural modifications can prevent water from entering the building (dry proofing) or reduce damages by means of flood-adapted use and equipment of buildings (wet proofing), thus reducing building and content vulnerability.

Results show that flood proofing of buildings generally has BCR values >1 across Europe (Supplementary Tables 1–16 and Fig. 2). This can be applied at smaller scales and a lower cost compared to hazard-reduction measures such as dykes and detention areas and hence targeted where they are cost-effective (Methods). However, prioritizing only areas with a positive benefit–cost balance may leave several other areas unprotected. Damage reduction measures applied at building scale have a low environmental impact, are relatively easy to implement and can be adapted to changing conditions³⁶. However, they cannot prevent other types of flood damage, such as to transport infrastructure³⁷ or agriculture³⁸. Furthermore, the reduction in damage attainable in Europe is 16% (6–30%), which is considerably lower than for hazard-reduction measures. More

importantly, because floods are not avoided, population exposure is not reduced (Fig. 1c), even though the degree to which people are affected is lowered.

Damage reduction rates with median values >10% are attained only in Sweden and the United Kingdom, due to the high economic exposure and projected increase in flood hazard. In few countries (such as Belgium, the Czech Republic and Spain), flood proofing provides reduction rates >10% in a relevant number of scenarios (as shown by the 75th percentile) because of lower protection standards and the presence of hotspots of exposed assets (Supplementary Table 16). Conversely, BCR values are <1 in the Netherlands, where country-scale high protection standards make flood proofing less likely to be used (Table 1). Overall, findings suggest that the economic convenience of flood proofing measures is more sensitive to uncertainty than hazard-reduction measures. Flood proofing of buildings is effective for protecting areas frequently exposed to low or moderate floods and with high concentration of exposed value and assets³⁹, whereas they are not suited for efficient protection of large areas.

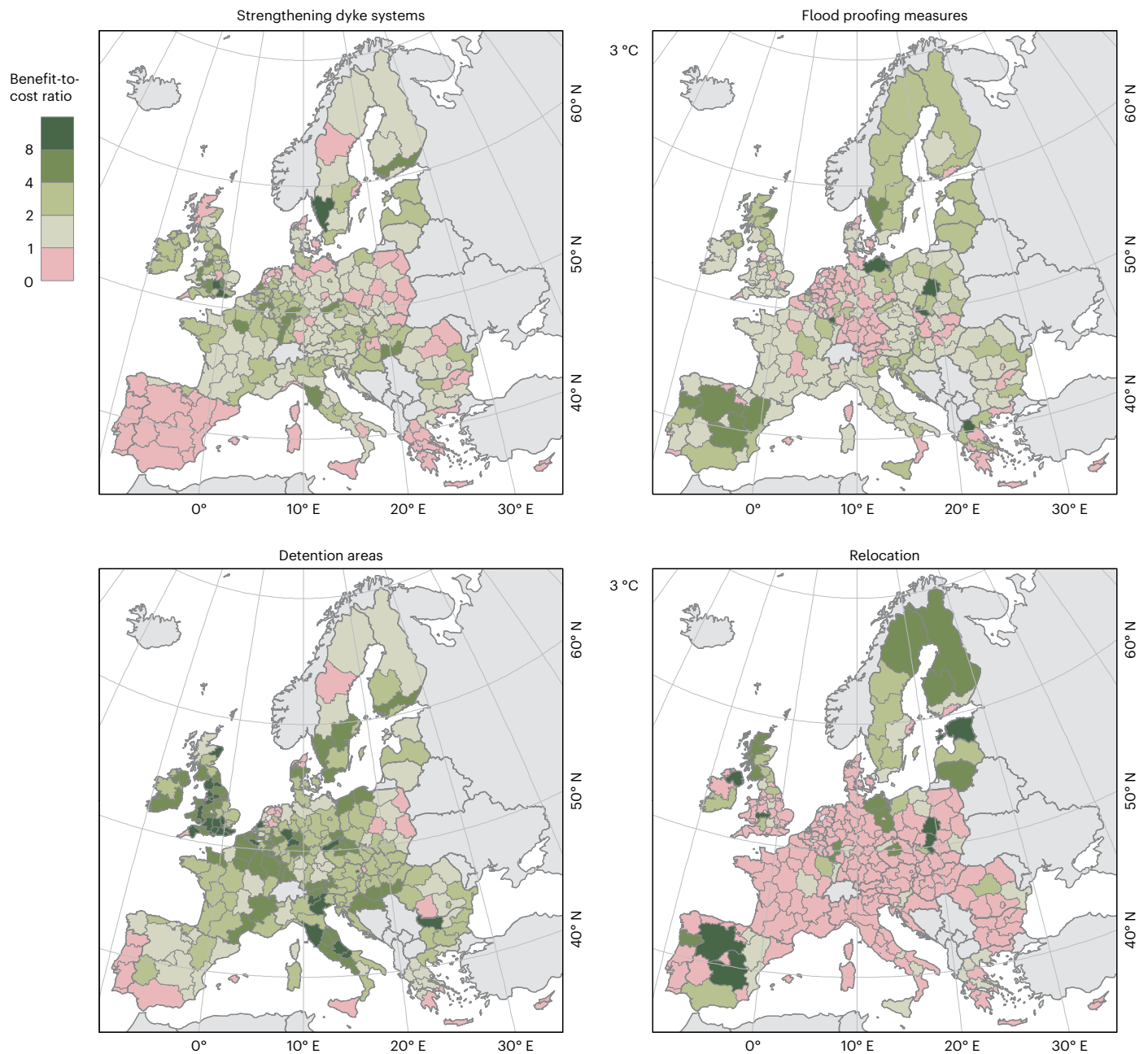


Fig. 2 | BCR at NUTS2 level for the adaptation strategies 'river dykes', 'detention areas', 'flood proofing measures' and 'relocation' for the 3 °C warming scenario. The values refer to the ensemble median. The layout of the maps is adapted from ref. ⁵¹.

Adaptation through relocation

Relocation aims at reducing the exposure of people and assets at risk of flooding by moving them to areas with negligible risk⁴⁰. Managed relocation of individuals, businesses and infrastructure is largely ignored as a possible strategy in the EU national flood risk management policies⁴¹.

The CBA shows that relocation is the least cost-effective measure among all the adaptation measures considered here (Fig. 1). The implementation across the areas with a positive benefit–cost balance would lead to an overall reduction in flood damages of just 0.2% (0.1–0.5%) with a BCR of 2.3 (1.9–2.8), while each year only 600 (200–1,700) fewer people would be exposed to floods. This is because relocation is economically convenient only in a few NUTS2 regions concentrated in the United Kingdom, Spain and around the Baltic region (Fig. 2). Costs of relocation are high as they include the demolishing of existing buildings, the acquisition of new land and the construction of new buildings

and structures. Furthermore, relocating large urban areas would pose additional challenges for identifying suitable settlement areas for relocated assets and people. Indeed, relocated people are generally offered a partial compensation for their properties by the local government⁴², thus suggesting that financial incentives are necessary to promote relocation measures. In regions with BCR values >1, long-term flood economic damage may become comparable to and greater than the value of new land and buildings because of either low protection standards or the concentration of high-value assets. These findings suggest that relocation can be cost-effective in localized areas, as well as for sensitive or critical buildings and infrastructures frequently exposed to floods.

Past flood events suggest that flood relocation primarily occurs after catastrophic events for which the reconstruction costs are of the same magnitude as buying a new property⁴³. There is also a low social

acceptance of relocation measures as people feel uncomfortable with losing ancestral lands and properties as well as breaking long-standing ties with their communities and other networks. On the other hand, relocation is the most robust long-term solution as flood risk is avoided through a removal of exposure and the land that has become available after relocation can be used for buffering flood peaks.

Discussion

According to our findings, the cost-effectiveness of all adaptation measures increases with the level of global warming in most of Europe. This occurs because benefits (avoided damages) are projected to grow faster than implementation costs, driven by increased flood frequency and exposure. At the same time, we find that with adaptation we can maintain flood impacts to present-day levels even for high levels of warming. This will require increasing investments, thus raising crucial questions about the allocation of adaptation benefits and costs in society⁴⁴.

We focused our analyses on adaptation scenarios based on the application of a single type of measure. The outcomes suggest that ‘hybrid’ strategies, with different measures working in synergy and optimized at the level of river basins are likely to be the best strategies to maximize local benefits and minimize drawbacks of each measure, in line with recent findings³⁹. For instance, it is advisable to use dykes to protect against frequent low-magnitude events and detention systems to mitigate extreme flood peaks. Foreseeing backup risk reduction measures, such as flood proofing of buildings, helps in minimizing impacts when hazard-protection measures fail or are not sufficient to prevent flooding. Integrating physical risk reduction measures with financial instruments such as insurance would further reduce overall impacts on the economy and society^{45,46}. The adoption of adaptation strategies should not be alternative to risk-informed land use planning. In past decades, urban areas expanded considerably in flood-prone areas under increasing population pressure and due to the benefits associated with settling close to river courses⁴⁷, a trend that has not slowed down even in recent years⁴⁸. Our projections show that socio-economic growth and urban expansion will increase economic losses by >70% across Europe in 2100 (Supplementary Table 4). As such, taking into account flood risk in planning could be an effective way to reduce future flood impacts.

The CBA applied here is based on different assumptions and has limitations (Supplementary Information). In particular, benefits are expressed in monetary terms as the reduction in expected annual damage (EAD) and do not include the reduction in population exposed as well as other social, environmental and cultural aspects. The inclusion of these aspects would probably improve the cost-effectiveness of nature-based solutions such as detention areas, as highlighted in previous studies³⁴ and could be carried out with multicriteria analysis methods⁴⁹. Furthermore, including concepts such as risk aversion and social vulnerability²⁷ would allow a better understanding of possible social inequalities in the distribution of flood risk and could favour the design of more equitable adaptation strategies.

Local cost-effectiveness of measures can deviate strongly from those presented herein due to site-specific characteristics. The present analysis is therefore not meant to replace detailed analyses at local and regional scale, which are necessary for effective and reliable design and implementation of adaptation measures. Similarly, optimal adaptation measures should interact and require engagement of local population, governments and actors⁵⁰, taking into consideration existing risk management policies⁴⁴. On the other hand, several large European rivers are transnational, therefore our analysis can provide a consistent, pan-European framework to evaluate and compare the costs and effectiveness of river flood adaptation measures under future scenarios.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information,

acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41558-022-01540-0>.

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Methods

We appraise costs and benefits of river flood adaptation using the IPCC risk framework⁵². The different modelling steps and data used in the hazard, vulnerability, exposure, risk and adaptation analysis are described in the following sections. Given the focus of this work on flood risk trends under climate change, we use the terms ‘mitigation’ and ‘adaptation’ following the IPCC terminology⁵³. The IPCC defines mitigation as ‘a human intervention to reduce the sources or enhance the sinks of greenhouse gases’, hence to ‘mitigate’ refers to climate change only. Adaptation is defined as ‘the process of adjustment in human systems to actual or expected climate and its effects, to moderate harm or exploit beneficial opportunities’. We note that our analysis does not cover coastal, pluvial and flash flooding. The geographical coverage of our analysis is the European Union and the United Kingdom, with the exception of Malta where flooding is caused by pluvial and flash flood events and water courses are too small to be represented in the river flood modelling framework applied here.

Climate projections

Projections of river streamflow with global warming are based on an ensemble of 11 bias-corrected regional climate projections from EURO-CORDEX (Supplementary Table 1) for Representative Concentration Pathways RCP 4.5 and RCP 8.5 from 1981 up to 2100⁵⁴. The period 1981–2010, hereinafter referred to as ‘base’, was used a reference. We consider future climate scenarios corresponding to an increase in global average temperatures of 1.5, 2 and 3 °C above pre-industrial temperature. The 1.5 and 2 °C warming scenarios are explicitly considered in the Paris Agreement, while a 3 °C global warming is a more realistic scenario to expect by the end of the twenty-first century if adequate mitigation strategies are not taken. We evaluate each warming scenario assuming stabilized climate from the time indicated in Supplementary Table 1; there is no further warming and climate conditions remain constant after the year of reaching a warming level. Climate at GWLs derived from transient climate projections may differ from stabilized climate at those warming levels. However, no high-resolution stabilized climate projections are available for Europe. Moreover, studies^{2,55} suggest that the effect of pathway to GWLs is small compared to the models’ variability, except for strongly not time-invariant variables such as sea level rise.

Flood hazard and risk projections

We used the climate projections to generate daily streamflow simulations with LISFLOOD, a distributed, physically based hydrological model, run at 5 km grid resolution^{56,57}. The extremes of river discharge were analysed by means of the non-stationary approach proposed by ref. ⁵⁸. This methodology allows using the whole time horizon of the simulations (1981–2100) to fit the extremes, providing more reliable estimations for high return periods, compared with stationary techniques that typically use 30-yr windows. For more information on the implementation of LISFLOOD and on the fit of the extremes, see ref. ¹².

We represent floodplain inundation processes following the approach described in ref. ⁵⁹. Specifically, flood hazard maps for a range of return periods from 10 to 500 yr were derived from two-dimensional hydraulic simulations with the LISFLOOD-FP model⁶⁰. The flood hazard maps characterize the flood extent according to flood magnitude simulated along the river network.

We derive exposure information from the European population density map of ref. ⁶¹ and the refined version of the CORINE Land Cover proposed by ref. ⁶². Both maps are available at the same resolution as the flood hazard maps (100 m).

Vulnerability to floods is included in the form of damage functions and through a flood protection map. We use country-specific depth–damage functions from ref. ⁶³ to link flood depth with the corresponding direct economic damage, considering land use classes and gross domestic product (GDP) per capita at local administrative level.

Spatial distribution of flood protection levels in Europe is obtained by combining available information on protection design levels with modelled protection standards calculated by ref. ⁶⁴ and ref. ⁶⁵ (Supplementary information).

Socioeconomic projections are based on the ECFIN 2015 Ageing Report⁶⁶. This scenario acts as a benchmark of current policy, market and demographic trends in the European Union. High-resolution population projections are derived by the LUISA modelling platform⁶⁷. These maps capture the fine-scale processes of population dynamics (for example, urban expansion, stagnation or de-growth) and concentration that represent key drivers of the future exposure of populations. The Ageing Report projections are available only until 2060. After that, land use was assumed static. The relative distribution of people in a country in 2060 was scaled according to country projections of population up to 2100, while the damage functions were corrected for the projected changes in GDP. Regarding the GDP projections, the Ageing Report assumes that two out of the three determinants of economic growth, technical progress and capital accumulation, would reach a steady state (with constant growth rates) by the year 2060. That was assumed as well for the following decades. The third contributor to growth (the labour input) was assumed to evolve in a proportional way with respect to population (that is, same growth rate). That means ignoring possible changes in the labour market conditions, such as the employment rate. Population projections for 2061–2100 are taken from the latest United Nations demographic report (medium variant) and they are explicitly considered in the computation of the economic growth figures (more details can be found in ref. ⁶⁸).

We represent river flood risk as expected annual economic damage (EAD) and expected annual population exposed (EAPE), following the approach described in ref. ⁶⁹. For the baseline scenario, EAD and EAPE are calculated by constructing impact–probability curves based on the six return periods considered by flood hazard maps and taking into account local protection levels. Changes in future flood impacts are derived considering the flood frequency shift for the six reference events (magnitudes corresponding to a return period of 10, 20, 50, 100, 200 and 500 yr under the baseline scenario) and for protection levels. All economic risk estimates in this work are expressed in 2015 Euro (€) values.

Data collection for adaptation modelling

For the adaptation analysis, we constructed a database of flood risk reduction investments based on literature review. We used information on size and cost of past applications in Europe to derive unit costs of adaptation measures suitable for application within a pan-European framework (for example, the cost to increase the height of one linear kilometre of dyke by one metre). We also compiled information to clarify the link between implementation costs and impact reduction (for example, damage reduction factors reported for specific flood proofing measures). We include in the adaptation analysis only measures for which we found sufficient and robust information on quantitative costs and performance estimates (Supplementary Information).

Modelling of the adaptation measures

Strengthening of dyke systems. Strengthening of dyke systems consists 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 (for example, urban or rural areas), ranging from earthen embankments to vertical floodwalls¹⁸. In our analysis, we consider only the construction of permanent barriers.

We model the increasing of dyke height along the river network following the approach proposed by ref. ²². We first estimate the present-day height of dykes along the river network on the basis of river

discharge and the level of flood protection. For instance, the height of dykes designed to contain the 1-in-100-year flood event is given by the water level corresponding to the 1-in-100-year discharge. To this end, we use height–discharge curves calculated by the hydrological model LISFLOOD. Then, for each future scenario we calculate spatial maps of increases in dyke heights required to raise protection standards up to the new design return levels. Implementation costs are calculated considering the overall length of dykes and the additional height required. Costs are derived from literature values on dyke construction and elevation costs (Supplementary Table 2).

Detention areas

River detention areas (or basins) are areas located along river channels designed to temporarily retain floodwater volumes, thus reducing and delaying peak flows during extreme events (Supplementary Information).

The modelling of detention areas involves different steps to determine the required level of protection, calculate available storage capacity, allocate storage areas within each river basin and calculate overall costs. Here, we propose a simplified design procedure based on flood volumes (Section 4 of the Supplementary Information provides a discussion of the limitations). First, we use the refined CORINE Land Cover map⁶² to calculate the extent of suitable areas considering agricultural areas (excluding permanent crops; for example, orchards and vineyards) and seminatural areas (for example, permanent grassland, wetlands, excluding forests) within the 1-in-500-year floodplain along the river network, as delineated by physically based inundation modelling⁵⁹. We identify ~165,000 km² of agricultural areas (which amounts to 10% of total cropland in EU + UK estimated by ref.⁷⁰) and 21,000 km² of seminatural areas potentially suitable for floodplain storage. Note, however, that only a fraction of this potential area is actually considered for detention areas. The extent of modelled storage areas can exceed 100 km² in river basins such as the Danube, which is comparable to the size of floodplains areas reported by ref.⁷¹.

Detention areas leverage the storage potential of natural floodplains by means of embankments and moderate or negligible slopes of the bottom surface, with the aim of obtaining water heights of the order of a few metres^{18,72}. To this end, here we assume a factor 3.5 to convert available storage area into storage volume, based on the values retrieved from literature (see the database on adaptation measures in the Supplementary Information). In other words, we assume that each square metre of floodplain area can be used to store on average 3.5 m³ of floodwater.

Then, we calculate flood volumes that can be accommodated by present-day protection standards and the flood volumes that need to be stored in each future scenario along the river network. Flood volumes are estimated for each point of the river network using synthetic hydrographs calculated with the LISFLOOD hydrological model, following the approach of ref.⁷³. Finally, the required storage volumes (scenario design minus present design volumes) are calculated iteratively along the river network starting from the most upstream reaches. The iterative procedure is executed separately for each design level of protection and assuming a constant return period of flood peaks in the entire river network (for example, assuming to protect the entire river basin against 1-in-100-year discharge). The iterative procedure calculates the reduction of flood volumes along the river network based on upstream storage. In other words, volumes stored in an upstream section of a river basin are subtracted from the flood volumes in all downstream branches. We assume that only half of the storage capacity of each area is actually available for downstream peak reduction. Such conservative assumption accounts for the variable spatial distribution and timing of flood waves in the upstream catchment area during real flood events, especially in large basins⁷⁴.

Implementation costs include construction and maintenance costs and are calculated for each NUTS2 region on the basis of the

location and storage capacity of detention areas (in m³; Supplementary Table 2). We do not include compensation costs because detention areas could still be used for agricultural practices compatible with either occasional flooding (for example, less than once per decade) or with periodic inundation (for example, pasture, timber and cultivation of flood-tolerant crops)⁷⁵. Further compensation and conversion costs are accounted for in the sensitivity analysis described in the related subsection.

Flood proofing measures

Flood proofing measures are structural and non-structural modifications of buildings aimed at preventing or minimizing flood damage to structures and/or their contents (Supplementary Information).

In this work, we assume that the implementation of flood proofing measures can reduce overall damage to exposed buildings by a specific fraction (for example, 10%, 30% and so on), which is taken as design criterion. Using the available database of adaptation measures, we relate damage reduction ratios with implementation costs, by averaging data from all case studies in which flood proofing measures were applied. In other words, the analysis considers a standard/average flood proofing implementation, based on available literature information. Given the scale of application, we assume that damage reduction and costs can be linearly correlated because the measures can be applied over an increasing number of buildings. Note that we excluded building elevation measures from the analysis because they are often not feasible for existing buildings and because their cost is comparable to relocation measures. We further assume that infrastructural and agricultural damages cannot be reduced through flood proofing measures of the built-up area, meaning that potentially, on average, 90% of the EAD can be reduced.

Cost of flood proofing measures are usually available at building scale. These were translated in unit costs related to building surface (€ m⁻²) using building area (if available) or assuming a standard building area of 100 m² where no information is available (Supplementary Table 2). We assume that the same costs apply to all building types, even though literature studies usually focus on residential buildings). We calculate implementation costs as a function of the total built-up area located within the 1-in-500-year flood extent and the damage reduction ratio required. The built-up area is derived from the global human settlement maps for Europe⁷⁶. Note that we assume that population exposed is not reduced by this adaptation strategy, as building-based measures do not prevent floods from occurring.

Relocation

Relocation measures are designed assuming that a fraction of the exposed buildings and population located in flood-prone areas are moved to a flood-safe area. We consider for relocation all built-up areas located within the 1-in-500-year flood extent, for consistency with the approach adopted for all the other measures. Additional tests run considering only built-up areas more frequently exposed (for example, located within the 1-in-50-year flood extent) did not show changes at European- and country-scale in terms of CBA.

Implementation costs are calculated considering the overall building footprint area to be relocated. We assume that implementation costs increase linearly with exposure reduction and that the exposure reduction for buildings can be used to determine the reduction in population exposed (for example, relocating 20% of buildings implies the relocation of 20% of local population). Overall costs include construction costs per m² provided by ref.⁶³, increased by 20% to account for additional expenses such as acquisition of new land, removal of building contents and demolition. The costs are further increased by 50% to account for relocation of buildings with multiple storeys. We assume that the same costs apply to residential, industrial and commercial buildings. We further assume that infrastructures and agricultural areas cannot be relocated, meaning that the corresponding damage is

not reduced (on average, 5–10% of the total direct flood damage). We do not make any assumption about the place of destination of relocated assets and people, as such a decision would be highly subjective, nor do we consider possible costs for resettlement, which can be very large for relocation of large urban areas (for example, realization of transport, water and energy networks).

Cost–benefit analysis of adaptation strategies

The evaluation of each adaptation strategy is performed using a CBA that optimizes the benefits (avoided economic damages) and the costs of implementation and maintenance over the lifetime of the measures, where the lifetime was considered from 2020 up to the end of this century. CBA methods are applied for flood risk management in several European countries^{27,44,49}, with variable criteria to allocate costs and avoided impacts. Here, the calculation of costs and benefits follows the framework proposed by ref.²². For all measures, except flood proofing, investment costs were calculated considering construction costs distributed between 2020 and 2050, while maintenance costs are considered from 2050 to 2100. Flood proofing measures have a limited life span compared to the other measures¹⁷, therefore during the period 2060–2090 we consider additional construction costs for replacement.

In accordance to the literature, we assume that maintenance costs amount to 1% of total construction costs^{18,22}. Similar to the implementation cost, we assume that the effect of the measures applied (protection level for dykes strengthening and detention areas or damage reduction rate for flood proofing and relocation) increases linearly from 2020 (no effect) to the design value in 2050 and then remains constant. Implementation costs are calculated differently for each adaptation measure as described in the section on Modelling of the adaptation measures.

For each adaptation measure we simulate different design options (for example, raising dykes over a river stretch by different height increases corresponding to a range of design return periods). For dyke strengthening and building of detention areas, the optimal design level for each strategy was considered to be the one providing the maximum NPV at NUTS2 level, defined as the sum of investment costs (that are negative) and economic benefits (avoided economic losses, positive) over the lifetime of the project. For relocation and flood proofing of buildings, NPV is calculated by aggregating costs and benefits at 5 km resolution, which corresponds to the grid used to aggregate flood impacts and derive future river flow projections^{11,12}.

Future costs and benefits are discounted to present-day values using a 5% discount rate for EU countries eligible for the EU Cohesion Fund and 3% for other EU Member States and the United Kingdom, following the European Commission's guidelines on infrastructure investments⁶⁶. The CBA is applied for the three warming scenarios to understand the performance of the adaptation options for different levels of global warming. As an indication of the performance we also present the BCR, which is the ratio of the total discounted benefits to costs. We calculate BCR values for NUTS2 regions, as well as countries and the EU + UK. For relocation and flood proofing of buildings, aggregation of results at NUTS2 level and country level is done taking into account only 25 km² areas with positive NPV (note that the size is given by the grid resolution of the hydrological model). We further present benefits of adaptation in terms of the reduction in population exposed to flooding, even though this aspect is considered separately from the economic analysis (see the Supplementary Information for a detailed analysis of the limitations of the methodology).

Validation of results

In the Supplementary Information, we provide an overview of the reliability of the data and models composing the risk modelling framework. All models and datasets used in this work have been validated to some extent against observed or higher resolution data in past research studies. In addition, we also compare modelled economic losses against reported losses retrieved from numerous sources.

We find that, in several countries, modelled loss estimates are comparable with reported losses, taking into account the uncertainty bounds of both. These countries account, respectively, for more than 60% and 85% of overall modelled and reported losses. Notably, modelled losses match observations in most countries where national-scale protection values are based on reported data, thus suggesting a satisfactory skill of the risk modelling framework. Losses are overestimated by more than 100% in France, in Scandinavian countries and in a number of medium-small countries. The complete analysis is reported in the Supplementary Information.

Sensitivity analysis

Complex modelling frameworks, such as the one applied in this study, are affected by multiple uncertainty sources⁷⁷. To explore how this may affect the outcomes of this study, we carry out a sensitivity analysis by performing multiple runs of the modelling framework, using different combinations of parameter values and modelling assumptions. We consider a total of 1,485 runs taking into account uncertainty in (1) climate projections, (2) hydrological and hydraulic modelling, (3) damage calculations and (4) adaptation costs, and assuming that the four main sources of uncertainty are independent of each other. A complete description is available in the Supplementary Information.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The full dataset of river flood discharges considered in this work is available from the JRC Data Catalogue at <https://data.jrc.ec.europa.eu/dataset/1019a72f-7b98-4318-8baf-fd9e2c00a92c>⁷⁸. The flood hazard maps⁵⁹ are available from the JRC Data Catalogue at <https://data.jrc.ec.europa.eu/dataset/1d128b6c-a4ee-4858-9e34-6210707f3c81>. The European population density map used to represent present-day population⁶¹ is available at <https://doi.org/10.6084/m9.figshare.6210392>. The land cover map and all the spatial projections of population and land cover are available from the JRC Data Catalogue at <https://data.jrc.ec.europa.eu/collection/luisa>. The flood damage functions and related data⁶³ are available from the JRC Publications Repository at <https://publications.jrc.ec.europa.eu/repository/handle/JRC105688>. The flood protection dataset and the dataset of adaptation measures developed for this work are available from the JRC Data Catalogue at <https://data.jrc.ec.europa.eu/dataset/1019a72f-7b98-4318-8baf-fd9e2c00a92c>⁷⁸. All the datasets used as input or generated during the current study to assess river flood risk and appraise costs and benefits of adaptation are available from the JRC Data Catalogue at <https://data.jrc.ec.europa.eu/dataset/1019a72f-7b98-4318-8baf-fd9e2c00a92c>⁷⁸. The dataset available online includes the minimum data that are necessary to interpret, verify and extend the research in the article. Additional datasets from the current studies are available from the corresponding authors on reasonable request.

Code availability

All the Bash and R codes⁷⁹ used to generate the results reported in the paper are available from the JRC Data Catalogue at https://jeodpp.jrc.ec.europa.eu/ftp/public/JRC-OpenData/PESETAIV/Paper_floods/scripts_HPC.zip⁷⁸. The open-source of the LISFLOOD hydrological model used in this work is available in Github at <https://ec-jrc.github.io/lisflood/>. The source code of LISFLOOD-FP8.0 is available in Zenodo under a GNU General Public License v.3.0 for any non-commercial use and can be downloaded at <https://doi.org/10.5281/zenodo.4073011>.

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Author contributions

This work was conceived by F.D. and L.F. Formal analysis was undertaken by F.D. and L.M. Investigations were conducted by F.D., L.M. and L.A. Methodology was developed by F.D, L.M. and L.A. Data curation was by L.M. and A.B. Validation and visualization were by F.D, L.F. and A.B. Project administration was undertaken by L.F. The original draft was written by F.D. and L.F., who were also involved in reviewing and editing the final manuscript along with L.M. and L.A.

Competing interests

The authors declare no competing interests.

Additional information

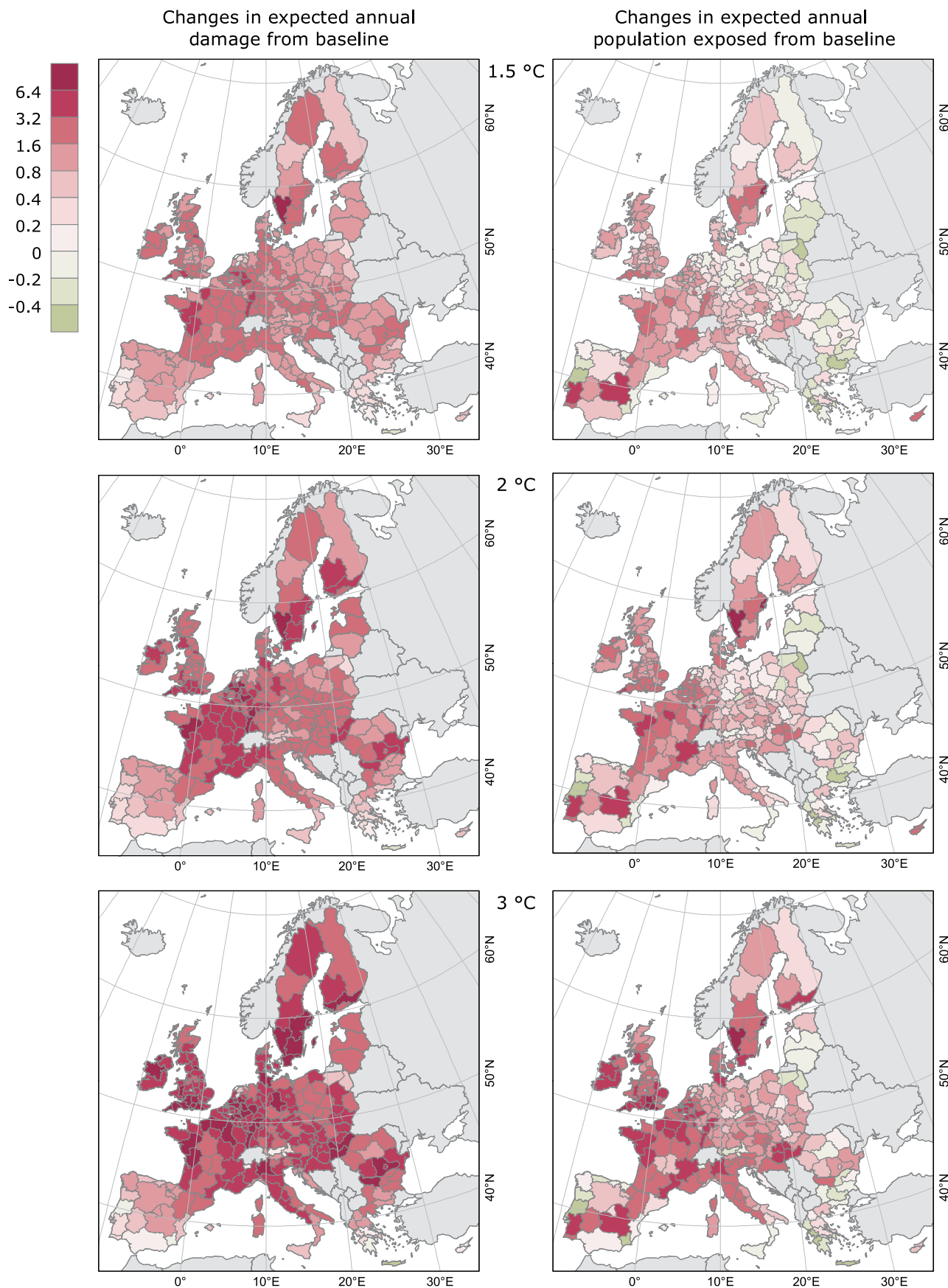
Extended data is available for this paper at <https://doi.org/10.1038/s41558-022-01540-0>.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41558-022-01540-0>.

Correspondence and requests for materials should be addressed to Francesco Dottori or Luc Feyen.

Peer review information *Nature Climate Change* thanks Giuliano Di Baldassarre and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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Extended Data Fig. 1 | Relative changes in expected annual impacts in 2100. Relative change in expected annual economic damage (left) and population exposed (right) for 1.5, 2 and 3 °C warming scenarios in 2100 with respect to the baseline. The values refer to the ensemble median. The layout of the maps is adapted from ^{25,51}.

Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

- | n/a | Confirmed |
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| <input type="checkbox"/> | <input checked="" type="checkbox"/> The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> The statistical test(s) used AND whether they are one- or two-sided
<i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i> |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> A description of all covariates tested |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| <input type="checkbox"/> | <input checked="" type="checkbox"/> A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
<i>Give P values as exact values whenever suitable.</i> |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

- | | |
|-----------------|--|
| Data collection | All necessary data were collected without using specific software |
| Data analysis | Hydrological simulations were performed using the open-source Lisflood model. Hydraulic simulations were performed using the open-source LISFLOOD-FP model. Data analysis was performed using custom scripts and algorithms developed in R (version 3.6.0 with packages ggplot2, ncd4, raster, rgdal, sp) and GNU Bash (version 4.2.46(2)). The Bash and R codes used to generate the results reported in the paper are available from the JRC Data Catalogue at https://jeodpp.jrc.ec.europa.eu/ftp/public/JRC-OpenData/PESETAIV/Paper_floods/scripts_HPC.zip . The open-source of the LISFLOOD hydrological model used in this work is available in Github at https://ec-jrc.github.io/lisflood/ . The source code of LISFLOOD-FP8.0 is available in Zenodo under a GNU General Public License v3.0 for any non-commercial use and can be downloaded at https://doi.org/10.5281/zenodo.4073011 . |

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

The maps of river flow extremes for the global warming scenarios considered in this work are available at the JRC Data Catalogue: <https://data.jrc.ec.europa.eu/dataset/20247f06-469c-4607-8af1-a5a670082471>. The full dataset of river flood discharges considered in this work is available at the JRC Data Catalogue at <https://data.jrc.ec.europa.eu/dataset/1019a72f-7b98-4318-8baf-fd9e2c00a92c>

The flood hazard maps are available at the JRC Data Catalogue: <https://data.jrc.ec.europa.eu/dataset/1d128b6c-a4ee-4858-9e34-6210707f3c81>

The European population density map used to represent present-day population is available as supplementary information of the work by Rosina et al. (2018) at the following address: <https://doi.org/10.6084/m9.figshare.6210392>

The land cover map and all the spatial projections of population and land cover are available at the JRC Data Catalogue: <https://data.jrc.ec.europa.eu/collecion/luisa>

The flood damage functions and related data are available as supplementary information of the report by Huizinga et al. (2017) at the JRC Publications Repository: <https://publications.jrc.ec.europa.eu/repository/handle/JRC105688>

The flood protection dataset and the dataset of adaptation measures developed for this work are available at the JRC Data Catalogue at <https://data.jrc.ec.europa.eu/dataset/1019a72f-7b98-4318-8baf-fd9e2c00a92c>.

All the datasets used as input or generated during the current study to assess river flood risk and appraise costs and benefits of adaptation are available at the JRC Data Catalogue at <https://data.jrc.ec.europa.eu/dataset/1019a72f-7b98-4318-8baf-fd9e2c00a92c>. The dataset available online include the minimum data that are necessary to interpret, verify and extend the research in the article. Additional datasets from the current studies are available from the corresponding authors on reasonable request

Human research participants

Policy information about [studies involving human research participants and Sex and Gender in Research](#).

Reporting on sex and gender

Not relevant

Population characteristics

Not relevant

Recruitment

Not relevant

Ethics oversight

Not relevant

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

Life sciences

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For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

The study is based on software simulations and analysis of software results

Research sample

Not relevant

Sampling strategy

No sample-size calculation was performed

Data collection

Data collection was performed using the most recent databases available in literature. Where necessary, we carried out a manual literature review to collect additional data (e.g. to produce the map of flood protection standards and the database of adaptation measures)

Timing and spatial scale

The manual literature review (to collect data on flood protection standards and adaptation measures) was carried out between September 2018 and October 2019.

Data exclusions

All data collected and relevant for the spatial scope of the present work were used

Reproducibility	All findings are based on software simulations and therefore are fully reproducible using the same data and software
Randomization	Not relevant
Blinding	Not relevant

Did the study involve field work? Yes No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involvement in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern

Methods

n/a	Involvement in the study
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<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging