European Commission

JRC TECHNICAL REPORT

Adapting to rising river flood risk in the EU under climate change

JRC PESETA IV project – Task 5

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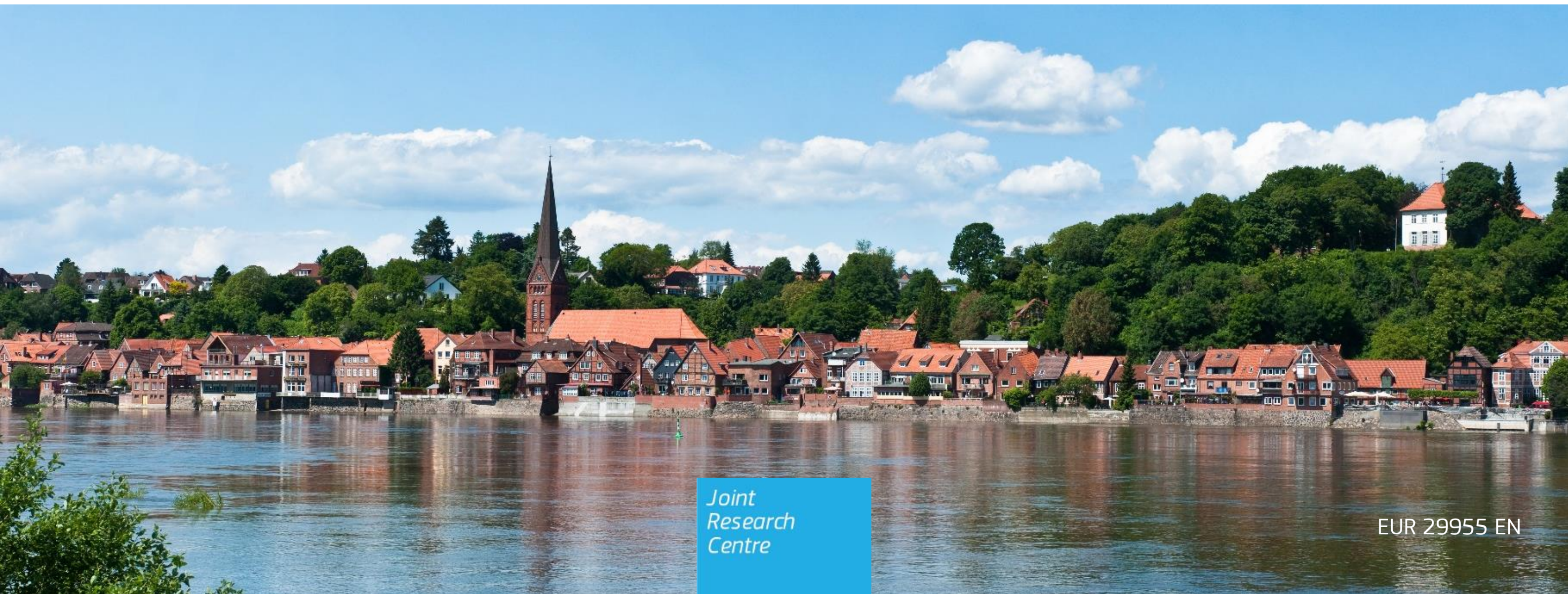
2020



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EU Science Hub
https://ec.europa.eu/jrc

JRC118425

EUR 29955 EN

PDF ISBN 978-92-76-12946-2 ISSN 1831-9424 doi:10.2760/14505

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Dottori F, Mentaschi L, Bianchi A, Alfieri L and Feyen L, *Adapting to rising river flood risk in the EU under climate change*, EUR 29955 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-12946-2 , doi:10.2760/14505, JRC118425.

Contents

Executive summary

River flooding is the costliest natural disaster in Europe. Global warming and continued development in flood prone areas will progressively increase river flood risk. Direct damages from flooding could become six times present losses by the end of the century in case of no climate mitigation and adaptation. Keeping global warming well below 2°C would halve these impacts. Adequate adaptation strategies can further substantially reduce future flood impacts. In particular, implementing building-based damage reduction measures and reducing flood peaks using retention areas can lower impacts in a cost-efficient way in most EU countries, even to flood risk levels that are lower than today. Restoring natural wetlands and floodplains to retain excess water also improves the state of water and ecosystems.

Current effects of river flooding

PESETA IV estimates that at present river flooding causes a damage of 7.8 €billion/year in the EU and UK, which is equivalent to around 0.06% of current GDP. Moreover, more than 170,000 people every year are exposed to river flooding in the EU and UK.

Future impacts of river flooding without adaptation

Global warming will progressively increase flood frequency and severity in most of Europe. At the same time, the projected social and economic growth will further increase exposure to flood events. If no mitigation and adaptation measures are taken, economic losses will grow to nearly 50 €billion/year at 3°C global warming by the end of this century, or more than six times compared to present, while nearly three times as many people would be exposed to flooding. Countries in eastern Europe will generally suffer higher losses relative to GDP, Limiting global warming to 1.5°C would halve the economic losses and population exposure to river flooding relative to unmitigated climate (Figure 1).

	Today	2100 - no adaptation			2100 - adaptation		
		1.5˚C	2˚C	3˚C	1.5˚C	2˚C	3˚C
Damages (€ billion/year)	7.8	24	33	48	8.6	9.6	8.6
People exposed (1000/year)	172	252	338	482	92	100	90

Figure 1. EU+UK annual damages and population exposed to river flooding in the present and by 2100 for different levels of global warming, with and without adaptation respectively. The "no adaptation" scenario refers to present-day flood protection measures. The "adaptation" scenario is based on the implementation of retention areas to store excess flood water to a level of protection that maximises their economic benefit.

Avoided river flood impacts with adaptation

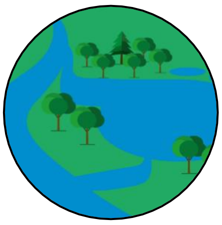
Flood risk reduction strategies can substantially reduce the projected increase in flood risk with global warming. In particular, reducing flood peaks using retention areas shows strong potential to lower impacts in a cost-efficient way in most EU countries (Figure 3). Implementing this strategy at EU level can reduce the economic damage and population exposed by the end of the century with more than 70%, as compared to no adaptation (Figure 1). Retention areas have additional benefits, such as restoring the natural functioning of floodplain areas and improving ecosystem quality. Strengthening existing dyke systems has lower but still favourable benefit-cost ratios (Figure 2), yet this can transfer risks downstream. It also tends to stimulate further development behind the flood barriers, which can result in catastrophic impacts in case of failure. Retention areas and dykes require high investments but bring a substantial reduction in economic and human impacts. Building-based flood proofing measures can strongly reduce damages typically with limited implementation investments. They also do not avoid floods to happen and therefore can only partially avoid flood damage. Relocation is the least cost-effective, their implementation costs are subject to large variability and they have lower social acceptance.

Strengthening of dyke systems:

2€ to 2.9€ saved for each € invested

41% to 68% reduction in economic damages

41% to 65% reduction in population exposed



Building of retention areas to store flood waters:

2.9€ to 3.5€ saved for each € invested

64% to 82% reduction in economic damage

63% to 81% reduction in population exposed

Damage reduction measures for buildings

5.2€ saved for each € invested

Up to 50% reduction in economic damage

No reduction in people exposed

Relocation to flood-safe areas

1.2€ saved for each € invested

17% reduction in economic damage

16% reduction in population exposed

Figure 2. Summary of the main outcomes of the analysis of four adaptation strategies considered in PESETA IV. All results are averaged at EU+UK level and calculated considering future socioeconomic conditions (2100 economy) under 1.5°C, 2°C and 3°C warming scenarios.

The present analysis is not designed to replace detailed analyses at local and regional scale, which are necessary for an effective and reliable design and implementation of adaptation measures. 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.

We focused our analyses on adaptation scenarios based on the application of a single type of measure. However, a combination of different measures working in synergy and optimised at the level of river basins is the best strategy to locally maximise benefits and minimise drawbacks of each measure. Moreover, the cost-benefit analysis does not include social, environmental and cultural aspects, which would require more complex multi-criteria analyses.

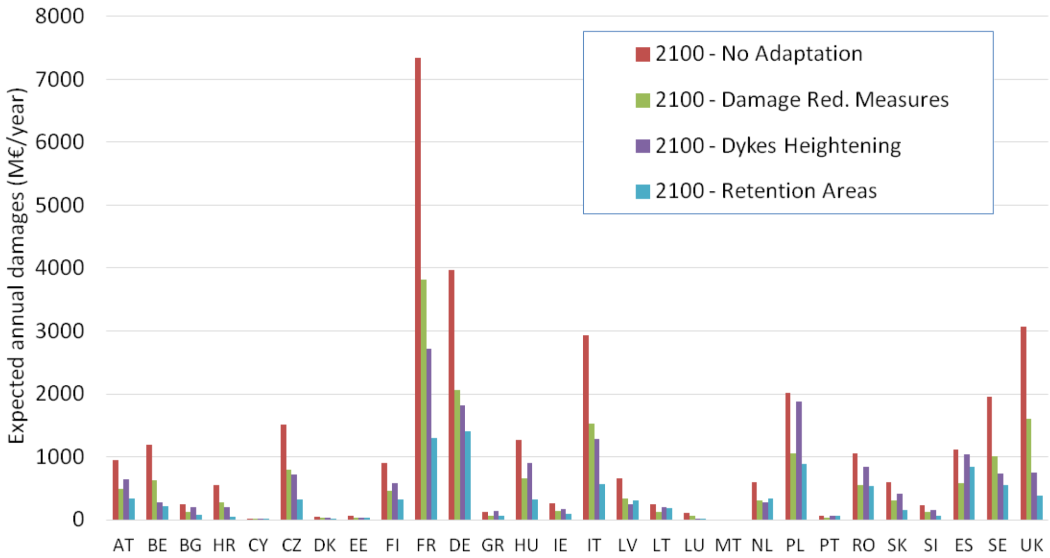


Figure 3. Comparison of expected annual damages in 2100 assuming no adaptation, and with the implementation of three different adaptation strategies. Results are calculated assuming a 2°C warming scenario.

Approach

A comprehensive modelling framework is applied to simulate river flows (LISFLOOD hydrological model), analyse the occurrence and intensity of flooding processes, and estimate the impacts on economy and people across Europe. We consider future climate scenarios corresponding to an increase of global average temperature of 1.5, 2 and 3°C above preindustrial temperature, combined with socioeconomic projections according to the ECFIN 2015 Ageing Report. We focus on four possible adaptation measures: strengthening of existing dyke systems, implementing flood damage reduction measures for buildings, building of retention areas to store flood waters, and relocation of people and buildings from flood-prone to flood-safe areas. The evaluation of each adaptation strategy is performed using a cost-benefit analysis that optimises the overall costs of implementation and avoided economic damages over the life time of the measure (up to 2100). The costs were calculated as the sum of capital investment costs to implement the measure and maintenance costs. The benefits are the damages avoided by implementing the measure, calculated as the difference between future 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. Discount rates are used to evaluate the cost-effectiveness of the investments required for the four adaptation measures considered. The benefit-to-cost ratio, which is the ratio of total benefits to total costs, is also based on discounted values and was calculated for each NUTS2 region and at country and EU+UK level.

1 Introduction

River floods are a major cause of economic and human losses in the world and in Europe (Alfieri et al., 2015). Despite the relevant efforts to reduce risk, river flood impacts appear to have increased in the last decades (Paprotny et al., 2018). Ongoing global warming and the projected economic growth and urban expansion are likely to further increase social and economic impacts in Europe (Alfieri et al., 2018a).

The potential rise of flood risk on future societies requires to identify adaptation strategies that are effective and sustainable from the economic, social and environmental point of view (e.g. capable of reducing flood risk without disproportionate economic, social and environmental costs). The evaluation of adaptation strategies requires not only assessing their effectiveness in impact reduction, but also their economic costs (e.g. for building and maintaining an infrastructure). While there is a large body of literature that evaluate the benefits of adaptation in reducing river flood risk, most assessments are limited to specific areas (Kreibich et al., 2015; Aerts, 2018). Continental and global scale studies so far only took into account single measures such as increasing dyke height (Ward et al., 2017) or generic vulnerability reduction (Kinoshita et al., 2018). However, a combination of different measures is necessary to find the most effective strategies and limiting side effects such as high economic costs, environmental impacts and maladaptation such as the "levee effect" (Jongman, 2018). Moreover, to our best knowledge, the use of "green" measures such as floodplain restoration has not been considered in large-scale studies.

Finally, several large European rivers are transnational, with flood protection programmes based on transregional or even international programmes and agreements (EEA, 2017). For instance, important flood prevention measures to protect Dutch cities located next to the Rhine are implemented in the upper Rhine valley, hundreds of km away as part of the "Integrated Rhine Programme[1]". As such, identification of suitable river flood adaptation strategies requires a pan-European approach.

[1] https://rp.baden-wuerttemberg.de/Themen/WasserBoden/IRP/Seiten/default.aspx

2 Methodology

In PESETA IV we use a comprehensive modelling framework to simulate the response of river flow to present and future climate conditions, to analyse the occurrence and intensity of flooding processes, and to estimate the impacts on economy and society across Europe. While the risk assessment structure of our methodology is similar to PESETA III (Alfieri et al., 2018b), here we made use of more recent data and updated modelling tools. Improvements include, among others, the latest climate simulations available for Europe (see Annex 1), a better representation of present flood protection levels, and updated functions to represent flood damage to buildings.

We focus on flooding from rivers while coastal flood risk is covered in the coastal study of PESETA IV. Our analysis also does not cover local pluvial or flash flooding. We assess river flood risk and adaptation for all EU countries 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.

We consider future climate scenarios corresponding to an increase of 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 scenario that could be expected by the end of the 21st century if adequate mitigation strategies are not taken. In order to disentangle the effects of global warming and socioeconomic dynamics on future flood risk we assess flood impacts of different warming levels assuming present socioeconomic conditions continue in the future as well as flood impacts with socioeconomic conditions in Europe in 2050 and 2100 as projected by the 2015[2] Ageing Report (Ciscar et al., 2017). We do not consider 3°C warming by mid-century as a realistic scenario, so only focus on the lower warming levels in 2050. Risk estimates are based on the average of the outputs of all available climate scenarios.

Based on the flood risk analysis with transient socioeconomic projections, we perform a pan-European assessment of the effectiveness of a range of adaptation strategies to reduce future flood risk. To this end, we collected information from scientific, grey and technical literature on main types of investments for flood risk mitigation, their size and costs for implementation, the decision-making tools that were applied to evaluate them, and performance indicators. The literature review showed that several adaptation strategies are available and have been applied in Europe to reduce flood risk (EEA, 2017; Aerts, 2018; GFDRR et al., 2019). Possible measures include investments that enhance the preparedness to floods (such as early warning systems), that reduce the frequency and magnitude of flood events (such as dyke systems and retention structures) and that mitigate the damage of floods (such as relocation and flood proofing of buildings). However, many case studies do not provide quantitative estimates on the effectiveness of adaptation measures, which are needed to perform a pan-European modelling. Based on the collected information, we focus our analysis on four possible adaptation measures for which we found sufficient quantitative cost and performance estimates to be considered in a pan-European framework. These are: strengthening of existing dyke systems, flood damage reduction measures for buildings, retention areas to store flood waters, and relocation of people and buildings from flood-prone to flood-safe areas (see Annex 1 for a more detailed description of each measure).

The evaluation of each adaptation strategy is performed using a cost-benefit analysis that optimises the costs of implementation and maintenance vs avoided economic damages (benefits) over the life time of the measure (see Annex 1 per the details). We applied discounting to both the costs and benefits considering a rate of 5% for countries eligible for the EU Cohesion Fund and 3% for other Member States, following European Commission's guidelines (EC, 2014). The benefit-cost ratio (BCR), which is the ratio of total benefits to total costs, is also based on discounted values and was calculated for each NUTS2 region as well as at country and EU+UK level. We note that in our cost-benefit analysis the benefits are limited to avoided flood losses until the end of the 21st century. Other potential benefits of some measures, such as restoring valuable ecosystems with retention areas, are also not included in the analysis. We also note that discount rates were assumed constant in time. Using lower, time-declining or zero social discount rates supports the view that we should act now to protect future generations. As such, we also present comparisons between present and future scenarios using undiscounted economic values, in order to give equal weight to present and future costs and benefits (EC, 2014). In addition, we present benefits of adaptation in terms of the reduction in population exposed.

[2] During the PESETA IV project, the 2018 Ageing projections became available but they could not be incorporated. Compared to the 2015 Ageing Report, GDP growth projections are slightly lower over the period 2025-2050 and marginally higher during 2055-2070. These updated projections do not affect the main conclusions of this report.

3 Results

In the first part of this section, we present projections of flood risk for future scenarios without adaptation. Then, we report the outcomes of the cost-benefit analysis of the four adaptation strategies considered in this study. We also provide a summary of other possible adaptation strategies not included in the analysis.

3.1 Flood risk projections without adaptation

We estimate that at present river flooding causes a damage of 7.8 €billion/year and more than 170,000 people are annually exposed to river flooding in the EU. This baseline estimate is somewhat larger than that obtained in PESETA III and relates mainly to an improved representation of present protection levels and updated flood damage functions for buildings. Table 1 provides an overview of how expected annual impacts for the EU are projected to change in view of global warming and socioeconomic conditions. Tables A3 and A4 in the Annex provide a breakdown for all EU countries, while Figures A1 and A2 show future increases in impacts at NUTS2 level. In the absence of additional adaptation, global warming will progressively increase flood risk in most of the European continent. Assuming present social and economic conditions (i.e. considering only the influence of climate change), economic losses and population exposed will be 50% higher even in the case of limiting global warming to 1.5°C. Under a 2°C and 3°C warming scenario, impacts in Europe would respectively double and triple. The projected changes are consistent with previous findings from PESETA III (Alfieri et al., 2018b).

Table 1. Summary of the expected annual damage (EAD, absolute and relative to country's GDP) and population exposed (EAPE) for EU+UK under present socioeconomic conditions (base), future socioeconomic conditions (2050 and 2100 economy) and climate scenarios (1.5°C, 2°C, 3°C warming)

	Base economy				Economy 2050		Economy 2100		
EU+UK	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
EAD in €billion (2015)	7,8	12,5	16,8	24,8	15,6	21,3	24,1	33,1	47,8
EAD as % GDP	0.06	0.10	0.13	0.20	0.07	0.10	0.05	0.07	0.11
EAPE in 1000 people	172	269	358	521	280	374	252	338	482

Future population projections according to the 2015 Ageing Report do not foresee drastic changes in exposure in most EU countries, with stable or even decreasing trends after 2050, especially in central and eastern European countries. As such, future increases in people annually exposed will mainly depend on climate conditions (Figures A1 and A2). The projected increase in the EU of the share of people older than 65 from 19% now to 30% by the end of this century, however, implies that more vulnerable people could be exposed to flooding.

Conversely, the interaction of global warming and projected economic growth will result in an amplification of flood losses in absolute terms. In 2050, that is, just 30 years from now, annual economic losses due to flooding in the EU can be 2.7 times larger assuming a 2°C warming scenario. Expressing losses relative to the size of the economy (losses as a fraction of GDP) shows that unless global warming is kept at 1.5°C, flood losses are projected to grow faster than GDP, and hence have a higher impact on the EU economy. Few areas will experience a small increase or even decrease in economic impacts, mainly areas in southern Europe (see Figures A1 and A2)

Table 2 provides the expected annual economic losses relative to GDP for all EU countries and the UK under present and future socioeconomic conditions, as in Table 1 for EU+UK. If global warming is kept below 2°C the projected economic growth will offset or even decrease the share of flood damages in most countries, even though absolute losses will increase. Conversely, under a 3°C scenario the share of flood losses will increase in most of the European Union, and exceed 0.5% of GDP in countries like Croatia, Hungary and Latvia. In general, countries in eastern Europe will suffer higher losses relative to GDP, However, results for a number of medium-small countries are uncertain due to limited information about local protection standards and historical losses (see Annex 1.4 for a discussion).

Table 2. Summary of the expected annual damage relative to country's GDP for all EU countries under present conditions (base), future socioeconomic conditions (2050 and 2100 economy) and climate scenarios (1.5°C, 2°C, 3°C warming).

	Base economy				Economy 2050		Economy 2100		
Country	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Austria	0.08%	0.11%	0.13%	0.17%	0.09%	0.11%	0.07%	0.09%	0.12%
Belgium	0.05%	0.09%	0.12%	0.19%	0.07%	0.10%	0.05%	0.07%	0.11%
Bulgaria	0.20%	0.26%	0.33%	0.44%	0.21%	0.26%	0.17%	0.22%	0.30%
Croatia	0.40%	0.71%	0.96%	1.31%	0.35%	0.49%	0.31%	0.43%	0.61%
Cyprus	0.03%	0.03%	0.02%	0.02%	0.02%	0.01%	0.01%	0.01%	0.01%
Czechia	0.26%	0.39%	0.49%	0.71%	0.28%	0.35%	0.20%	0.25%	0.38%
Denmark	0.01%	0.01%	0.01%	0.02%	0.00%	0.01%	0.00%	0.00%	0.01%
Estonia	0.27%	0.34%	0.46%	0.66%	0.14%	0.15%	0.11%	0.13%	0.14%
Finland	0.13%	0.15%	0.23%	0.34%	0.12%	0.17%	0.09%	0.13%	0.19%
France	0.06%	0.11%	0.16%	0.20%	0.08%	0.12%	0.06%	0.09%	0.11%
Germany	0.03%	0.06%	0.09%	0.13%	0.05%	0.07%	0.04%	0.06%	0.09%
Greece	0.04%	0.05%	0.07%	0.09%	0.03%	0.04%	0.02%	0.03%	0.05%
Hungary	0.26%	0.45%	0.65%	1.13%	0.35%	0.51%	0.28%	0.42%	0.72%
Ireland	0.04%	0.05%	0.07%	0.14%	0.04%	0.05%	0.03%	0.04%	0.07%
Italy	0.05%	0.09%	0.10%	0.15%	0.06%	0.08%	0.05%	0.06%	0.08%
Latvia	0.86%	1.04%	1.32%	1.70%	0.85%	1.08%	0.70%	0.90%	1.15%
Lithuania	0.29%	0.38%	0.46%	0.62%	0.28%	0.33%	0.21%	0.25%	0.32%
Luxembourg	0.04%	0.06%	0.09%	0.12%	0.03%	0.05%	0.03%	0.04%	0.05%
Malta	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Netherlands	0.01%	0.02%	0.05%	0.07%	0.02%	0.04%	0.02%	0.03%	0.04%
Poland	0.14%	0.20%	0.25%	0.40%	0.15%	0.19%	0.15%	0.19%	0.29%
Portugal	0.03%	0.03%	0.04%	0.03%	0.02%	0.02%	0.02%	0.02%	0.02%
Romania	0.23%	0.33%	0.45%	0.68%	0.22%	0.29%	0.17%	0.23%	0.34%
Slovakia	0.19%	0.32%	0.40%	0.59%	0.24%	0.30%	0.20%	0.25%	0.37%
Slovenia	0.16%	0.25%	0.35%	0.52%	0.19%	0.26%	0.14%	0.20%	0.30%
Spain	0.04%	0.05%	0.05%	0.05%	0.04%	0.04%	0.03%	0.03%	0.03%
Sweden	0.05%	0.10%	0.18%	0.35%	0.06%	0.12%	0.05%	0.08%	0.16%
United Kingdom	0.03%	0.05%	0.07%	0.12%	0.04%	0.05%	0.03%	0.04%	0.06%
EU+UK	**0.06%**	**0.09%**	**0.13%**	**0.19%**	**0.07%**	**0.10%**	**0.05%**	**0.07%**	**0.10%**

3.2 Flood risk reduction with adaptation

In this section we discuss the results of the cost-benefit analysis of the four adaptation measures considered in this study. Figure 4*Figure 7* presents at country scale the benefit-to-cost ratio (BCR) of the design option for each measure that optimises costs and benefits of the investment considering 2°C warming by 2100. Country-scale BCR results for the 1.5°C and 3°C scenarios are shown in the annex in Tables A5 to A8. Figure 5 and Figure 6 present BCR results at NUTS2 administrative level for all the adaptation measures and all the warming scenarios considered. In the sections below we describe results for each of the measures. Results reported in the main text refer to the 2°C warming scenario, unless otherwise specified. Results for the 1.5°C and 3°C scenarios are shown in Annex 2.

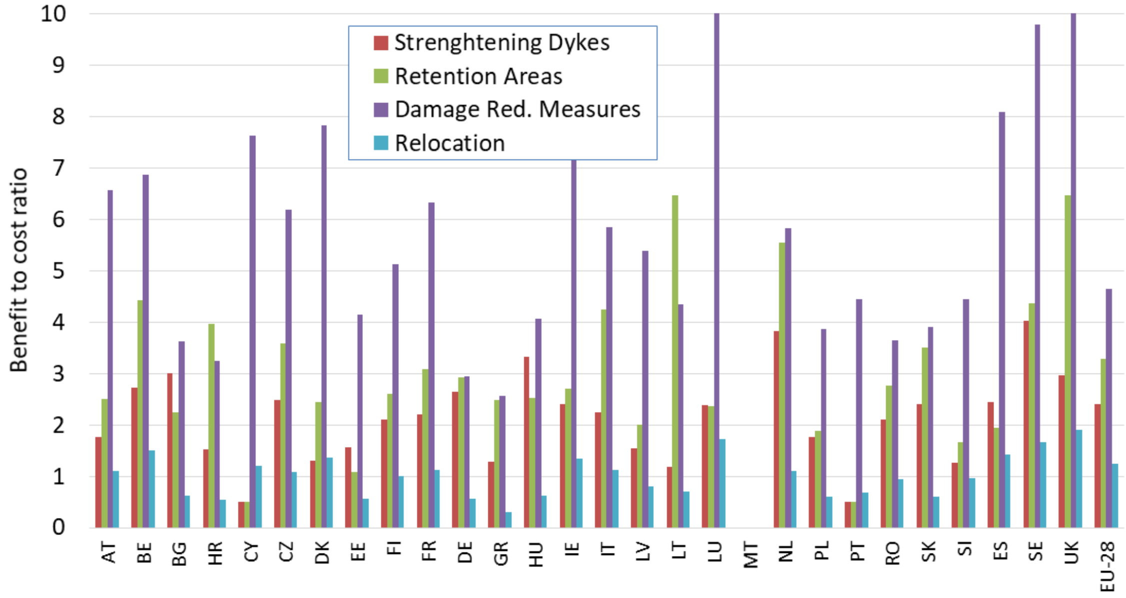


Figure 4. Benefit-to-cost ratio (BCR) values for the adaptation measures considered in PESETA IV, assuming a 2°C warming scenario and socioeconomic projections up to 2100 according to the 2015 Ageing Report. BCR values are based on total discounted costs and benefits over the period 2020-2100.

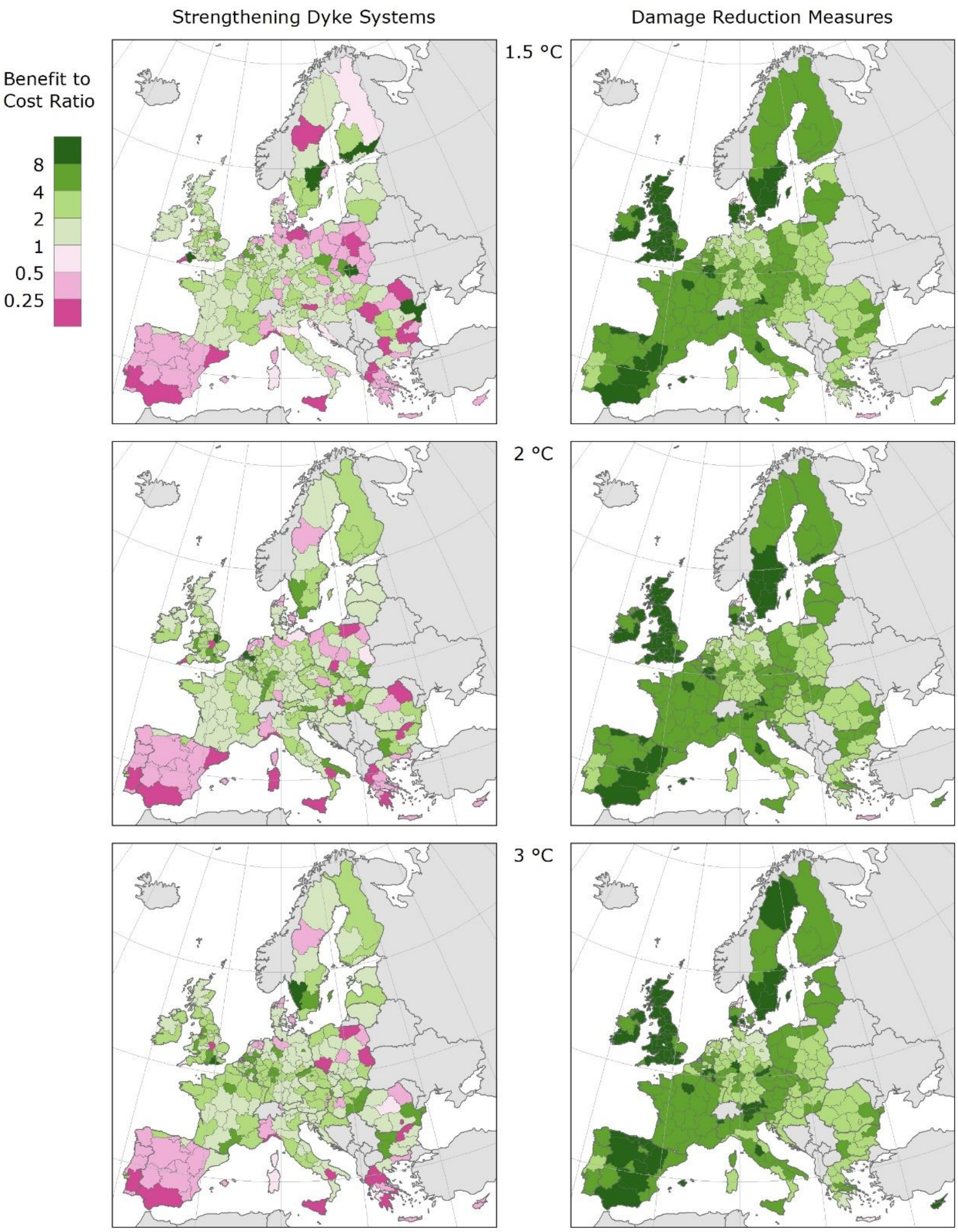


Figure 5. Overview of benefit-cost ratios (dimensionless) at NUTS2 level for the adaptation strategies "dyke strengthening" (left column) and "damage reduction" (right column), for all the warming scenarios considered. Annual costs and benefits are averaged over the period 2020-2100.

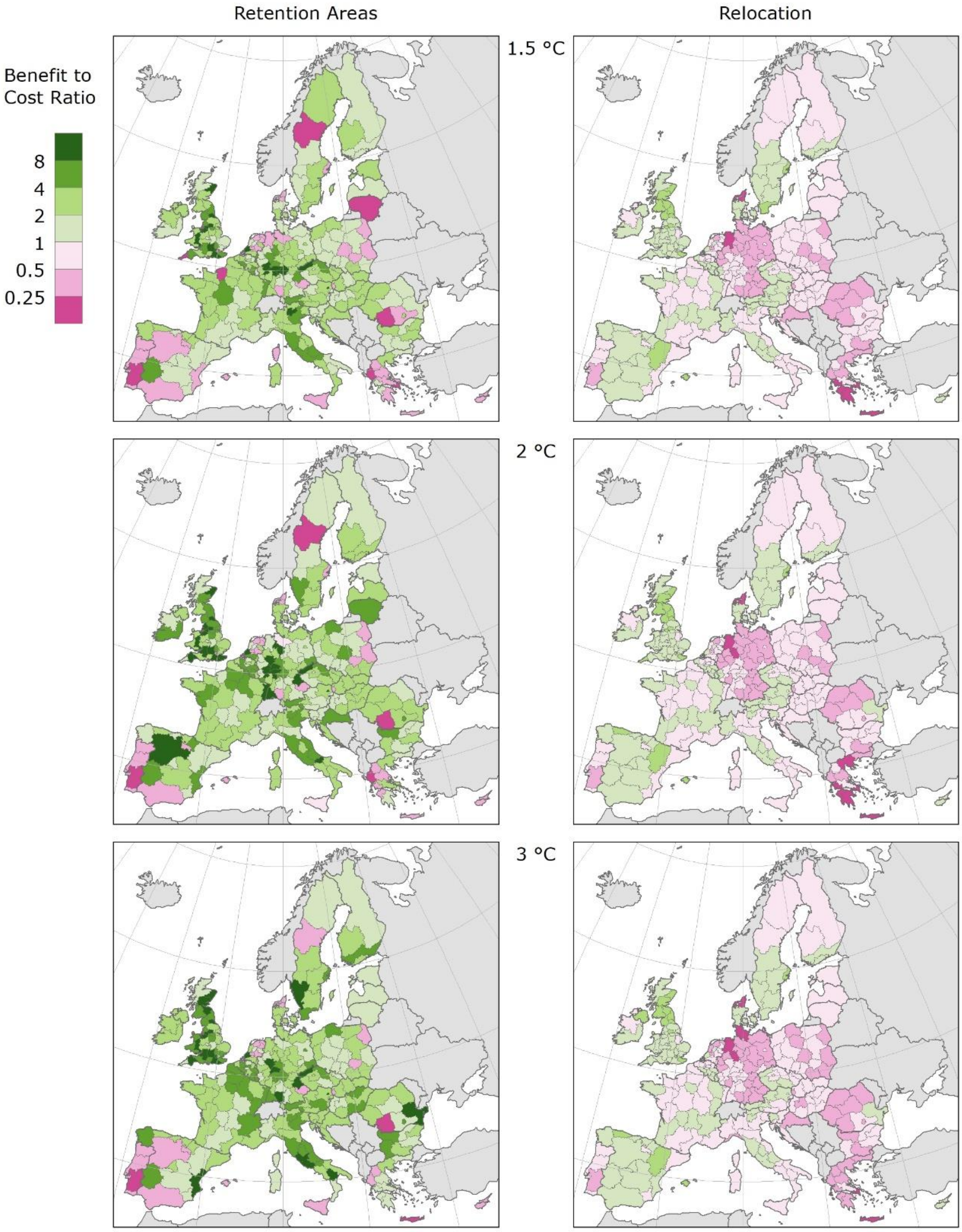


Figure 6. Overview of benefit-cost ratios at NUTS2 level for the adaptation strategies "retention areas" (left column) and "relocation" (right column), for all the warming scenarios considered. Annual costs and benefits are averaged over the period 2020-2100.

3.2.1 Adaptation through strengthening dyke systems

The cost-benefit analysis across the EU shows that strengthening existing dyke systems by increasing their height is economically convenient in most countries and regions, although with considerable variations in some regions. With lower levels of global warming, the BCR is below one in parts of eastern and southern Europe (Figure 5), but with increasing warming and consequently a stronger rise in flood risk, heightening dykes becomes more cost-effective. In countries such as Spain, Portugal and Greece, dyke heightening is economically convenient only in some administrative regions (Figure 5**Error! Reference source not found.**). This is mainly a consequence of the little increase (or even decreases) in flood impacts foreseen in Mediterranean and parts of eastern Europe (see Figures A1 and A2). However, increases in flood protection in these areas can still be a valid option in places with a high concentration of people and economic activity. Figure 7 shows at country scale the reduction in damage (left) and population exposed (right) in 2100 attainable with the optimal dyke heightening design option under the 2C warming scenario. Reductions in damage for the single countries ranges from 6% in Spain to 82% in Luxembourg, due to different levels of implementation given by the optimal design option. Reduction rates in population exposed are broadly similar.

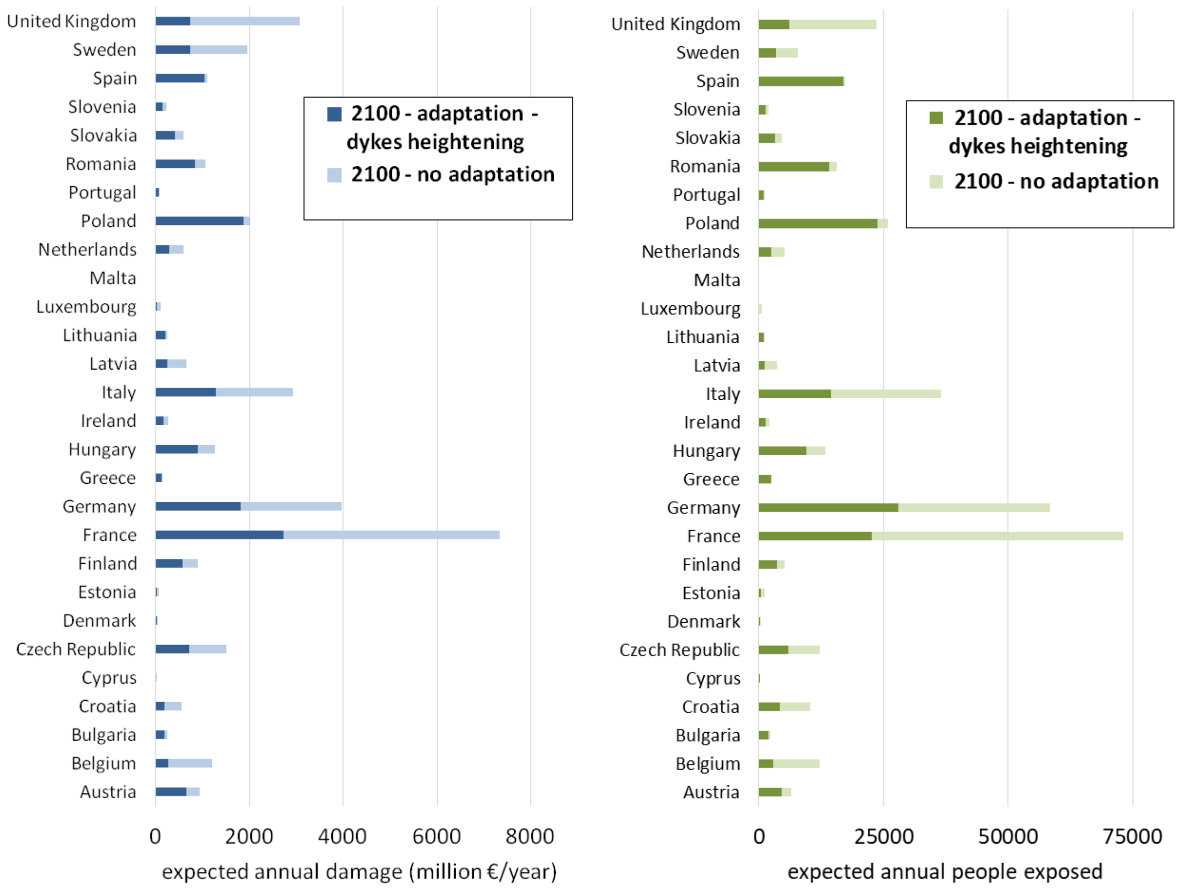


Figure 7. Annual flood losses (left) and population exposed (right) without adaptation (light colours) and with the optimal implementation of the “dyke heightening” strategy (dark colours) assuming a 2°C warming scenario by the end of this century.

At EU level, implementing the optimal design for the 2°C warming scenario would require an average annual investment of 2.1 €billion/year (average over 2020-2100 of undiscounted costs; costs at country scale are reported in Table A5). The corresponding increased level of protection would lower annual flood damages to 16.5 €billion/year by the end of the century compared to 33 €billion/year in case of no adaptation, or a reduction of 50%. Also 49% less people would be exposed by the end of this century compared to when dykes are not strengthened (Table A5). Similar as the BCR values also the avoided damages and people exposed grow with the level of global warming, showing the increasing relevance of adaptation as global temperature rises.

Even when economically convenient, it has to be considered that dyke systems have several social and environmental drawbacks. Heightening river dykes can increase the magnitude of peak flows downstream, thus amplifying flood hazard and risk downstream. Moreover, raising flood protection and the consequent reduction in the frequency of flooding events favours the loss of flood memory. This can lead to increasing exposure in flood-prone areas, which is usually referred to as “levee effect”. In case of unexpected and sudden failures of the flood defences this could lead to catastrophic consequences. Therefore, it might be advisable to use dykes only to protect against frequent low-magnitude events, and use retention systems to mitigate extreme flood peaks, or to foresee backup protection systems.

3.2.2 Adaptation through retention areas

This adaptation option is based on creating areas within or aside the river network that can be flooded in a controlled manner when the river stage reaches critical levels (Arrighi et al. 2018). We do not consider here retention reservoirs created by dams as they require larger investments and can have negative environmental implications.

The cost-benefit analysis shows that the use of retention basins to store flood water is economically convenient in most NUTS2 regions and countries and, Portugal and Cyprus being the only exceptions (Figure 6, Table A6). Retention areas allow for a larger reduction in social and economic impacts (Figure 8) compared with the other measures considered herein. They generally also show higher BCR values compared to dyke strengthening (Figure 4) indicating that this adaptation strategy can be more cost-efficient to increase protection standards at regional level. At EU level, implementing the optimal design for the 2°C warming scenario would require an average annual investment of 2.5 €billion/year over the period 2020-2100 (undiscounted values). Such level of investment would reduce economic damages by 71% (from 33 to 9.6 €billion/year) and population annually exposed by 70% (from 338,000 to 100,000) by the end of the century.

These findings are consistent for all the warming scenarios considered, and in most countries the cost-effectiveness increases with increased warming, as well as the avoided impacts (see Table A6). Moreover, retention areas offer additional environmental benefits. While they may require large structural investments (e.g. diversions, dykes), retention areas can be designed to reconnect floodplain areas to the river network. Restoring the natural functioning of floodplain areas may improve ecosystem quality and provide additional services (e.g. reduction of pollutants, regulation of sediment fluxes (EEA, 2017; GFDRR et al., 2019). The inclusion of environmental services would further increase the cost-effectiveness of retention areas, as highlighted in previous studies (EEA 2017). Moreover, in some areas existing wetlands can be adapted to reduce flood peaks, thus combining environmental restoration with reduced costs.

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 then are no longer available for intensive uses (e.g. agriculture, urbanisation). Hence, land use and agricultural policies should aim at favouring the use of floodplains for retention. Moreover, narrow floodplains may be not suited for this measure For instance, the low cost-efficiency for Portugal relates to the reduced width of many floodplain areas and scarce availability of not urbanised areas, which increases construction costs for retention areas.

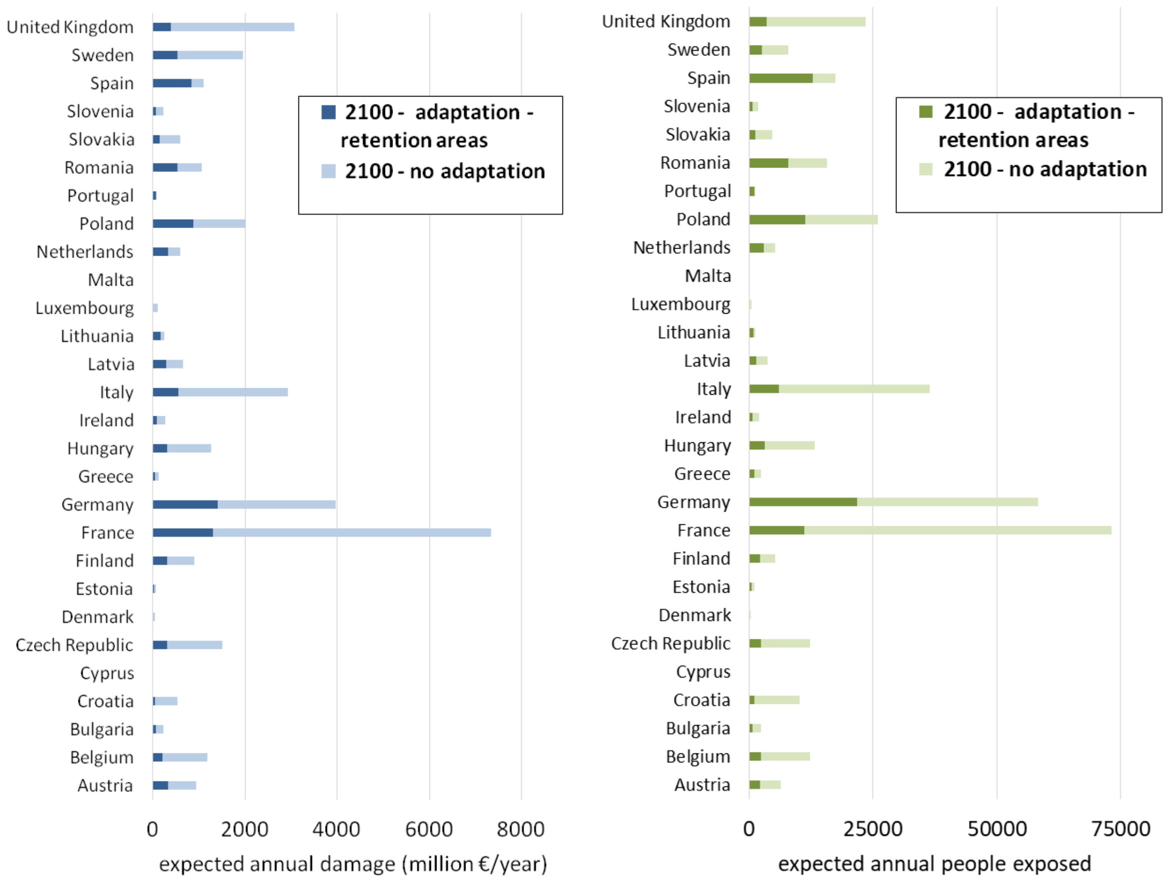


Figure 8. Reduction in economic damage (left) and population exposed (right) attainable with the optimal implementation of the "retention areas" adaptation strategy, assuming a 2°C warming scenario. Data refer to 2100 socioeconomic scenario. Economic damages are not discounted.

It is important to note 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 hydrological basin. This has to be considered when evaluating BCR results at NUTS2 level (Figure 6), because areas located downstream can benefit from upstream retention areas, and hence reduce local implementation costs. Ideally, implementation costs should be shared among all regions within the same river basin. Planning in transboundary rivers such as the Danube may be complex, although some projects have already been successfully carried out (EEA, 2017).

3.2.3 Adaptation through damage reduction measures

Flood proofing represents structural and non-structural modifications of buildings to prevent or reduce flood damage to structures and/or their contents. Dry flood proofing intends to make a building watertight or substantially impermeable to floodwaters up to the expected flood water height. Wet flood proofing reduces damage from flooding by allowing flood water to easily enter and exit a structure in order to minimise structural damages, as well as by using flood resistant materials and elevating important utilities. Wet proofing is generally less expensive but also less effective. Reported costs and loss reduction potential of both wet and dry proofing varies widely among studies. We used average implementation costs that are a function of the built-up area exposed and the damage reduction ratio required (more details in Annex 1). However, we also performed additional simulations using increased construction and maintenance costs, which showed that overall conclusions drawn here are still valid under more stringent hypotheses.

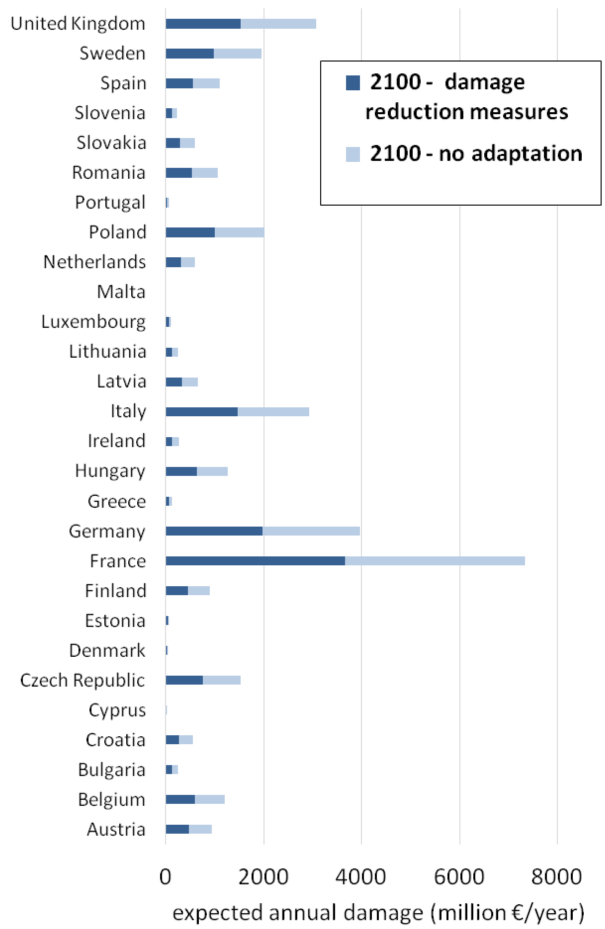


Figure 9. Annual flood losses without adaptation (light blue) and with a 50% reduction target for the "damage reduction to buildings" adaptation strategy (dark blue) assuming a 2°C warming scenario by the end of this century.

Reducing flood damages through specific improvements in buildings is economically convenient in all EU countries. Figure 9 presents the results for the flood proofing design option of reducing damage by 50% for each country under the 2°C warming scenario (benefit-to-cost ratio in this case does not depend to the level of implementation), while Figure 5 presents the results at NUTS2 administrative level. Note that in this case we do not calculate the reduction in population exposed as this measure does not avoid the floods to happen and therefore only influences economic losses (even though people can be protected to some extent).

Implementation costs (950 €million/year at EU level for the 2°C warming scenario) are considerably lower compared to structural measures such as dykes (country scale costs are reported in Table A7). Moreover, damage reduction measures applied at building scale have a low environmental impact and are relatively easy to implement and can be adapted to changing conditions. On the other hand, the degree of damage reduction attainable is subject to considerable uncertainty, and the highest reduction rates (above 50-60%) reported require more expensive solutions that may be less cost-effective. Most importantly, damage reduction measures cannot completely prevent flood damage to all exposed assets (e.g. infrastructural and agricultural damages are not influenced by this measure), and as it does not avoid floods to happen population exposure is not reduced (although the degree to which people are affected can be reduced). Therefore, it might be advisable to use damage reduction measures in combination with other structural or natural hazard-reduction measures in order to minimise impacts in case the other measures cannot avoid the flood to happen.

3.2.4 Adaptation through relocation

Relocation of people and assets appears to be the least cost-effective measure among all the adaptation measures considered in PESETA IV. As can be seen from Figure 4 , Figure 6 *Figure 5* and Table A8, relocation shows to be economically convenient in less than half of EU countries and in a minority of NUTS2 regions, mainly in the UK, Luxembourg, Spain, Sweden and Belgium. This suggests that in these countries future expected annual flood damages may become comparable to the value of buildings. Moreover, the analysis of implementation costs for those countries with BRC>1(e.g. Belgium, Sweden, UK) shows that relocation costs (Table A8) are comparable with those of dikes strengthening and building of retention areas (Table A5 and Table A6), yet with much lower reduction rates. Indeed, reported costs of relocation are very high, as they not only include the demolishing of existing buildings, but also the acquisition of new land and the construction of new infrastructure.

Results for relocation are more prone to uncertainty than for the other measures here considered. Real market values of acquired land and relocated buildings should be considered, which could substantially change implementation costs. In addition, relocation costs are highly sensitive to variables that have less influence on the other adaptation measures here considered, such as number of dwellings and storeys in buildings in flood-prone areas. Such information is not available at European scale, therefore we modelled implementation costs considering demolition, land acquisition and construction costs reported in literature. Results are based on average cost values from literature, but sensitivity analyses showed that relocation becomes not cost-effective in a large majority of NUTS regions (i.e. benefit-to-cost ratio drops below one) when higher implementation costs are considered.

It is also important to note that relocated people are generally offered a partial compensation for their properties by the local government (Kick et al., 2011: López-Carr and Marter-Kenyon 2015), thus suggesting that financial incentives are necessary to promote relocation measures. Moreover, large scale relocations might be unfeasible due to the difficulty in finding new settlements areas for relocated people and assets elsewhere. There is also a low social acceptation 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, it has to be considered that relocation is the most robust solution, as flood risk is completely avoided. Therefore, it should be considered as a “last resort” option.

3.2.5 Other adaptation measures

The four adaptation strategies analysed in PESETA IV are not the only solutions to mitigate river flood risk. We describe here some other widely applied measures, with a review of their cost-effectiveness taken from literature, and we briefly discuss the issues that prevented their inclusion in the present study. Note that we focus our review on non-structural and nature-based solutions (e.g. measures that strategically conserve or restore natural ecosystems to mitigate flood risk (GFDRR 2019).

3.2.5.1 Early warning systems

Flood Early Warning Systems (EWS) are generally based on numerical models that simulate the evolution of river flow variables (mainly discharge and water level) across the river catchment(s) of interest, on the basis of numerical weather predictions and river flow observations. Thus, operational centres managing the EWS are able to forecast river flow conditions with a lead time up to hours, days or even weeks, depending on weather conditions and catchment characteristics. Flood forecasts issued by EWS give to emergency management crucial information to take decisions in accordance with the emergency plans.

Early warning systems are widely used in several countries and river basins in Europe. However, to our best knowledge there is not a database of all existing EWSs at European scale, therefore it is not possible to understand which areas in Europe would benefit from EWS development or improvements.

Limited information exist about the cost-effectiveness of EWS. Pappenberger et al. (2015) provide evidence of the monetary benefit in cross-border continental-scale flood EWSs. The benefits were estimated to be of the order of €400 for every euro invested (Pappenberger et al., 2015). However, local-scale studies (e.g. Meyer et al., 2012) calculated much lower cost-to-benefit ratios. Moreover, we could not find studies that provide unit costs for EWS development or improvement based on, say, the extension of the river network to be monitored.

3.2.5.2 Emergency measures

Emergency measures can be defined as temporary, quick actions that can be taken in case of a flood alert to increase preparedness and reduce impacts. They include, for instance, manoeuvring of hydraulic structures such as sluice gates and diversions, the preparation and deployment of temporary barriers made with sandbags, the evacuation of people and removal of valuable assets from flood-prone zones, the alerting of people. Decisions regarding the deployment of emergency measures are generally made on the basis of risk thresholds. Hence, when observations and/or forecasts exceed a threshold value (warning level) a number of corresponding mitigation actions can be implemented (Molinari et al., 2013).

Emergency measures are routinely applied during major floods in Europe (Dottori et al., 2017). However, similar as for EWS, we could not find information regarding the extent and application and the few studies available in literature showed that emergency costs are affected by a high degree of uncertainty. Molinari et al (2013) estimated emergency costs to be equal to 10% of damage to buildings. As for the benefits, the same authors estimated a damage reduction between 7% and 26%, depending on the flood scenario considered and on the measures taken.

3.2.5.3 Improvement of urban drainage systems

The capacity of urban drainage systems to store and absorb storm water allows to decrease surface runoff and to reduce flood peaks, hence reduce the risk of pluvial flooding due to intense rainfall and flooding in minor river networks.

Drainage systems can be improved through the implementation of both structural and nature-base solutions, such as green roofs, permeable pavements, retention areas and wetlands. For instance, the implementation of green roofs may reduce stormwater volumes between 50 and 100%, while permeable pavements may reduce runoff volumes up to 90%. Beyond helping control urban flooding, nature-based solutions can prevent stormwater pollution, mitigate the heat island effect in urban centres and improve ecosystem functionality (GFDRR et al., 2019).

Measures to improve drainage systems were not considered in PESETA IV framework because they are generally more related with flood hazard caused by pluvial floods or excessive runoff, which is not considered in our risk modelling framework.

3.2.5.4 River re-naturalisation

In Europe, floodplains and rivers have lost their capacity to temporarily store water due to land drainage, intensive urbanisation and river channelisation. Restoring the floodplain roles in terms of their retention capacity and ecosystem functions and reconnecting them to the river constitutes the most natural way to minimise flood risk. In PESETA IV analysis, this has been accounted in the design of retention areas, which can effectively be used for restoration and management of floodplains and wetlands.

Other natural water retention measures that can be implemented regard the re-naturalisation of stream beds, for instance through riparian buffer installation and development and river re-meandering. However, evidence on the direct impacts of these measures on run-off control and storage capacity is not available in literature (EEA, 2017).

4 Conclusions

The adaptation analysis performed in PESETA IV shows that adequate flood risk reduction strategies can substantially reduce the projected increase in flood risk with global warming. In particular, reducing flood peaks using retention areas shows strong potential to lower impacts in a cost-efficient way. They also allow restoring the natural functioning of floodplain areas, thus improving ecosystem quality. Strengthening existing dyke systems can also avoid floods to happen, yet they can transfer risks downstream and stimulate further development behind the flood barriers. Implementing building-based damage reduction measures do not avoid floods to happen but have the highest cost-benefit ratio due to limited implementation investments. Strengthening of dyke systems and creation of retention areas require much higher investments. Relocation is less cost-effective and subject to large variability of implementation cost, and has lower social acceptance.

Local cost-effectiveness of different measures can deviate strongly from those presented herein due to site-specific characteristics. Moreover, the results of the analysis are sensitive to some implementation choices (see Annex 1). 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, advice regarding optimal adaptation measures should require engagement of local 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.

We focused our analyses on adaptation scenarios based on the application of a single type of measure. However, a combination of different measures working in synergy and optimised at the level of river basins is likely to be the best strategy to locally maximise benefits and minimise drawbacks of each measure. Moreover, the cost-benefit analysis does not include social, environmental and cultural aspects, which would require more complex multi-criteria analyses. 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].

Considering future research avenues, other adaptation measures could be included in the framework, provided that enough data are made available for their implementation in a continental-scale modelling framework. Furthermore, the analysis of future risk trends linked to extreme precipitation and flash floods would complement the river and coastal flood risk analyses carried out in PESETA IV, and provide a detailed picture of overall inland flood risk in Europe.

References

Aerts, J.C.J.H. (2018). A Review of Cost Estimates for Flood Adaptation. *Water*, 10(11), 1646. https://doi.org/10.3390/w10111646

Alfieri, L., Feyen, L., Dottori, F., Bianchi, A. (2015). Ensemble flood risk assessment in Europe under high end climate scenarios, *Global Environmental Change* 35, 199–212, https://doi.org/10.1016/j.gloenvcha.2015.09.004

Alfieri, L., Feyen, L., Di Baldassarre, G, (2016a). Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. *Climatic Change* 136, 507-521.

Alfieri, L., Feyen, L., Salamon, P., Thielen, J., Bianchi, A., Dottori, F., and Burek, P., (2016b). Modelling the socio-economic impact of river floods in Europe, *Natural Hazards and Earth System Sciences*, 16, 1401–1411, https://doi.org/10.5194/nhess-16-1401-2016.

Alfieri, L., Dottori, F., Betts, R., Salamon, P., Feyen, L. (2018) Multi-model projections of river flood risk in Europe under global warming. *Climate* 6, 6.

Alfieri, L., Dottori, F., Feyen L. (2018). PESETA III – Task 7: River floods, EUR 29422 EN, *Publications Office of the European Union*, Luxembourg, https://doi.org/10.2760/849948.

Amadio, M., Scorzini, A. R., Carisi, F., Essenfelder, A. H., Domeneghetti, A., Mysiak, J., and Castellarin, A., 2019. Testing empirical and synthetic flood damage models: the case of Italy, *Natural Hazards and Earth System Sciences*, 19, 661–678, https://doi.org/10.5194/nhess-19-661-2019.

Arrighi, C., Rossi, L., Trasforini, E., Rudari, R., Ferraris, L., Brugioni, M., Franceschini, S., Castelli, F. (2018). Quantification of Flood risk mitigation benefits: A building-scale damage assessment through the RASOR platform. *Journal of Environmental Management*, 207, 92-104.

Batista e Silva, F., Rosina, K., Schiavina, M., Marín-Herrera, M., Freire, S., Ziemba, L., Craglia, M., Lavalle, C. (2018). 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

Bates, P. D., Horritt, M. S., Fewtrell, T. J. (2010). A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *Journal of Hydrology*, 387, 33-45.

Burek, P., Knijff van der, J., Roo de, A. (2013). LISFLOOD, Distributed Water Balance and Flood Simulation Model Revised User Manual 2013. *Publications Office of the European Union*, Luxembourg.

Ciscar, J.C., Mongelli, I., Szewczyk, W. (2017). 'PESETA III: Task 2 - Socioeconomic scenarios dataset', Technical Report, European Commission.

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., & Stacke, T. (2014). First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proceedings of the National Academy of Sciences*, 111(9), 3257-3261.

De Moel, H., Aerts, J. C. J. H., 2011. Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates, *Natural Hazards*, 58, 407-425.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., & Blöschl, G. (2015). Debates - Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resources Research*, 51(6), 4770-4781.

Dottori, F., Kalas, M., Salamon, P., Bianchi, A., Alfieri, L., Feyen, L. (2017). An operational procedure for rapid flood risk assessment in Europe, *Natural Hazards and Earth System Sciences*, 17, 1111–1126, https://doi.org/10.5194/nhess-17-1111-2017

Dottori, F., Szewczyk, W., Ciscar, J.C., Zhao, F., Alfieri, L., Hirabayashi, Y., Bianchi, A., Mongelli, I., Frieler, K., Betts, R.A., Feyen, L. 2018. Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change*, 8, 781–786.

European Commission (2014). Guide to Cost-Benefit Analysis of Investment Projects. doi:10.2776/97516

European Environmental Agency. Green Infrastructure and Flood Management. EEA Report No 14/2017, https://www.eea.europa.eu/publications/green-infrastructure-and-flood-management

Gersonius, B., Zevenbergen, C., Puyan, N., Billah, M.M.M. (2008). Efficiency of private flood proofing of new buildings=adapted redevelopment of a floodplain in the Netherlands. WIT *Transactions on Ecology and the Environment*, Vol 118: Flood Recovery, Innovation and Response DOI 10.2495/FRIAR080241

GFDRR, World Bank Group, Profor, WRI (2019): 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).

Huizinga, J., Moel, H. de, Szewczyk, W. (2017). 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

Jacobs-Crisioni, C., Diogo, V., Perpiña Castillo, C., Baranzelli, C., Batista e Silva, F., Rosina, K., Kavalov, B., Lavalle, C. (2017). The LUISA Territorial Reference Scenario 2017. A technical description, *Publications Office of the European Union*, Luxembourg, ISBN 978-92-79-73866-1.

Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J. C. J. H., Mechler, R., Botzen, W. J. W., Bouwer, L. M., Pflug, G., Rojas, R., and Ward, P. J. (2014). Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change* 4, 264–268, doi:10.1038/nclimate2124.

Jongman, B. (2018). Effective adaptation to rising flood risk, *Nature Communications* 9-1986, doi: 10.1038/s41467-018-04396-1

Kick, E. L., Fraser, J. C., Fulkerson, G. M., McKinney, L. A., De Vries, D. H. (2011). Repetitive flood victims and acceptance of FEMA mitigation offers: an analysis with community–system policy implications. *Disasters*, 35(3), 510-539.

King, D., Bird, D., Haynes, K., Boon, H., Cottrell, A., Millar, J., Okada, T., Boxe, P., Keogh, D., Thomas, M. (2014). Voluntary relocation as an adaptation strategy to extreme weather events. *International journal of disaster risk reduction*, 8, 83-90.

López-Carr, D., Marter-Kenyon, J. (2015). Human adaptation: manage climate-induced resettlement. *Nature* 517, 265–267, doi:10.1038/517265a

Kinoshita, Y., Tanoue, M., Watanabe, S., Hirabayashi, Y. (2018). Quantifying the effect of autonomous adaptation to global river flood projections: application to future flood risk assessments. *Environmental Research Letters* 13, 014006, https://doi.org/10.1088/1748-9326/aa9401

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

Kreibich, H., Bubeck, P., Van Vliet, M., De Moel, H. (2015). 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.

Kuik, O., Scussolini, P., Mechler, R., Mochizuki, J., Hunt,A., Wellman J. (2016) Assessing the economic case for adaptation to extreme events at different scales. Report of the ECONADAPT project https://econadapt.eu/sites/default/files/docs/Deliverable%205-1%20approved%20for%20publishing_1.pdf, accessed on 6/7/2018.

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.

McSweeney, C.F.; Jones, R.G., 2016. How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP? *Climate Services* 1, 24–29.

Meyer, V., Priest, S., Kuhlicke, C. (2012). Economic evaluation of structural and non-structural flood risk management measures: examples from the Mulde River. *Natural Hazards* 62:301–324, DOI 10.1007/s11069-011-9997-z.

Molinari, D., Ballio, F., Menoni, S. (2013). Modelling the benefits of flood emergency management measures in reducing damages: A case study on Sondrio, Italy. *Natural Hazards and Earth System Sciences*, 13, 1913-1927.

Pappenberger, F., Cloke, H. L., Parker, D.J., Wetterhall, F., Richardson, D.S, Thielen, J. (2015). The monetary benefit of early flood warnings in Europe. *Environmental Science & Policy* 51, 278-291.

Paprotny, D., Sebastian, A., Morales-Napoles, O., Jonkman, S. (2018) Trends in flood losses in Europe over the past 150 years. *Nature Communications* 9(1), 1985, https://doi.org/10.1038/s41467-018-04253-1.

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, 1737–1751, (2013) doi:10.1016/j.gloenvcha.2013.08.006.

Rosina K., Batista e Silva, F., Vizcaino, P., Marín Herrera M., Freire S., Schiavina M. (2018). 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

Scussolini, P., Aerts, J. C., Jongman, B., Bouwer, L. M., Winsemius, H. C., de Moel, H., Ward, P. J. (2016). FLOPROS: an evolving global database of flood protection standards. *Natural Hazards and Earth System Sciences*, 16(5), 1049-1061.

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

Ward, P. J., Jongman, B., Aerts, J. C., Bates, P. D., Botzen, W. J., Loaiza, A. D., Hallegatte, S., Kind J.M., Kwadijk, J., Scussolini, P., Winsemius, H. C. (2017). A global framework for future costs and benefits of river-flood protection in urban areas. *Nature Climate Change*, 7(9), 642-646.

Annexes

Annex 1. Methodology

A1.1 Climate projections

Projections of river streamflow with warming are based on an ensemble of regional climate models (RCM) driven by different general circulation models (GCMs) (Table A1). The GCM and RCM runs are forced using Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCP4.5 may be viewed as a moderate-emissions-mitigation-policy scenario and RCP8.5 as a high-end emissions scenario. The combination of RCP forcing, GCMs and RCMs results in an ensemble with 22 model realisations. Statistical and quantitative hazard analyses in this report are performed over 30-year time periods. The reference scenario spans the period 1981-2010, hereinafter referred to as "base". We compare impacts for the baseline with those over 30-year time slices centred on the year that global average temperature is 1.5, 2 and 3°C above preindustrial temperature (Table A1). The 1.5°C and 2°C warming scenarios are explicitly considered in the Paris Agreement, while a 3°C global warming is a scenario that could be expected by the end of the 21st century if adequate mitigation strategies are not taken.

Table A1. Regional climate projections used in river flood impact analysis and corresponding year of exceeding 1.5, 2 and 3°C warming.

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

It should be noted that we derived climate at global warming levels from transient climate projections, which may differ from stabilized climate at those warming levels. Studies (e.g., Maule et al., 2017) suggest that the effect of pathway to global warming levels is small compared to the models' variability, expect for strongly not time-invariant variables such as sea level rise.

A1.2 Flood hazard and risk projections

We used the historical climate scenarios and future projections generated by the climate models described in Section A 1.1 to run continuous 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). LISFLOOD is also used in other tasks of PESETA IV to evaluate future changes in river flow linked to water resources availability and drought conditions. However, our analysis is focused on high-flow conditions representative of hazardous flood events.

Two-dimensional hydraulic simulations to derive flood hazard maps are performed with LISFLOOD -FP (Bates et al., 2010), using flood hydrographs with statistical features derived by LISFLOOD hydrological simulations. Such simulations allows to represent floodplain inundation processes.

Exposure information is given by the European population density map by Batista e Silva et al. (2018) and by the refined version of the CORINE Land Cover proposed by Rosina et al. (2018). Both maps are consistent with official statistical data at European scale, and available at the same resolution of flood hazard maps (100m).

Vulnerability to floods is included in the form of damage functions and through a flood protection map. Country specific depth-damage functions from Huizinga et al. (2017) are used to link flood depth with the corresponding direct economic damage, considering LUISA land use classes and gross domestic product (GDP) per capita at local administrative level. Spatial information on the flood protection level in Europe was obtained from a new datasets of flood protection standards specifically developed for PESETA IV. The new dataset combine information on protection design levels with modelled protection standards calculated by Jongman et al. (2014) and Scussolini et al. (2016).

To disentangle the effects of climate change and socioeconomic development, we calculate flood risk scenarios assuming present exposure values (static economic analysis, only accounts for the effects of climate change) and combining the warming scenarios with social and economic conditions in Europe in 2050 and 2100 as projected by the EU Reference economic scenario (2015 Ageing Report projections, Ciscar et al., 2017). We do not consider 3°C warming by mid-century as a realistic scenario, so only focus on the lower warming levels in 2050.

Social and economic Projections are based on the ECFIN 2015 Ageing Report, further referred to as EU Reference Scenario. This scenario acts as a benchmark of current policy, market and demographic trends in the EU. High-resolution population projections based on the EU Reference Scenario were derived with 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. As the Ageing report deals with projections only to the year 2060, the projections have been extended to the year 2100. The 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).

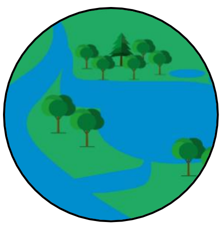
All the risk estimates in this report are based on averaging the results of the ensemble of all available climate scenarios.

A1.3 Evaluation of adaptation strategies

We base our analysis on a database of flood risk reduction investments in Europe specifically developed for PESETA IV, derived from a detailed review of scientific, grey and technical literature. The database provides an overview of the main types of investments applied in a number of case studies, mainly in Europe. We use the information regarding size and costs of implementation to derive unit costs of the different adaptation measures, suitable for application within a pan-European flood risk evaluation framework (e.g. the cost to increase the height of one linear kilometre of dyke by one meter). Moreover, we derived useful information to clarify the link between implementation costs and impact reduction (e.g. damage reduction factor given by a specific flood-proofing measure). Table A2 provide a description of the four adaptation measures considered in PESETA IV.

The calculation of cost and benefits follows the framework proposed by Ward et al. (2017). Investment costs are calculated considering construction costs starting in 2020 and finalizing in 2050, while maintenance costs are considered from 2050 to 2100. In accordance to literature, we assumed that maintenance costs amount to 1% of total construction costs. We assume that the protection level (or damage reduction, depending on the measure applied) deriving from the implementation increases linearly from present value in 2020 to the design value in 2050, and then remains constant. Implementation costs are calculated differently for each adaptation measure. For each warming scenario, we calculate the design values as the average of the model ensemble for the year 2100.

Table A2. Adaptation measures considered in PESETA IV analysis.

Sector	Description
Dyke systems 	Dyke systems consist 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. Different typologies of dykes can be used depending on the context (e.g. urban or rural areas). While this measure requires limited space to be implemented, it keeps the flood storage to minimum levels, hence the magnitude of the flood peak can remain unchanged for long river reaches, thus potentially increasing flood hazard downstream (Alfieri et al., 2016a). Moreover, raising flood protection and the consequent reduction in the frequency of flooding events can lead to increasing exposure in flood-prone areas, because the area is perceived as free of hazard (Di Baldassarre et al., 2015). This process is usually referred to as “levee effect” and can expose the society to catastrophic consequences in case of failures of the flood defences.
Damage reduction measures 	Building precautionary measures aim at minimising damage by means of flood-adapted use and equipment of buildings, i.e. wet flood proofing or by means of sealing, reinforcement and shielding, i.e. dry flood proofing (Kreibich et al., 2015). An example of wet flood proofing is to adapt the interior fitting which means that in endangered storeys, only waterproofed building material and movable small interior decoration and furniture are used. Dry flood proofing measures include, for instance, to adapt the building structure, e.g. via an elevated configuration or to waterproof seal the cellar (Gersonius et al., 2008). Such measures are especially recommended when new houses or even settlements are being built or extensively renovated (Kreibich et al., 2015).
Relocation 	Relocation reduces the exposure of people and assets at risk of flooding by moving them to areas with negligible risk (King et al. 2014). It has been observed in past events that flood relocation is primarily driven by economic evaluations and mostly occurs after catastrophic events which makes the reconstruction costs of the same magnitude of buying a new property (López-Carr and Marter-Kenyon 2015).
Storage areas 	This adaptation option aims at reducing flood hazard by reducing and delaying peak flows during extreme events. This is achieved by setting up areas within or aside the river network that can be flooded in a controlled manner when the river stage reaches critical levels (Arrighi et al. 2018). Beyond direct flood protection, this measure can be used for restoration of floodplain ecosystems, thus providing a range of significant additional ecosystem services, depending on the degree of restoration. Restoration of floodplains can improve aquatic and riparian ecosystems through improved water quality, vegetation population and improved habitat conditions for a variety of species. Moreover, restored floodplains contribute to reduce pollutant load (e.g. nutrients/pesticides) and control erosion and sediment transport. Finally, they provide recreational opportunities (EEA 2017).

Dyke heightening is calculated following the approach proposed by Ward et al (2017). We first estimate the present height of dykes in all the river network based on present-day river discharge and flood protection standards (e.g. 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). Then, for each future scenario we calculate spatial maps of increases of dyke heights required to raise protection standards up to the new design return levels. Implementation costs are calculated based on literature values on dyke constructions costs.

The design of retention areas requires to calculate storage capacity and allocate storage areas within each river basin. We first calculate maximum storage capacity along the floodplains, taking into account agricultural areas (excluding permanent crops, e.g. orchards, vineyards), semi natural areas (e.g. permanent grassland, wetlands, excluding forests). 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, for all the river network. Finally, we use an iterative procedure to allocate required storage volumes along the river network (i.e. future minus present volumes) starting from the most upstream reaches. Implementation costs are calculated based on the flood volumes to be stored. The advantage of storage structures is that upstream storage allows to reduce flood volumes downstream, thus benefiting all downstream branches.

Damage reduction measures for buildings are modelled with a simplified approach in which the design criterion is the ratio of damage reduction required. In other words, we assume that the implementation reduces damage to exposed buildings by a specific fraction (e.g. 10%, 30% etc.). Implementation costs are calculated as a function of built-up area exposed and the damage reduction ratio required. Based on literature, we assume that implementation costs increase linearly with the damage reduction ratio, and that damage reduction cannot exceed 50%. This is justified by the fact that higher reduction ratios would require more expensive measure (e.g. elevation of buildings) and not all impacts can be reduced through flood-proofing (e.g. agricultural damage). Note that ideally, the effect of these measures should be modelled by modifying the damage functions used to calculate economic impacts, but lack of data in literature does not allow such approach.

Relocation measures are designed assuming 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 area located within the 1-in-500-year flood extent maps, without making any assumption about the place of destination of relocated assets and people, as such decision would be highly subjective. 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). Given the complexity of putting in place large-scale permanent relocation measures, we assume that relocation in each NUTS2 region cannot exceed 50% of the total exposure.

For each adaptation measure considered (dyke heightening, relocation, damage reduction, and retention areas) we simulate different design options (e.g. raising dykes over a river stretch by different height increases). The evaluation of the optimal design level per strategy is performed with a cost-benefit analysis that optimises the net present value, or the sum of investment costs (that are negative) and economic benefits (avoided economic losses) over the lifetime of the project (Kuik et al., 2016). The latter is here considered to be the period 2020-2100. In the cost-benefit analysis we discount future costs and benefits to present-day values using a 5% discount rate for countries eligible for the EU Cohesion Fund and 3% for other Member States, following European Commission's guidelines (EC 2014). Note that the adaptation analysis (hence costs and avoided losses) is based on the flood risk projections with transient socioeconomic conditions according the 2015 Ageing Report. The cost-benefit analysis is repeated for the three warming scenarios considered in order to understand the performance of the adaptation options for different levels of global warming. We select for each warming scenario and each adaptation measure the design option that maximises the net present value at NUTS2 level. 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. Moreover, for each scenario we calculate the reduction in number of people exposed.

A1.4 limitations and uncertainty in the modelling framework

Modelling present and future river flood impacts at continental scale requires inevitable simplifications, and there is substantial uncertainty pertaining to models and datasets representing hazard, exposure and vulnerability (Dottori et al., 2018). As such, we discuss here the main sources of uncertainty of the modelling framework, and we review previous research works regarding the validation of the modelling components.

The hydrological and hydraulic modelling framework, based on the LISFLOOD and LISFLOOD-FP models, have been extensively validated in present-day conditions in previous works (Alfieri et al. 2015, 2016b). Using an ensemble of hydrological models might better represent the uncertainty of future hydrological changes, since previous research (Dankers et al., 2014; Dottori et al., 2018) showed that future streamflow and inundation projections are significantly affected by the choice of hydrological and flooding components.

The use of an ensemble with 22 model realisations characterises the uncertainty regarding future climate projections. However, the ensemble might still underrepresent the real uncertainty in future climate (McSweeney and Jones, 2015). Other factors like the bias correction of climate projections and the spatial resolution of the input data may influence results though probably to a smaller degree (Alfieri et al., 2018).

The flood impact modelling framework has been previously applied by Alfieri et al. (2016b). These authors observed that the methodology successfully reproduces recorded impacts of major flood events in Europe. Nevertheless, methods for evaluating economic losses due to floods are amongst the most relevant source of uncertainty in evaluating flood impacts (De Moel and Aerts, 2011). Huizinga et al. (2017) observed that the potential uncertainty of the damage functions adopted in this study can exceed ± 50%, although this value is in line with the typical accuracy of damage models (De Moel and Aerts, 2011). Indeed, previous applications of Huizinga et al. damage functions showed mixed performances (Jongman et al., 2012; Amadio et al., 2019).

Flood protection standards are possibly the most relevant source of uncertainty in large-scale modelling exercises. Indeed, information regarding design protection standards is available only in few areas in Europe, therefore protection standards needs to be either modelled or derived comparing observed and simulated historical flood loss data, where available (Jongman et al., 2014; Scussolini et al., 2016). Accurate modelling of historical loss data is further complicated by the temporal and spatial variability of exposure and vulnerability. Therefore, local protection standards may largely differ from the values used in the present analysis, thus affecting present and future risk estimates. In particular, the overall confidence about risk estimates is lower in a number of medium-small countries (e.g. Croatia, Latvia, Lithuania, Bulgaria), where information about protection standards and historical losses is scarce.

Finally, the results of the cost and benefit analysis are sensitive to some implementation choices. Reported implementation costs and benefits are widely variable among studies. For instance, some studies report higher costs of raising dykes in urbanised areas (Aerts, 2018). Descriptions of flood proofing measures report variable costs according to the type of measure (e.g. wet or dry proofing, elevation), the attainable damage reduction and the level of hazard (e.g. protection up to 1m of water depth). For relocation, implementation costs are largely dependent on building parameters (e.g. extent, number of storeys, market value) which are not all available at EU scale. Therefore, the results showed in the present report were based on average cost values and implementation parameters. Additional simulations using less favourable parameters (e.g. increased construction and maintenance costs) showed that all adaptation strategies are still cost-effective, with the notable exception of relocation (see main text).

We based our cost-benefit analysis on optimising each adaptation measure separately for each NUTS2 region, meaning that the level of implementation is uniform within this level of administrative region. On the one hand, using uniform design levels may be not ideal since exposure can be highly variable within NUTS2 regions and therefore protection measures may be needed only in certain parts of a region, such as in urban and densely populated areas. This is especially true for measures based on exposure and vulnerability reduction (i.e. relocation and damage reduction measures), for which cost/benefit analysis can be applied even over small areas. On the other hand, having different standards for nearby regions may pose problems in the implementation of measures based on hazard reduction (i.e. dykes strengthening and retention areas), which require more uniform levels of protection along longer stretches of the river network.

The outcomes are also sensitive to discounting, which gives more weight to present capital costs and downgrades the benefits that will mostly come later in the century. We used discount rates in line with the EC Guide to Cost-Benefit Analysis of Investment Projects (EC, 2014) that were assumed constant in time. Using lower or time-declining social discount rates supports the view that we should act now to protect future generations. As such, we also presented comparisons between present and future scenarios (both with and without adaptation) using undiscounted economic values, in order to give equal weight to present and future costs and benefits (EC 2014). Similarly, adaptation measures are optimised considering the most likely river flow projections in 2100 under the 1.5°C, 2°C and 3°C warming scenarios. Stakeholders could select a more conservative criterion and aim to protect against the high-end, less probable future extreme sea level scenarios. This would require higher investments but imply less risks for future generations.

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

Annex 2. Extended results

A2.1 Maps of impacts for different warming levels

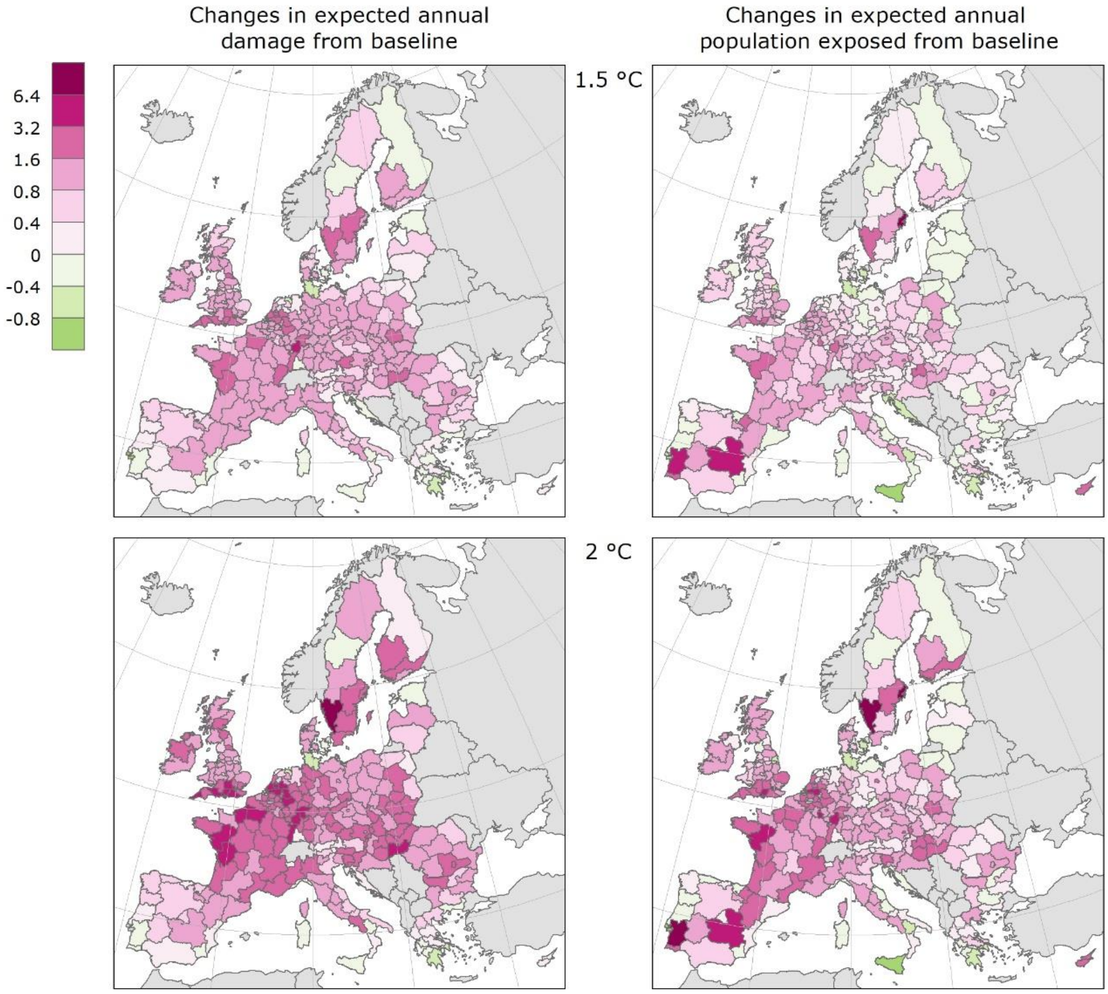


Figure A1. Map of increase in expected annual economic damage (left) and population exposed (right) foreseen for the 2050 economy and society, in respect to the baseline scenario. The 1.5°C and 2°C warming scenarios are considered.

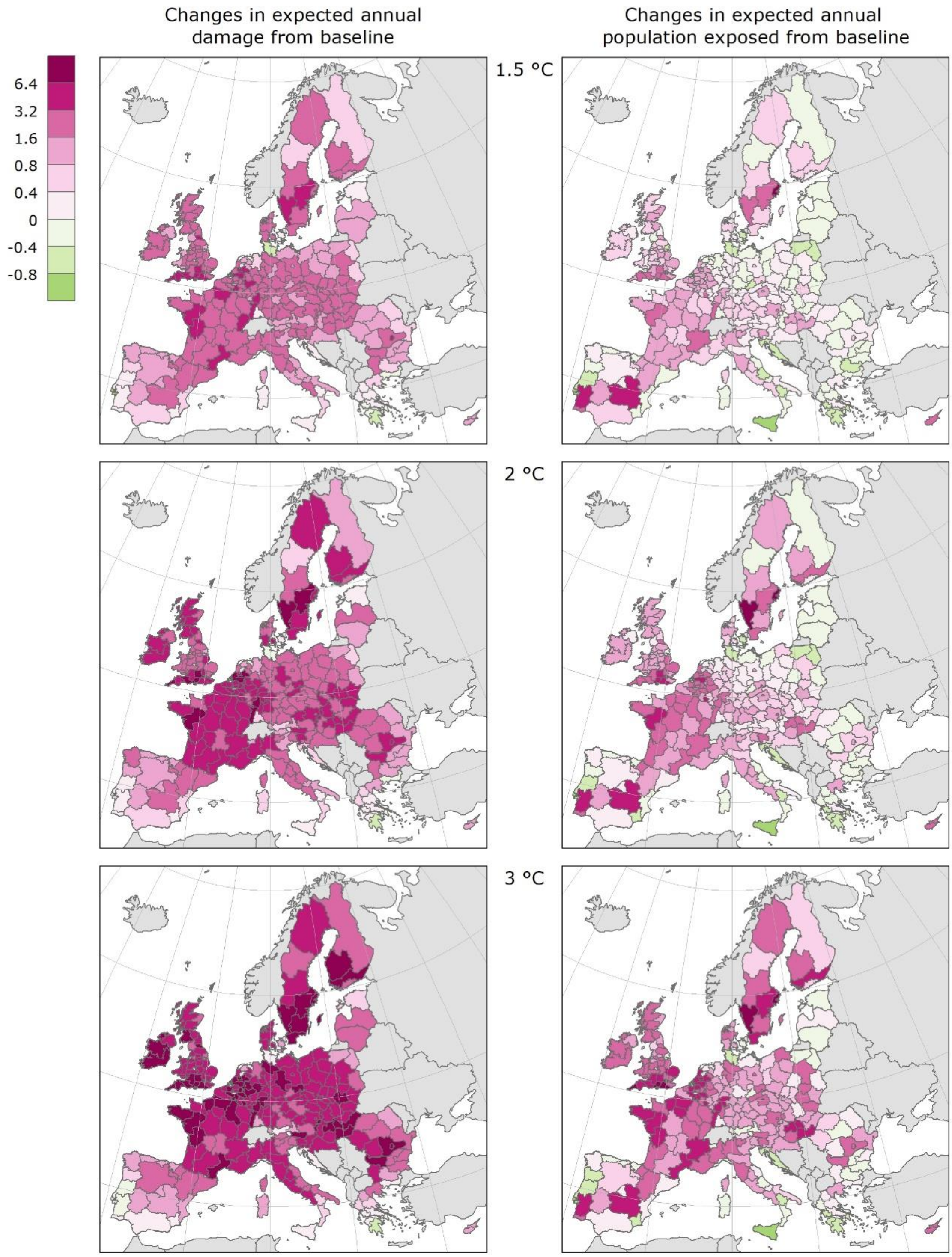


Figure A2. Map of increase in expected annual economic damage (left) and population exposed (right) foreseen for the 2100 economy and society, in respect to the baseline scenario. The 1.5°C, 2°C and 3°C warming scenarios are considered.

A2.2 Tables of impacts for different warming levels

Table A3. Summary of the expected annual damage (in €million, 2015 values) for all EU countries under present conditions (base), future socioeconomic conditions (2050 and 2100 economy) and climate scenarios (1.5°C, 2°C, 3°C warming).

	EAD Base economy				EAD Economy 2050		EAD Economy 2100		
Country	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Austria	262	364	411	556	523	603	812	943	1316
Belgium	212	340	481	753	494	707	831	1198	1802
Bulgaria	83	110	136	182	141	179	191	243	334
Croatia	176	309	421	573	263	369	387	546	767
Cyprus	4	4	4	3	5	5	9	9	7
Czechia	405	596	744	1086	755	947	1201	1519	2255
Denmark	14	22	29	47	23	30	38	51	81
Estonia	53	66	89	128	44	48	64	70	77
Finland	252	292	437	659	383	558	611	895	1336
France	1283	2378	3430	4215	3048	4432	5031	7335	8861
Germany	922	1718	2399	3703	2052	2870	2829	3963	5973
Greece	74	86	113	153	79	106	96	130	189
Hungary	260	452	651	1127	618	905	862	1264	2185
Ireland	60	93	123	238	117	156	199	268	489
Italy	847	1325	1614	2412	1550	1922	2342	2925	4269
Latvia	211	255	325	418	345	439	515	660	847
Lithuania	106	139	169	230	144	169	208	247	315
Luxembourg	19	29	42	55	41	60	78	114	143
Malta	NA	NA	NA	NA	NA	NA	NA	NA	NA
Netherlands	79	146	284	434	201	393	306	599	864
Poland	571	839	1055	1649	1115	1411	1586	2018	3158
Portugal	53	57	58	53	51	52	66	68	63
Romania	341	494	675	1007	573	762	792	1057	1544
Slovakia	144	243	301	445	312	391	473	596	882
Slovenia	56	90	124	184	111	153	168	234	348
Spain	451	515	531	528	679	718	1038	1109	1101
Sweden	228	420	780	1544	582	1068	1061	1950	3627
UK	642	1066	1419	2391	1358	1818	2277	3073	4991
EU+UK	**7,809**	**12449**	**16843**	**24775**	**15609**	**21268**	**24072**	**33081**	**47824**

Table A4. Summary of the expected annual population exposed (in thousand people) for all EU countries under present conditions (base), future socioeconomic conditions (2050 and 2100 economy) and climate scenarios (1.5°C, 2°C, 3°C warming).

	EAPE Base economy				EAPE Economy 2050		EAPE Economy 2100		
Country	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Austria	3.9	5.3	6.1	8.1	6.1	6.9	5.8	6.6	9.0
Belgium	4.0	6.4	8.9	13.9	8.3	11.6	9.0	12.6	18.8
Bulgaria	2.8	3.6	4.5	6.0	2.8	3.5	2.0	2.4	3.3
Croatia	4.6	8.2	11.4	15.8	6.4	9.3	4.9	7.1	11.5
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czechia	6.9	10.2	12.7	18.4	11.0	13.7	10.0	12.4	18.4
Denmark	0.1	0.2	0.3	0.4	0.2	0.2	0.2	0.2	0.4
Estonia	0.8	1.0	1.3	1.8	0.7	0.7	0.5	0.6	0.7
Finland	3.7	3.8	5.4	8.6	3.5	4.9	3.6	5.0	8.0
France	22.5	41.3	60.9	73.7	46.8	69.6	50.2	74.7	88.3
Germany	28.5	53.3	73.9	116.6	49.0	67.9	41.4	57.2	88.4
Greece	1.8	2.0	2.6	3.4	2.3	3.0	1.7	2.3	3.2
Hungary	6.7	11.6	16.7	28.7	11.9	17.0	9.7	13.8	22.9
Ireland	0.9	1.4	1.8	3.4	1.3	1.7	1.5	1.9	3.3
Italy	18.9	29.0	35.0	51.2	30.6	37.6	27.7	33.9	48.7
Latvia	4.1	5.0	6.4	8.2	3.4	4.3	2.8	3.5	4.5
Lithuania	1.3	1.6	2.0	2.6	1.0	1.2	0.9	1.0	1.3
Luxembourg	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.6	0.7
Malta	NA	NA	NA	NA	NA	NA	NA	NA	NA
Netherlands	1.6	2.9	5.7	8.6	3.1	5.9	3.0	5.7	8.3
Poland	19.2	27.8	34.8	53.5	29.8	37.8	20.8	26.1	41.0
Portugal	0.8	0.9	0.9	0.8	1.2	1.3	1.0	1.0	1.0
Romania	12.8	16.8	20.9	28.9	16.5	20.5	12.4	15.3	21.2
Slovakia	3.2	5.3	6.6	9.6	5.0	6.3	3.8	4.7	7.1
Slovenia	1.0	1.6	2.3	3.5	1.6	2.2	1.4	1.9	2.9
Spain	11.1	12.3	12.7	12.5	18.4	19.3	16.6	17.4	16.9
Sweden	2.0	3.2	5.2	9.6	3.9	6.6	4.7	8.0	14.4
UK	8.1	13.7	18.6	32.3	14.6	20.2	16.1	22.3	37.8
EU+UK	**171.6**	**268.8**	**357.7**	**520.6**	**279.6**	**373.6**	**252.0**	**338.4**	**481.8**

A2.2 Tables of results of adaptation measures for different warming levels

In this section we report the main outcomes of the economic analysis for all the adaptation measures considered in PESETA IV, under all warming scenarios. Note that we do not report the reduction in population exposed because percentages are broadly similar those of economic damage.

Table A5. Summary of economic analysis for the adaptation measure "Strengthening of Dyke Systems" for all EU countries under the considered warming scenarios. BCR: benefit to cost ratio over the period 2020-2100. EAD red.: reduction in expected annual damage (EAD) as compared with the "no adaptation" scenario for the year 2100. Costs: undiscounted total costs (annual average over the period 2020-2100 in €million/year).

	Strengthening of Dyke Systems								
	1.5°C			2°C			3°C		
Country	**BCR**	**EAD red.**	**Costs (€M/y)**	**BCR**	**EAD red.**	**Costs (€M/y)**	**BCR**	**EAD red.**	**Costs (€M/y)**
Austria	1.7	37%	69	1.8	31%	80	2.2	64%	96
Belgium	2.3	68%	81	2.7	77%	109	3.2	87%	122
Bulgaria	1.9	11%	2	3.0	20%	2	3.3	39%	5
Croatia	1.4	56%	44	1.5	64%	64	2.4	73%	86
Cyprus	<1	NA	0	<1	NA	0	<1	NA	0
Czechia	2.3	49%	56	2.5	53%	76	2.6	68%	125
Denmark	1.1	26%	2	1.3	38%	4	1.6	51%	5
Estonia	1.3	39%	18	1.6	63%	28	1.6	73%	28
Finland	1.8	19%	12	2.1	35%	46	2.3	66%	127
France	1.9	48%	406	2.2	63%	564	2.7	72%	623
Germany	2.1	46%	255	2.7	54%	311	2.9	72%	458
Greece	1.1	1%	<1	1.3	7%	1	1.3	19%	2
Hungary	1.9	27%	16	3.3	28%	19	3.7	61%	51
Ireland	1.5	36%	10	2.4	38%	13	2.2	72%	36
Italy	2.0	54%	220	2.2	56%	243	2.2	72%	380
Latvia	1.4	53%	39	1.5	62%	71	3.1	72%	91
Lithuania	3.7	8%	5	1.2	16%	10	2.0	37%	14
Luxembourg	2.8	74%	4	2.4	82%	5	5.2	86%	12
Malta	NA	NA	NA	NA	NA	NA	NA	NA	NA
Netherlands	2.1	28%	18	3.8	53%	20	4.2	69%	26
Poland	1.4	5%	18	1.8	7%	32	1.9	34%	87
Portugal	<1	NA	0	<1	NA	0	1.8	3%	<1
Romania	2.0	7%	8	2.1	20%	25	2.5	44%	40
Slovakia	2.0	32%	17	2.4	30%	23	2.2	63%	43
Slovenia	1.2	21%	13	1.3	32%	21	1.7	60%	23
Spain	1.4	8%	19	2.4	6%	6	1.5	6%	9
Sweden	2.4	36%	32	4.0	62%	70	8.1	79%	79
United Kingdom	2.4	72%	228	3.0	76%	246	3.8	87%	328
EU+UK	**2.0**	**41%**	**1592**	**2.4**	**50%**	**2089**	**2.9**	**68%**	**2896**

Table A6. Summary of economic analysis for the adaptation measure "Retention Areas" for all EU countries under the considered warming scenarios. BCR: benefit to cost ratio over the period 2020-2100. EAD red.: reduction in expected annual damage (EAD) as compared with the "no adaptation" scenario for the year 2100. Costs: undiscounted total costs (annual average over the period 2020-2100 in €million/year).

	Retention Areas								
	1.5°C			2°C			3°C		
Country	**BCR**	**EAD red.**	**Costs (€M/y)**	**BCR**	**EAD red.**	**Costs (€M/y)**	**BCR**	**EAD red.**	**Costs (€M/y)**
Austria	2.3	66%	89	2.5	64%	98	3.1	81%	99
Belgium	2.7	76%	84	4.4	82%	67	4.4	90%	93
Bulgaria	2.1	62%	18	2.2	67%	22	3.1	78%	21
Croatia	2.4	89%	66	4.0	90%	45	3.2	96%	83
Cyprus	<1	NA	0	<1	NA	0	<1	NA	0
Czech Republic	3.2	78%	86	3.6	79%	94	4.0	87%	117
Denmark	2.2	83%	6	2.5	85%	8	2.8	87%	8
Estonia	2.7	39%	<1	1.1	50%	32	1.3	66%	35
Finland	2.1	53%	48	2.6	64%	76	2.6	79%	129
France	2.8	73%	420	3.1	82%	645	3.1	87%	745
Germany	3.4	58%	189	2.9	64%	379	3.2	79%	517
Greece	2.5	53%	5	2.5	53%	11	2.7	71%	15
Hungary	2.2	73%	78	2.5	75%	106	3.5	88%	121
Ireland	2.0	64%	21	2.7	67%	20	2.6	86%	53
Italy	4.6	79%	156	4.2	81%	215	3.9	87%	306
Latvia	1.8	44%	39	2.0	54%	47	1.7	72%	77
Lithuania	<1	NA	0	6.5	27%	<1	1.7	50%	12
Luxembourg	1.8	79%	14	2.4	86%	13	8.0	86%	3
Malta	NA	NA	NA	NA	NA	NA	NA	NA	NA
Netherlands	6.2	21%	4	5.6	43%	11	3.8	57%	27
Poland	1.9	46%	109	1.9	56%	182	2.2	73%	257
Portugal	<1	NA	0	<1	NA	0	5.3	3%	<1
Romania	1.6	34%	57	2.8	49%	49	2.1	65%	121
Slovakia	2.9	71%	33	3.5	73%	34	2.9	88%	68
Slovenia	1.7	61%	22	1.7	71%	30	3.1	82%	17
Spain	1.5	24%	58	1.9	24%	41	1.7	30%	49
Sweden	1.8	52%	97	4.4	72%	88	6.1	86%	144
United Kingdom	4.7	86%	153	6.5	87%	141	7.4	94%	199
EU+UK	**2.9**	**64%**	**1855**	**3.3**	**71%**	**2458**	**3.5**	**82%**	**3320**

Table A7. Summary of economic analysis for the adaptation measure "Damage reduction measures" for all EU countries under the considered warming scenarios. BCR: benefit to cost ratio over the period 2020-2100. EAD red.: reduction in expected annual damage (EAD) as compared with the "no adaptation" scenario for the year 2100. Costs: undiscounted total costs (annual average over the period 2020-2100 in €million/year).

	Damage reduction measures for buildings								
	1.5°C			2°C			3°C		
Country	**BCR**	**EAD red.**	**Costs (€M/y)**	**BCR**	**EAD red.**	**Costs (€M/y)**	**BCR**	**EAD red.**	**Costs (€M/y)**
Austria	6.8	50%	19	6.6	50%	22	7.3	50%	29
Belgium	6.6	50%	19	6.9	50%	25	6.2	50%	40
Bulgaria	3.5	50%	7	3.6	50%	9	3.5	50%	12
Croatia	3.1	50%	24	3.2	50%	30	3.5	50%	35
Cyprus	7.5	50%	<1	7.6	50%	<1	9.7	50%	<1
Czech Republic	6.2	50%	22	6.2	50%	27	5.6	50%	44
Denmark	8.8	50%	1	7.8	50%	1	8.0	50%	2
Estonia	4.0	50%	4	4.1	50%	5	5.6	50%	4
Finland	5.3	50%	17	5.1	50%	27	5.9	50%	35
France	6.2	50%	121	6.3	50%	173	5.8	50%	225
Germany	3.0	50%	172	2.9	50%	240	3.0	50%	337
Greece	2.3	50%	6	2.6	50%	8	2.6	50%	11
Hungary	3.9	50%	28	4.1	50%	38	3.6	50%	78
Ireland	7.6	50%	4	7.7	50%	6	7.2	50%	9
Italy	6.0	50%	70	5.9	50%	85	5.5	50%	131
Latvia	5.1	50%	12	5.4	50%	15	4.3	50%	22
Lithuania	4.4	50%	6	4.4	50%	8	4.2	50%	12
Luxembourg	12.2	50%	1	12.0	50%	1	10.3	50%	2
Malta	NA	NA	NA	NA	NA	NA	NA	NA	NA
Netherlands	5.7	50%	8	5.8	50%	14	5.6	50%	19
Poland	3.9	50%	50	3.9	50%	63	3.5	50%	108
Portugal	4.3	50%	3	4.5	50%	3	5.2	50%	2
Romania	3.3	50%	34	3.6	50%	42	3.8	50%	60
Slovakia	3.9	50%	14	3.9	50%	17	3.3	50%	32
Slovenia	4.3	50%	4	4.4	50%	6	3.9	50%	10
Spain	7.9	50%	21	8.1	50%	21	8.4	50%	21
Sweden	9.1	50%	15	9.8	50%	26	10.2	50%	50
United Kingdom	11.9	50%	30	11.8	50%	40	10.8	50%	68
EU+UK	**5.2**	**50%**	**711**	**5.3**	**50%**	**954**	**5.1**	**50%**	**1400**

Table A8. Summary of economic analysis for the adaptation measure “Relocation” for all EU countries under the considered warming scenarios. BCR: benefit to cost ratio over the period 2020-2100. EAD red.: reduction in expected annual damage (EAD) as compared with the “no adaptation” scenario for the year 2100. Costs: undiscounted total costs (annual average over the period 2020-2100 in €million/year).

	Relocation								
	1.5°C			2°C			3°C		
Country	**BCR**	**EAD red.**	**Costs (€M/y)**	**BCR**	**EAD red.**	**Costs (€M/y)**	**BCR**	**EAD red.**	**Costs (€M/y)**
Austria	1.1	38%	82	1.1	37%	82	1.1	32%	92
Belgium	1.4	23%	40	1.5	24%	53	1.4	22%	67
Bulgaria	<1	NA	NA	<1	NA	NA	<1	NA	NA
Croatia	<1	NA	NA	<1	NA	NA	<1	NA	NA
Cyprus	1.2	40%	1	1.2	40%	1	1.4	40%	<1
Czech Republic	1.1	22%	60	1.1	23%	62	1.2	24%	58
Denmark	1.4	40%	4	1.4	40%	6	1.3	40%	9
Estonia	<1	NA	NA	<1	NA	NA	<1	NA	NA
Finland	<1	NA	NA	<1	NA	NA	1.0	17%	66
France	1.1	22%	285	1.1	23%	447	1.1	21%	715
Germany	<1	NA	NA	<1	NA	NA	<1	NA	NA
Greece	<1	NA	NA	<1	NA	NA	<1	NA	NA
Hungary	<1	NA	NA	<1	NA	NA	<1	NA	NA
Ireland	1.3	29%	14	1.3	30%	18	1.2	29%	28
Italy	1.1	21%	159	1.1	21%	208	1.1	21%	171
Latvia	<1	NA	NA	<1	NA	NA	<1	NA	NA
Lithuania	<1	NA	NA	<1	NA	NA	<1	NA	NA
Luxembourg	1.9	40%	4	1.7	40%	8	1.8	40%	9
Malta	NA	NA	NA	NA	NA	NA	NA	NA	NA
Netherlands	1.1	17%	14	1.1	17%	17	<1	NA	NA
Poland	<1	NA	NA	<1	NA	NA	<1	NA	NA
Portugal	<1	NA	NA	<1	NA	NA	<1	NA	NA
Romania	<1	NA	NA	<1	NA	NA	<1	NA	NA
Slovakia	<1	NA	NA	<1	NA	NA	<1	NA	NA
Slovenia	<1	NA	NA	<1	NA	NA	<1	NA	NA
Spain	1.4	33%	80	1.4	33%	79	1.5	34%	69
Sweden	1.5	35%	70	1.7	37%	106	1.6	37%	225
United Kingdom	1.9	39%	148	1.9	39%	197	1.8	39%	351
EU+UK	**1.2**	**19%**	**961**	**1.2**	**20%**	**1282**	**1.2**	**19%**	**1860**

List of abbreviations and definitions

BCR	Benefit-to-Cost Ratio
EAD	Expected Annual Damage
EAPE	Expected Annual Population Exposed
EWS	Early Warning System
GDP	Gross Domestic Product
IPCC AR5	Intergovernmental Panel on Climate Change - Assessment Report 5
NUTS2	Nomenclature of Territorial Units for Statistics
RCP	Representative Concentration Pathway
WL	Warming Level

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KJ-NA-29955-EN-N

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Publications Office
of the European Union

doi:10.2760/14505

ISBN 978-92-76-12946-2