Adaptation is cost-effective to offset rising river flood risk in Europe

Francesco Dottori (francesco.dottori@ec.europa.eu)
European Commission, Joint Research Centre (JRC) https://orcid.org/0000-0002-1388-3303
Lorenzo Mentaschi
European Commission, Joint Research Center, Ispra https://orcid.org/0000-0002-2967-9593
Alessandra Bianchi
FINCONS SPA
Lorenzo Alfieri
CIMA Foundation
Luc Feyen
European Commission, Joint Research Centre (JRC) https://orcid.org/0000-0003-4225-2962

Article

Keywords: global warming, development, river flooding

Posted Date: May 21st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-519118/v1

Adaptation is cost-effective to offset rising river flood risk in Europe

Francesco Dottori[1], Lorenzo Mentaschi[12], Alessandra Bianchi[i3], Lorenzo Alfieri[4] and Luc Feyen[1]

1: European Commission, Joint Research Centre (JRC), Ispra, Italy

2: Department of Physics and Astronomy “Augusto Righi” (DIFA), University of Bologna, 40127 Bologna, Italy

3: FINCONS SPA, Italy

4: CIMA Research Foundation, Savona, Italy

Abstract

River flooding 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 mitigate flood risk across Europe based on detailed flood risk modelling and cost-benefit analysis. We find that reducing flood peaks using retention areas is economically the most attractive option. In a scenario without climate mitigation, they can lower projected flood losses in Europe by the end of the century from 42 to 7.5 €billion/year and population exposed by 81%, or achieve a risk level comparable to today. This would require an investment of 2.9 €billion/year over 2020-2100, with a return of 4€ for each 1€ invested. The risk-reduction potential of economically-optimised strengthening of dykes is somewhat lower with 71% for a comparable annual investment. These measures avoid floods to happen and their cost-effectiveness increases with the level of global warming. Implementing building-based flood proofing measures and relocating people and assets are less cost-effective but can reduce impacts in localized areas.

Main Text

Introduction

River floods are a major cause of damage in Europe (Wallemacq and House, 2018). Absolute losses have generally 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 (Bouwer, 2011; Merz et al., 2012). The number of fatalities and damage expressed relative to the exposed value and size of the economy, however, have dropped (Paprotny et al., 2018) in Europe as well as other regions of the world (Jongman et al., 2012a; Tanoue et al., 2016). Hence, improved protection against floods has counter-balanced the effects of increasing exposure on risk and resulted in a strong reduction in vulnerability (Formetta and Feyen, 2019).

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 Europe (Hall et al., 2014), despite a trend towards increasing floods in northwestern Europe and decreasing flood hazard in southern and eastern Europe (Blöschl et al., 2019). However, there is growing consensus that climate change will intensify the hydrological cycle (Wu et al., 2013; Madakumbura et al., 2019) and amplify the intensity and probability of floods in most parts of Europe (e.g., Alfieri et al., 2015; Mentaschi et al., 2020). Fuelled with continued development and urbanisation in floodplains this could give rise to an unprecedented increase in flood risk (Feyen et al., 2009; Alfieri et al., 2018).

European societies will therefore need to implement effective flood adaption strategies. There exist a broad range of measures that can be targeted at reducing the hazard, vulnerability or exposure, or at managing the consequences. Despite the wide literature on flood risk mitigation, there are relatively few studies that have quantified costs and benefits of different measures (Kreibich et al., 2015; Aerts, 2018; Yamamoto et al., 2021). The limited continental and global scale studies considered a generic vulnerability reduction (Kinoshita et al., 2018), performed a sensitivity analysis (Alfieri et al., 2016) or only focused on increasing dyke height (Ward et al., 2017). However, to find the most effective strategy, limit potential negative environmental effects and avoid maladaptation, it is essential to consider a range of measures (Jongman, 2018). Among those, nature-based solutions have recently gained attention as more environmentally sustainable ways to reduce flood risk (Faivre et al., 2017). To our best knowledge, their effectiveness has not been appraised in large-scale studies.

Here, we present the first quantitative assessment of the costs and benefits across Europe of four key flood adaptation options: raising dykes, retention areas, flood proofing and relocation. First, flood hazard and risk were projected up to end of the century for different Global Warming Levels (GWL = 1.5, 2 and 3°C) assuming present flood protection based on a large ensemble of climate projections and long-term socioeconomic projections for the EU. Each adaptation strategy was appraised using a cost-benefit analysis that optimises the Net Present Value (NPV), which integrates the discounted overall costs of implementation and avoided economic damages over the life time 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 (see 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. 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 (more details in Methods, with an evaluation of the skill of the modelling components in Supplementary information).

Future flood risk scenarios

We estimate that at present river flooding causes an annual damage of 7.6 €billion/year and exposes to inundation around 170,000 people in the EU+UK (Figure 1). In the absence of further climate mitigation

(3°C in 2100) and adaptation (assuming present vulnerability), flood damage would rise to 42 €billion/year by the end of the century, while annually nearly half a million Europeans would be exposed to river flooding. Stringent climate mitigation would roughly halve the risk, yet the likelihood that global warming be stabilized at well below 2°C above pre-industrial levels is low (Raftery et al., 2017). This means that adaptation will be needed to offset the projected rise in flood risk.

Adaptation through river dykes

Structural defences such as river dikes have a very old tradition to protect people and economic activities in floodplains (Kundzewicz, 2002). 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 shows to be economically convenient to reduce the projected flood impacts on economy and society (Figure 1, Table 1). The implementation of the optimal design in the whole study area (EU + UK) for the 3°C warming scenario would require an average annual investment of 3 €billion/year (average of undiscounted costs over 2020-2100). The corresponding increased level of protection would lower annual flood damages by 30 €billion/year by the end of the century, or a reduction of 71%. Also 350,000 (68%) less people would be exposed to flooding (Figure 1 and Table S3). The overall discounted benefit-to-cost ratio (BCR) of the dyke investments is 2.9. The BCR and impact reduction capacity grow with GWL (Tables S5 and S7), 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 regional variation in risk reduction potential and BCR (Table 1 and Figure 2). The damage reduction potential for single countries ranges from 7% and 10% in Portugal and Spain to 90% and 89% in Belgium and the United Kingdom. The large variability in risk reduction rate is due to the variability of optimal design option (i.e. 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 several areas of the Mediterranean Region (Iberian Peninsula, southern Italy and Greece) and in some regions in Eastern Europe and in the Alps, projections indicate limited increases in flood impacts that are mostly driven by increasing exposure value (Figure 3 and Table S4). Hence, the costs of adaptation are not compensated by avoided impacts. In other regions in Central and Western Europe (e.g. the Netherlands), protection standards are already high (Figure S1), and the reduction in residual risk is not enough to make additional dyke heightening economically efficient. Reduction rates in population exposed are broadly similar (Tables S5 and S7).

Despite the favourable outcome of the cost-benefit analysis in most regions of Europe and the fact that limited implementation space is required, it has to be considered that extensive reliance on dyke systems can have socioeconomic and environmental drawbacks. Heightening river dykes generally increases the magnitude of peak flows and hence flood risk downstream (Di Baldassarre et al., 2009). The reduction in flood frequency and sense of safety favours the loss of flood memory and further development in flood-prone areas. This levee effect can in the unlikely case of flood defence failure lead to catastrophic consequences (Lane et al., 2011; Di Baldassarre et al., 2015). Dykes further distort the natural functioning of wetlands and riparian floodplains due to the lost hydraulic connectivity with the river channel (Gumiero et al., 2013).

Adaptation through retention areas

We consider natural retention in floodplains only, because structural (dams) flood control reservoirs have high costs and negatively impact ecosystems (Barbarossa et al., 2020). This is achieved by setting up areas within or aside the river network that can be flooded in a controlled manner to store excess water when the river stage reaches critical levels (Arrighi et al. 2018). The cost-benefit analysis shows that the use of natural retention areas can be highly effective to reduce flood risk in Europe. At the EU level, implementing the optimal design for the 3°C warming scenario would require an average annual investment of 2.9 €billion/year over the period 2020-2100 (undiscounted values), with a BCR of 4 (Figure 1). The resulting storage capacity would reduce flood economic damages by up to 82% (from 42 to 7.5 €billion/year) and population annually exposed by 81% (from 507,000 to 97,000) by the end of the century, hence to a risk level that is comparable in absolute terms to that of today. Because retention areas reduce the hazard by attenuating the flood hydrograph they become increasingly effective when flood hazard rises with global warming.

Natural retention areas are economically convenient practically everywhere except for some NUTS2 regions (Figure 2) where projected increases in flood impacts are small (e.g. in Portugal, Spain and Greece), where protection standards are high (e.g. the Netherlands), and where floodplains are too narrow to accommodate retention areas (e.g. Portugal). In general, retention areas show higher BCR values compared with river dykes and their optimal implementation results in a stronger reduction in socioeconomic impacts (Table 1). The higher efficacy in reducing flood hazard at regional level occurs because retention areas reduce flood peaks for all downstream river reaches, rather than locally containing it with river dykes. Furthermore, retention areas offer additional benefits not considered in the economic optimisation. 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 (Schindler et al., 2016; Nilsson et al., 2018). The monetary evaluation and inclusion of environmental services would further increase the cost-effectiveness of retention areas.

On the other hand, retention areas require the occupation of large portions of land (according to our calculations, the largest retention areas can exceed 10 km^2), which would no longer be available for intensive use (e.g. agriculture, urbanisation). Moreover, narrow floodplains may not be suited for this measure. For instance, the low cost-efficiency in Portugal depends on the limited increase of future flood risk, but it also relates to the limited width of many floodplains and scarce availability of non-urbanised land, which increases costs for implementing retention areas.

It is worth noting that the spatial attribution of costs and benefits of retention 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 retention 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 out (EEA, 2017).

Adaptation through flood proofing of buildings

A large share of flood losses relates to damage to buildings and their content (Jongman et al., 2012b). Structural and non-structural modifications can prevent water to enter 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. Given the wide range of measures and the large variability in their costs and damage reduction potential (Table 2), we based our cost-benefit analysis on central cost and damage reduction estimates derived from literature (See Methods).

Results show that flood proofing of buildings has generally BCR values above 1 across Europe (Figure 2). They can be applied at smaller scales and at lower cost compared to hazard-reduction measures such as dykes and retention areas, and hence targeted where they are cost-effective (see 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 conditions (Akadiri et al. 2012). However, they cannot prevent other types of flood damage, such as to transport infrastructure (Bubeck et al., 2019) or agriculture (Tapia-Silva et al., 2011). As a result the average reduction in damage attainable in Europe is 12%, which is considerably lower than hazard-reduction measures. More importantly, because floods are not avoided population exposure is not reduced (Figure 1c), even though the degree to which people are affected is lowered.

Flood proofing is more effective (reduction in damage above 10%) in Eastern Europe countries such as Estonia, Hungary and Czech Republic, because of lower protection standards and the presence of hotspots of exposed assets (Table 1). Damage reduction ratios above European average are also attainable in Sweden, Belgium and United Kingdom, due to the high economic exposure. Conversely, BCR values are below one in the Netherlands, where country-scale high protection standards make flood proofing less likely to be used (Table 1). Overall, findings suggest that flood proofing of buildings is effective for protecting areas frequently exposed to low or moderate floods and with high concentration of exposed value and assets (Richert et al., 2019), whereas they are not suited for an efficient protection of large areas.

Adaptation through relocation

Relocation aims at reducing the exposure of people and assets at risk of flooding by moving them to areas with negligible risk (King et al. 2014). Managed relocation of individuals, businesses, and infrastructure is largely ignored as a possible strategy in the EU national flood risk management policies (Mayr et al., 2020).

The cost-benefit analysis shows that it is the least cost-effective measure among all the adaptation measures considered here (Figure 1). The implementation across the areas with a positive benefit-cost balance would lead to an overall reduction in flood damages of just 2%, corresponding to a BCR of 2.3, while each year only 4700 (1%) less people would be exposed to floods. This is because relocation is economically convenient in a minority of NUTS2 regions concentrated in UK, Spain and around the Baltic region (Figure 2). Costs of relocation are high as they include the demolishing of existing buildings, the acquisition of new land and the construction of new infrastructures. Indeed, relocated people are generally offered a partial compensation for their properties by the local government (Kick et al., 2011), thus suggesting that financial incentives are necessary to promote relocation measures. In regions with BCR > 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 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 property (López-Carr and Marter-Kenyon 2015). 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 the retention of flood peaks.

Discussion

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 optimised at the level of river basins are likely to be the best strategies to maximise local benefits and minimise drawbacks of each measure, in line with recent findings (Du et al., 2020). For instance, it is advisable to use dykes to protect against frequent low-magnitude events, and retention systems to mitigate extreme flood peaks. Foreseeing backup risk-reduction measures, such as flood proofing of buildings, helps minimising 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 (Kron et al., 2019).

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 courses (Kummu et al. 2011), a trend that has not slowed down even in recent years (Mård, et al. 2018). Our projections show that socioeconomic growth and urban expansion will increase economic losses by more than 70% across Europe in 2100 (Table S4). As such, taking into account flood risk in planning could be an effective way to reduce future flood impacts.

The cost-benefit analysis does not include social, environmental and cultural aspects, which would require more complex multi-criteria analyses (e.g. using the concept of social vulnerability as in Kind et al., 2020). The inclusion of these aspects would likely improve the cost-effectiveness of nature-based solutions such as retention areas, as highlighted in previous studies (EEA, 2017).

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 an effective and reliable design and implementation of adaptation measures. Similarly, optimal adaptation measures should interact and require engagement of local population, governments and actors. 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.

Methods

We appraise costs and benefits of river flood adaptation using the IPCC risk framework (IPCC, 2014). The different modelling steps and data used in the hazard, vulnerability, exposure, risk and adaptation analysis are described in the following sections. We note that our analysis does not cover coastal, pluvial and flash flooding. The geographical coverage of our analysis is the EU and UK, 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 here applied.

Climate projections

Projections of river streamflow with global warming are based on an ensemble of 11 bias-corrected regional climate projections from EURO-CORDEX (Table S1) for Representative Concentration Pathways RCP4.5 and RCP8.5 from 1981 up to 2100 (Jacob et al., 2014). 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 temperature of 1.5, 2 and 3°C above preindustrial temperature. The 1.5°C 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 21st century if adequate mitigation strategies are not taken. We evaluate each warming scenario assuming stabilized climate from the time indicated in Supplementary Table S1, i.e. there is no further warming and climate conditions remain constant after the year of reaching a warming level. Climate at global warming levels 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 (e.g., Maule et al., 2017; Mentaschi et al., 2020) suggest that the effect of pathway to global warming levels 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 5km grid resolution (Burek et al., 2013; van der Knijff et al., 2010). The extremes of river discharge were analysed by means of the non-stationary approach proposed by Mentaschi et al. (2016). 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-year windows. For more information on the implementation of Lisflood, and on the fit of the extremes, the reader is referred to Mentaschi et al. (2020).

We represent floodplain inundation processes following the approach described in Alfieri et al. (2015). Specifically, flood hazard maps for a range of return periods from 10 to 500 years were derived from two-dimensional hydraulic simulations with the Lisflood-FP model (Bates et al., 2010). 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 by Batista e Silva et al. (2018) and the refined version of the CORINE Land Cover proposed by Rosina et al. (2018). Both maps are available at the same resolution of the flood hazard maps (100m).

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 Huizinga et al. (2017) 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 Jongman et al. (2014) and Scussolini et al. (2016) (see Supplementary information).

Socioeconomic Projections are based on the ECFIN 2015 Ageing Report (EC 2015). This scenario acts as a benchmark of current policy, market and demographic trends in the EU. High-resolution population projections are derived by the LUISA modelling platform (Jacobs-Crisioni et al., 2017). These maps capture the fine-scale processes of population dynamics (e.g., 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 (i.e. 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 Ciscar et al., 2017).

We represent river flood risk as expected annual economic damage (EAD) and expected annual population exposed (EAPE), following the approach described by Rojas et al. (2013). 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 (i.e. magnitudes corresponding to a return period of 10, 20, 50, 100, 200 and 500 years under the baseline scenario) and for protection levels. All economic risk estimates in this work are expressed in €2015 values.

We evaluated the overall reliability of the data and models composing the risk modelling framework (Supplementary Information). Most of the models and datasets have been validated to some extent against observed or higher resolution data in past research studies. We also compared 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 difference between modelled and reported losses is within 50%. These countries account respectively for more than 50% and 70% of overall modelled and reported losses. Losses are overestimated by more than 100% in France, in Scandinavian countries and in a number of medium-small countries. A detailed analysis is reported in the Supplementary Information.

Data collection for adaptation modelling

For the adaptation analysis, we constructed a database of flood risk reduction investments based on a review of scientific, grey and technical literature. The database provides an overview of the main types of investments applied in case studies, mainly in Europe (Kuik et al., 2016; EEA, 2017; Aerts, 2018; GFDRR et al., 2019). The database is available as electronic spreadsheet in the supplement material. We used information on size and cost of past applications in literature to derive unit costs of adaptation measures suitable for application within a pan-European framework (e.g. the cost to increase the height of one linear kilometre of dyke by one meter). We also compiled information to clarify the link between implementation costs and impact reduction (e.g. damage reduction factors reported for specific flood-proofing measures). We decided to include in the adaptation analysis only measures for which we found sufficient information on quantitative costs (especially unit costs) and performance estimates. Table S2 provides a description of the four adaptation measures considered in this study, while Table 2 summarizes the unit costs derived from the database of adaptation measures.

Modelling of the adaptation measures

Strengthening of dyke systems

We model the increasing of dyke height along the river network following the approach proposed by Ward et al. (2017). We first estimate the present-day height of dykes along the river network based on 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 dikes and the additional height required. Costs are derived from literature values on dyke construction and elevation costs (Table 2).

Retention areas

The design and modelling of retention areas requires the development of an algorithm to allocate storage areas within each river basin, based on the available storage capacity and the required level of protection. We first calculate the maximum storage capacity in floodplains along the river considering agricultural (excluding permanent crops, e.g. orchards, vineyards) and semi-natural (e.g. permanent grassland, wetlands, excluding forests) areas within the 1-in-500-year floodplain, derived from the refined CORINE Land Cover (Rosina et al., 2018). 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 by Alfieri et al.

(2014). Finally, the required storage volumes are calculated iteratively along the river network (i.e. design minus present volumes) starting from the most upstream reaches. The iterative procedure is designed to calculate the reduction of flood volumes along the river network given by upstream storage. In other words, part of the flood volumes stored in a section of a river basin is subtracted from the flood volumes in all downstream branches. 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 (e.g. assuming to protect the entire river basin against 1-in-100-year discharge). Implementation costs are calculated based on the overall flood volume to store (Table 2).

Flood proofing measures

There is a wide range of flood proofing measures applicable at the building scale, depending on local flood and exposure characteristics (e.g. expected range of flood water depths, type and structure of the building to be protected). Most research works on these measures provide an overview of costs and benefits for specific case studies (Kreibich et al., 2015; Aerts, 2018), and few studies report analytical analyses of different measures on real cases (Du et al., 2020) or standardized buildings (Richert et al., 2020).

In this work, we assume that the implementation of flood proofing measures can reduce overall damage to exposed buildings by a specific fraction (e.g. 10%, 30% etc.), 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 expected annual damage can be reduced.

Cost of flood-proofing measures are usually available at building scale. These were translated in unit costs related to building surface (€/m2) using building area (if available), or assuming a standard building area of $100m^2$ where no information is available (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 Europe (Florczyk et al., 2019). 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 (e.g. 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. We do not make any assumption about the place of destination of relocated assets and people, as such decision would be highly subjective, nor do we consider possible costs for resettlement (e.g. realization of infrastructure networks). 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 (e.g. relocating 20% of buildings implies the relocation of 20% of local population).

Analysis of adaptation strategies

The evaluation of each adaptation strategy is performed using a cost-benefit analysis that optimises 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 end of this century. The calculation of costs and benefits follows the framework proposed by Ward et al. (2017). 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 measures (Kreibich et al., 2015), 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 (Ward et al., 2017; Aerts, 2018). Similar as the implementation cost, we assume that the effect of the measures applied (protection level for dykes strengthening and retention 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 “Modelling approach for adaptation measures”.

For each adaptation measure we simulate different design options (e.g. raising dykes over a river stretch by different height increases corresponding to a range of design return periods). For dikes strengthening and building of retention areas, the optimal design level for each strategy was considered to be the one providing the maximum net present value (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 5km resolution, which corresponds to the grid used to aggregate flood impacts and derive future river flow projections (Alfieri et al., 2015; Mentaschi et al., 2020).

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 Member States and the UK, following the European Commission's guidelines on infrastructure investments (EC, 2014). The cost-benefit analysis is applied for the three warming scenarios in order to understand the performance of the adaptation options for different levels of global warming. As an indication of the performance we also present the Benefit-to-Cost Ratio (BCR), which is the ratio of the total discounted benefits to costs. We calculate BCR values for NUTS2 administrative regions, as well as countries and the EU + UK. For relocation and flood-proofing of buildings, aggregation of results at NUTS2 and country level is done taking into account only 5km areas with positive NPV. We further present benefits of adaptation in terms of the reduction in population exposed to flooding.

Note that we could not quantify the environmental costs and benefits of the available adaptation measures. However, we provide a qualitative assessment of these factors in the discussion of results. Moreover, the reduction in population exposed was not monetized in the cost/benefit analysis, due to the lack of accurate information on impacts (both physical and social) and sensitivity issues in attributing economic value to human lives.

Data availability:

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 can be provided upon reasonable request to the authors.

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/collection/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 as supplementary material of the present manuscript.

All the other datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability:

The open-source 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 .

All the other computer codes or algorithms used to generate the results reported in the paper are available from the corresponding author on reasonable request.

Acknowledgements: the research that led to these results received funding from DG CLIMA of the European Commission as part of the 'PESETAIV-Climate Impacts and Adaptation in Europe' project (Administrative Agreement JRC 34547–2017 / 340202/2017/763714/SER/CLIMATE.A.3). We further thank Munich Re for providing loss data from the NatCatSERVICE database.

Author contributions FD: conceptualization, formal analysis, investigation, data curation, writing (original draft, review and editing); LM: methodology, formal analysis, investigation, data curation, writing (review and editing); AB: data curation, validation, visualization; LA: methodology, investigation, writing (review and editing); LF: conceptualization, project administration, writing (original draft, review and editing)

Competing Interests: the authors declare no competing interest

References (main text)

1. Aerts, J.C.J.H. A Review of Cost Estimates for Flood Adaptation. Water, 10(11), 1646 (2018).
2. Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. Global warming increases the frequency of river floods in Europe. Hydrology and Earth System Sciences, 19(5), 2247-2260 (2015).
3. Alfieri, L., Feyen, L., Di Baldassarre, G. Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. Climatic Change 136, 507-521 (2016).
4. Alfieri, L., Dottori, F., Betts, R., Salamon, P., Feyen, L. Multi-model projections of river flood risk in Europe under global warming. *Climate* 6, 6 (2018).
5. Akadiri, P. O., Chinyio, E. A., & Olomolaiye, P. O. Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. Buildings, 2(2), 126-152 (2012).
6. Arrighi, C., et al. Quantification of Flood risk mitigation benefits: A building-scale damage assessment through the RASOR platform. Journal of Environmental Management, 207, 92-104 (2018).
7. Barbarossa, V., Schmitt, R. J. P., Huijbregts, M. A. J., Zarfl, C., King, H., & Schipper, A. M. Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide. Proceedings of the National Academy of Sciences of the United States of America, 117(7), 3648-3655. doi:10.1073/pnas.1912776117 (2020).
8. Blöschl, et al. Changing climate both increases and decreases European river floods. Nature, 573(7772), 108-111 (2019).
9. Bouwer, L. M. Have disaster losses increased due to anthropogenic climate change? Bull. Am. Meterol. Soc., 92(1), 39-46 (2011).

10. Bubeck, P., Dillenardt, L., Alfieri, L., Feyen, L., Thieken, A. H., & Kellermann, P. Global warming to increase flood risk on european railways. Climatic Change, 155(1), 19-36 (2019).
11. Di Baldassarre, G., Castellarin, A., & Brath, A. Analysis of the effects of levee heightening on flood propagation: Example of the river Po, Italy. Hydrological Sciences Journal, 54(6), 1007-1017 (2009).
12. Di Baldassarre, G., et al. Debates -Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. Water Resources Research, 51(6), 4770-4781 (2015).
13. European Environmental Agency. Green Infrastructure and Flood Management. EEA Report No 14/2017 (2017). https://www.eea.europa.eu/publications/green-infrastructure-and-flood-management
14. Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., & Vandewoestijne, S. Nature-based solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environmental Research, 159, 509-518 (2017).
15. Feyen, L., Barredo, J.I., & Dankers R. Implications of global warming and urban land use change on flooding in Europe. In: Feyen J, Shannon K, Neville M (eds) Water and urban development paradigms -towards an integration of engineering, design and management approaches. CRC Press, London, pp 217–225 (2009).
16. Gumiero, B., Mant, J., Hein, T., Elso, J., & Boz, B. Linking the restoration of rivers and riparian zones/wetlands in Europe: Sharing knowledge through case studies. Ecological Engineering, 56, 36-50 (2013).
17. Hall, J. et al. Understanding flood regime changes in Europe: a state of the art assessment. Hydrol. Earth Syst. Sci. 18, 2735–2772 (2014).
18. Jongman, B. Effective adaptation to rising flood risk. Nature Communications, 9(1) (2018)

19. Jongman, B., Ward, P. J. & Aerts, J. C. J. H. Global exposure to river and coastal flooding: long term trends and changes. Glob. Environ. Chang 22, 823-835 (2012a).
20. Jongman, B., et al. Comparative flood damage model assessment: Towards a European approach. Natural Hazards and Earth System Science, 12(12), 3733-3752 (2012b).
21. Kick, E. L., et al. Repetitive flood victims and acceptance of FEMA mitigation offers: an analysis with community-system policy implications. Disasters, 35(3), 510-539 (2011).
22. Kind, J., Botzen, W.J.W., Aerts, J.C.J.H., Social vulnerability in cost-benefit analysis for flood risk management. Environment and Development Economics, 25 (2), 115-134 (2020)
23. King, D., et al. Voluntary relocation as an adaptation strategy to extreme weather events. International journal of disaster risk reduction, 8, 83-90 (2014).
24. Kinoshita, Y., Tanoue, M., Watanabe, S., Hirabayashi, Y. Quantifying the effect of autonomous adaptation to global river flood projections: application to future flood risk assessments. Environmental Research Letters 13, 014006 (2018)
25. Kreibich, H., Bubeck, P., Van Vliet, M., De Moel, H. A review of damage-reducing measures to manage fluvial flood risks in a changing climate. Mitigation and Adaptation Strategies for Global Change, 20(6), 967-989 (2015).
26. Kron, W., Eichner, J., & Kundzewicz, Z. W. Reduction of flood risk in Europe – reflections from a reinsurance perspective. Journal of Hydrology, 576, 197-209 (2019).
27. Lane, S.N., Landström, C., & Whatmore, S.J. Imagining flood futures: risk assessment and management in practice. Phil Trans R Soc A, 369:1784-1806 (2011).
28. López-Carr, D. & Marter-Kenyon, J. Human adaptation: manage climate-induced resettlement. Nature 517, 265-267 (2015).
29. Madakumbura, G. D. et al. Event-to-event intensification of the hydrologic cycle from 1.5°C to a 2°C warmer world. Scientific Reports, 9(1) (2019).

30. Mård, J., Di Baldassarre, G., Mazzoleni, M. Nighttime light data reveal how flood protection shapes human proximity to rivers. Science Advances 8, eaar5779 (2018)

31. Mayr, B., Thaler, T. & Hübl, J. Successful small-scale household relocation after a millennial flood event in Simbach, Germany 2016. Water, 12(1), 156 (2020).

32. Mentaschi, L., et al. Independence of future changes of river runoff in Europe from the pathway to global warming. Climate, 8(2) (2020).

33. Merz, B., Kundzewicz, Z. W., Delgado, J., Hundecha, Y., & Kreibich, H. Detection and attribution of changes in flood hazard and risk. IAHS-AISH Publication, (SPEC. ISS. 10), 435-458 (2012).

34. Nilsson, C., Riis, T., Sarneel, J. M., & Svavarsdóttir, K. Ecological restoration as a means of managing inland flood hazards. Bioscience, 68(2), 89-99 (2018).

35. Paprotny, D., Sebastian, A., Morales-Napoles, O., & Jonkman, S. Trends in flood losses in Europe over the past 150 years. Nature Communications 9(1), 1985 (2018).

36. Raftery, A. E., Zimmer, A., Frierson, D. M. W., Startz, R., & Liu, P. Less than 2°C warming by 2100 unlikely. Nature Climate Change, 7(9), 637-641. doi:10.1038/nclimate3352 (2017).

37. Richert, C., Boisgontier, H., and Grelot, F.: Economic assessment of precautionary measures against floods: insights from a non-contextual approach, Nat. Hazards Earth Syst. Sci., 19, 2525–2539 (2019).

38. Schindler, S. et al. Multifunctional floodplain management and biodiversity effects: A knowledge synthesis for six European countries. Biodiversity and Conservation, 25(7), 1349-1382 (2016).

39. Tanoue, M., Hirabayashi, Y. & Ikeuchi, H. Global-scale river flood vulnerability in the last 50 years. Sci. Rep. 6, 36021 (2016).

40. Tapia-Silva, F. et al. Estimation of flood losses to agricultural crops using remote sensing. Physics and Chemistry of the Earth, 36(7-8), 253-265 (2011).

41. Wallemacq, P. & House, R. Economic losses, poverty & disasters: 1998-2017. CRED and UNISDR Report (2018).
42. Ward, P. J., et al. A global framework for future costs and benefits of river-flood protection in urban areas. Nature Climate Change, 7(9), 642-646 (2017).
43. Wu, P., Christidis, N., & Stott, P. Anthropogenic impact on earth's hydrological cycle. Nature Climate Change, 3(9), 807-810 (2013).
44. Yamamoto, T., et al. Evaluation of flood damage reduction throughout Japan from adaptation measures taken under a range of emissions mitigation scenarios. Climatic Change 165, 60 (2021).

References (Methods)

45. Alfieri, L. et al. Advances in pan-European flood hazard mapping. Hydrological processes 28.13, 4067-4077 (2014).
46. Alfieri, L., Feyen, L., Dottori, F., Bianchi, A. Ensemble flood risk assessment in Europe under high end climate scenarios, *Global Environmental Change* 35, 199–212, (2015).
47. Integrated Rhine Programme. Accessed on 2/2/2020 at https://rp.baden-wuerttemberg.de/Themen/WasserBoden/IRP/Seiten/default.aspx
48. Batista e Silva, F., et al. From place of residence to place of activity: towards spatiotemporal mapping of population density in Europe. In: *Proceedings of the AGILE Conference 2018*, Lund, Sweden (2018)
49. Bates, P. D., Horritt, M. S., Fewtrell, T. J. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *Journal of Hydrology* 387, 33-45. (2010)

50. Burek, P., Knijff van der, J., Roo de, A. LISFLOOD, Distributed Water Balance and Flood Simulation Model Revised User Manual 2013. *Publications Office of the European Union*, Luxembourg (2013).
51. Ciscar, J.C., Mongelli, I., Szewczyk, W. 'PESETA III: Task 2 - Socioeconomic scenarios dataset', Technical Report, European Commission (2017).
52. Dottori, F., Alfieri, L., Bianchi, A., Skoien, J., and Salamon, P.: A new dataset of river flood hazard maps for Europe and the Mediterranean Basin region, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2020-313, in review (2021).
53. Du, S. et al., Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. Global Environmental Change 61, 2020, 102037 (2020).
54. European Commission. Guide to Cost-Benefit Analysis of Investment Projects. doi:10.2776/97516 (2014)
55. European Commission. The 2015 Ageing Report; Economic and budgetary projections for the 28 EU Member States (2013-2060), *Publications Office of the European Union*, Luxembourg (2015)
56. Florczyk, A. et al. GHSL Data Package 2019 (Publications Office of the European Union, 2019); https://publications.jrc.ec.europa.eu/repository/handle/111111111/56552
57. GFDRR, World Bank Group, Profor, WRI: Nature-based solutions for disaster risk management. https://reliefweb.int/sites/reliefweb.int/files/resources/134847-NBS-for-DRM-booklet.pdf (accessed on 20-9-2019) (2019).
58. Huizinga, J., Moel, H. de, Szewczyk, W. Global flood depth-damage functions. Methodology and the database with guidelines. *Publications Office of the European Union*, Luxembourg, EUR 28552 EN. doi: 10.2760/16510 (2017).

59. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Field, C.B., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, (2014).

60. Jacob, D., et al. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Change 14(2), 563-578 (2014)

61. Jacobs-Crisioni, C., et al. The LUISA Territorial Reference Scenario 2017. A technical description, *Publications Office of the European Union*, Luxembourg, ISBN 978-92-79-73866-1. (2017)

62. Jongman, B., et al. Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change* 4, 264–268, (2014)

63. Kreibich, H., Müller, M., Thieken, A. H., Merz, B. Flood precaution of companies and their ability to cope with the flood in August 2002 in Saxony, Germany. *Water Resources Research*, 43(3). (2007)

64. Kuik, O., et al. Assessing the economic case for adaptation to extreme events at different scales. Report of the ECONADAPT project ,accessed on 6/7/2018 at https://econadapt.eu/sites/default/files/docs/Deliverable%205-1%20approved%20for%20publishing_1.pdf (2016).

65. Kundzewicz, Z. Flood protection—sustainability Issues, Hydrological Sciences Journal, 44:4, 559-571 (1999).

66. Maule, C. F., Mendlik, T., Christensen, O. B., (2017). The effect of the pathway to a two degrees warmer world on the regional temperature change of Europe. *Climate Services*, 7, 3–11

67. Mentaschi, L., et al. The transformed-stationary approach: a generic and simplified methodology for non-stationary extreme value analysis, Hydrol. Earth Syst. Sci., 20, 3527–3547 (2016).

68. Rojas, R., Feyen, L., & Watkiss, P. (2013). Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. Global Environmental Change, 23(6), 1737-1751.

69. Rosina K., et al.. Increasing the detail of European land use/ cover data by combining heterogeneous data sets, *International Journal of Digital Earth,* DOI: 10.1080/17538947.2018.1550119 (2018).

70. Scussolini, P., et al. FLOPROS: an evolving global database of flood protection standards. *Natural Hazards and Earth System Sciences*, 16(5), 1049-1061 (2016)

71. Van der Knijff, J.M., Younis, J., de Roo, A.P.J., LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. *International Journal of Geographic. Information. Science* 24, 189–212 (2010).

Table 1. Overview of four adaptation strategies at country level for the 3°C warming scenario in 2100. Benefit-Cost Ratio (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/year) reflect average of undiscounted costs over period 2020-2100. All values refer to the ensemble average.

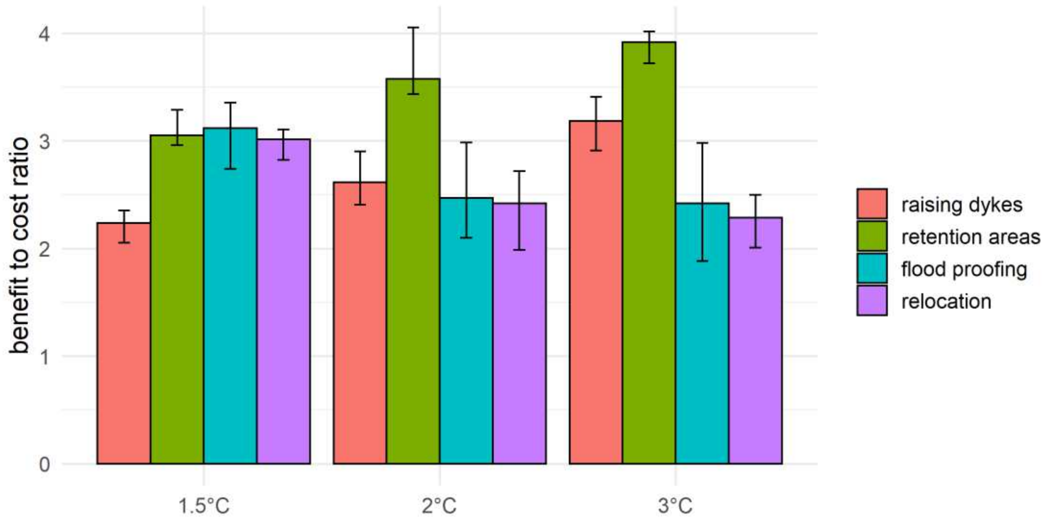
	Retention areas			Dikes strenghtening			Flood proofing			Relocation		
Country	**BCR**	**EAD red.**	**Costs €M/y**	**BCR**	**EAD red.**	**Costs €M/y**	**BCR**	**EAD red.**	**Costs €M/y**	**BCR**	**EAD red.**	**Costs €M/y**
Austria	2.8	83%	108.8	2.4	71%	108.1	3.4	0.3%	0.8	0.2	0%	0.0
Belgium	4.2	91%	93.1	3.6	90%	107.4	10.2	12%	37.4	5.9	0.0%	0.0
Bulgaria	3.1	78%	18.7	2.5	42%	10.8	2.0	6%	3.1	0.9	0.1%	0.0
Croatia	3.1	96%	84.1	2.2	74%	79.1	2.1	0.6%	1.2	0.5	0.0%	0.0
Cyprus	0.0	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0	0%	0.0
Czechia	4.4	88%	97.9	2.7	73%	129.9	1.8	15%	55.7	3.5	0.1%	0.1
Denmark	3.6	91%	6.8	1.7	59%	7.8	0.6	6%	1.5	0.0	0%	0.0
Estonia	1.1	74%	17.6	2.3	74%	11.0	18.1	27%	3.9	237.1	1.3%	0.4
Finland	3.5	80%	91.5	3.3	70%	76.5	4.4	17%	31.2	8.8	0.4%	0.8
France	3.3	87%	651.2	2.8	74%	629.6	2.3	2%	36.3	4.7	0.0%	0.2
Germany	3.8	79%	395.2	3.2	74%	439.3	2.8	1%	16.1	5.0	0.0%	0.2
Greece	2.7	73%	12.9	0.8	41%	12.4	3.8	1%	0.6	2.6	0.2%	0.0
Hungary	3.2	87%	119.5	2.8	71%	120.1	12.2	8%	35.4	14.6	0.0%	0.0
Ireland	3.2	86%	35.5	2.5	75%	39.1	1.6	5%	5.1	15.0	0.0%	0.0
Italy	4.6	88%	264.7	2.7	76%	386.3	1.9	6%	75.2	33.2	0.1%	0.3
Latvia	2.5	67%	40.0	2.1	72%	49.7	2.5	18%	27.5	5.3	0.1%	0.0
Lithuania	2.3	48%	29.0	1.8	40%	19.2	5.7	1%	1.0	52.5	0.1%	0.0
Luxembourg	4.0	91%	7.9	3.5	91%	8.8	1.0	15%	3.7	0.0	0%	0.0
Netherlands	3.9	58%	22.9	4.1	71%	26.5	0.1	0%	0.0	0.0	0%	0.0
Poland	2.3	71%	205.1	1.7	41%	137.0	3.3	3%	17.5	0.0	0%	0.0
Portugal	2.6	9%	0.9	1.8	7%	0.8	6.8	0.3%	0.0	4.6	0.1%	0.1
Romania	2.5	62%	94.1	2.7	46%	59.7	3.1	15%	35.6	5.6	0.2%	0.0
Slovakia	3.6	87%	47.6	2.5	66%	50.5	3.4	0.1%	0.3	2.1	0.7%	1.1
Slovenia	2.5	82%	23.0	1.7	59%	22.5	4.1	0.5%	0.3	0.3	0.0%	0.0
Spain	1.8	32%	64.7	1.8	10%	22.1	3.1	3%	4.1	1.5	0.1%	0.0
Sweden	5.9	87%	118.2	8.3	81%	89.3	3.7	65%	144.2	3.2	0.5%	0.6
United Kingdom	7.4	94%	181.2	3.8	89%	329.3	2.2	27%	250.1	2.7	32.5%	110.5
EU+UK	4.0	82%	2869	3.2	71%	3020	2.6	12%	788	2.2	0.2%	1.0

Table 2. Summary of unit costs derived from the database of adaptation measures. The table reports also the damage reduction ratios for Flood-proofing measures for buildings. The complete database is available as supplementary material.

		Normalized unit cost (2015)		
		Average	25% quantile	75% quantile
Dike systems reinforcement	€/m/m	6405	1829	9514
Retention areas	€/m3	3.73	1.05	5.00
Flood-proofing measures	€/m2	376	493	156
Relocation	€/m2	1373	906	1826
		Damage reduction ratio (average)		
		Average	25% quantile	75% quantile
Flood-proofing measures	(-)	41%	10%	80%

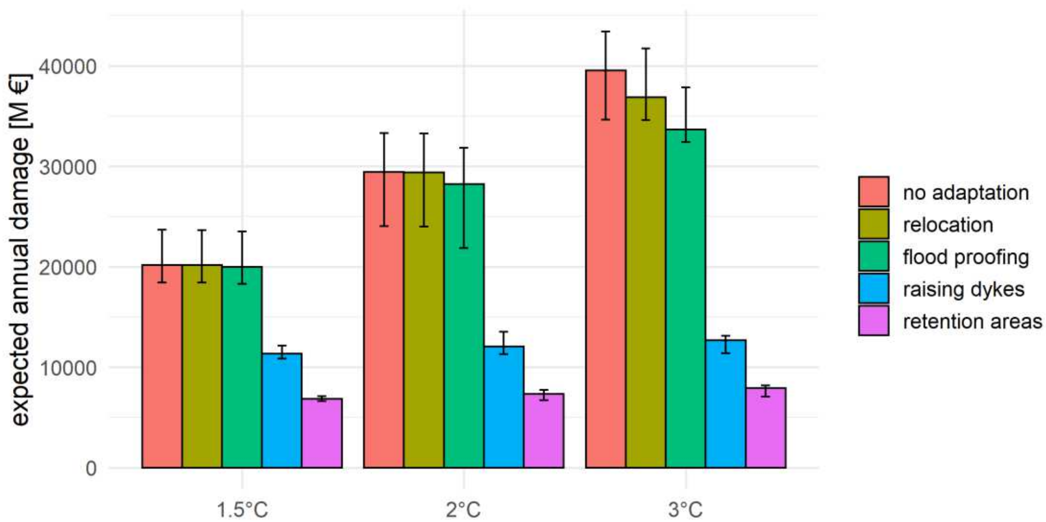
Figures

A



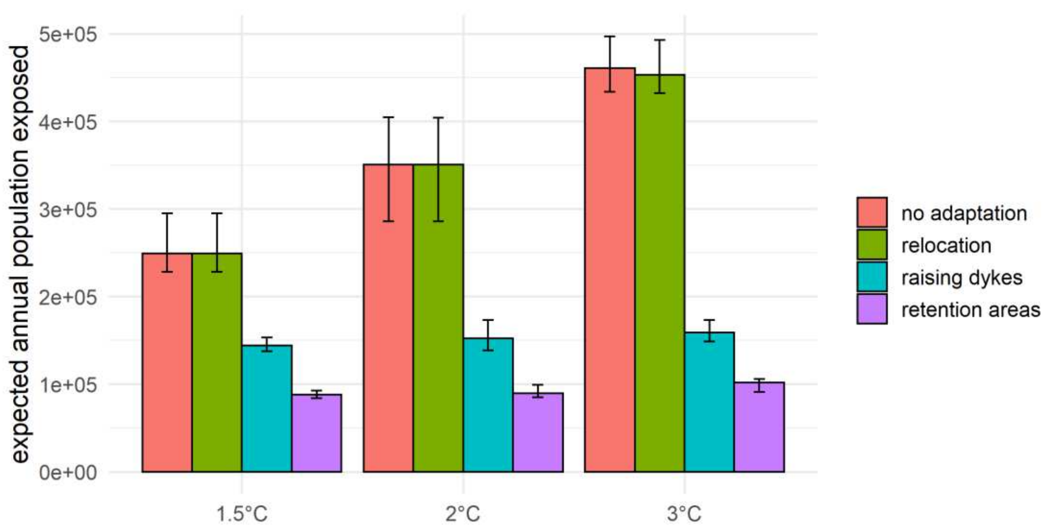
benefit to cost ratio
0
1
2
3
4
1.5°C
2°C
3°C
raising dykes
retention areas
flood proofing
relocation

B



expected annual damage [M €]
0
10000
20000
30000
40000
1.5°C
2°C
3°C
no adaptation
relocation
flood proofing
raising dykes
retention areas

C



expected annual population exposed
0e+00
1e+05
2e+05
3e+05
4e+05
5e+05
1.5°C
2°C
3°C
no adaptation
relocation
raising dykes
retention areas

Figure 1. Summary of the outcomes for the four adaptation strategies considered under 1.5°C, 2°C and 3°C warming scenario. Panel (A) shows the benefit to cost ratio (A) calculated from total discounted benefits and costs over the period 2020-2100. Panels (B) (C) describe future undiscounted economic damages (B) and population exposed (C) for the year 2100, calculated under a no-adaptation scenario and optimizing each of the four adaptation strategies. Coloured bars and error bars indicate respectively the average and the 75th-25th quantiles of the model ensemble. All results are based on averaged at EU + UK level.

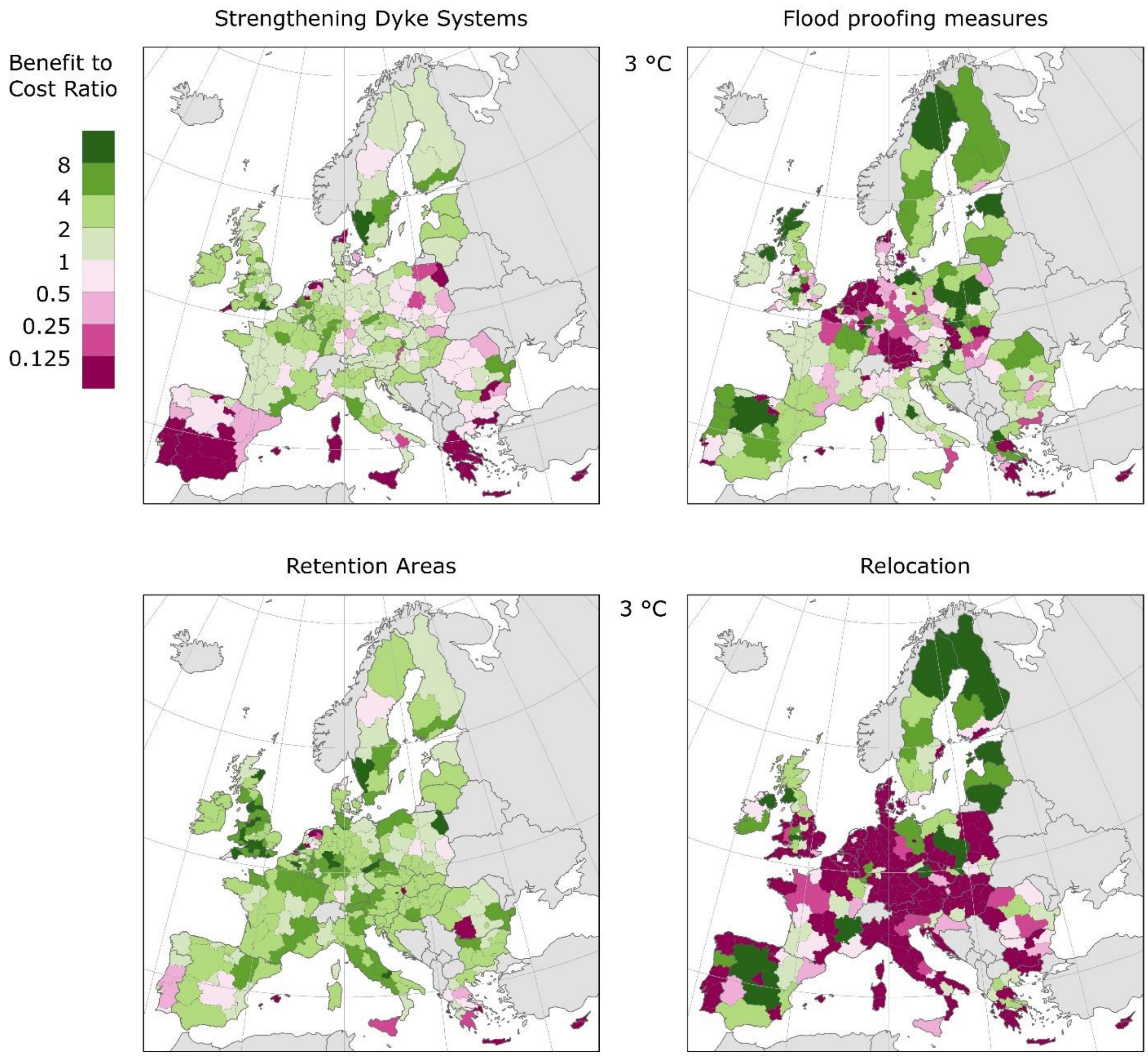
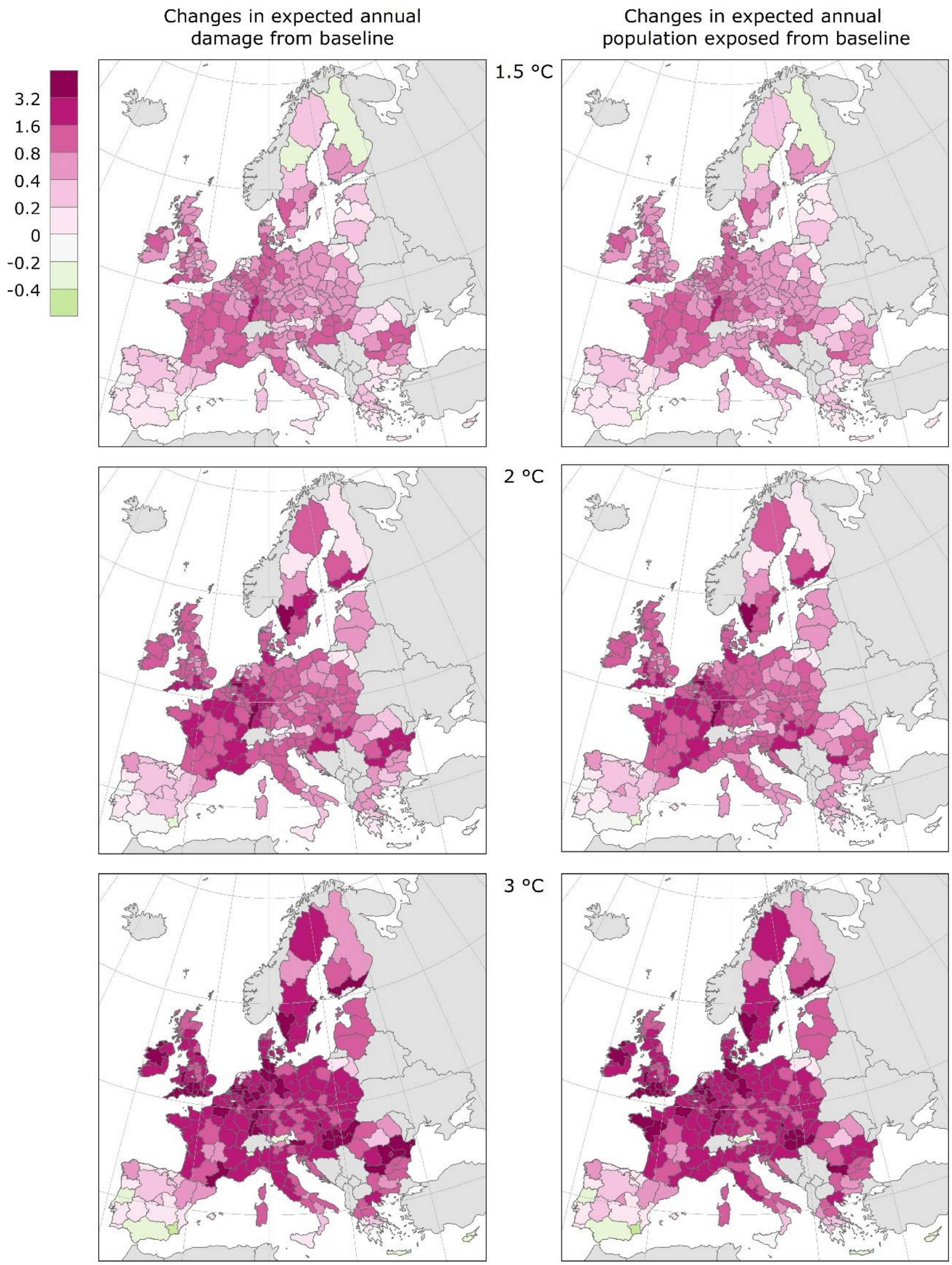


Figure 2. Benefit-cost ratio (BCR) at NUTS2 level for the adaptation strategies ‘river dikes’, ‘retention areas’, ‘flood proofing measures’ and ‘relocation’ for the 3°C warming scenario. The values refer to the ensemble average.



Changes in expected annual damage from baseline
Changes in expected annual population exposed from baseline
3.2
1.6
0.8
0.4
0.2
0
-0.2
-0.4
1.5 °C
2 °C
3 °C

669

Figure 3. 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 average.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Databaseadaptationcostspaper.xlsx
- DottorietalAdaptationsupplementv5.pdf
- floodProtectionv2019paper3.zip
- DottorietalAdaptationsupplementv6.pdf