European
Commission

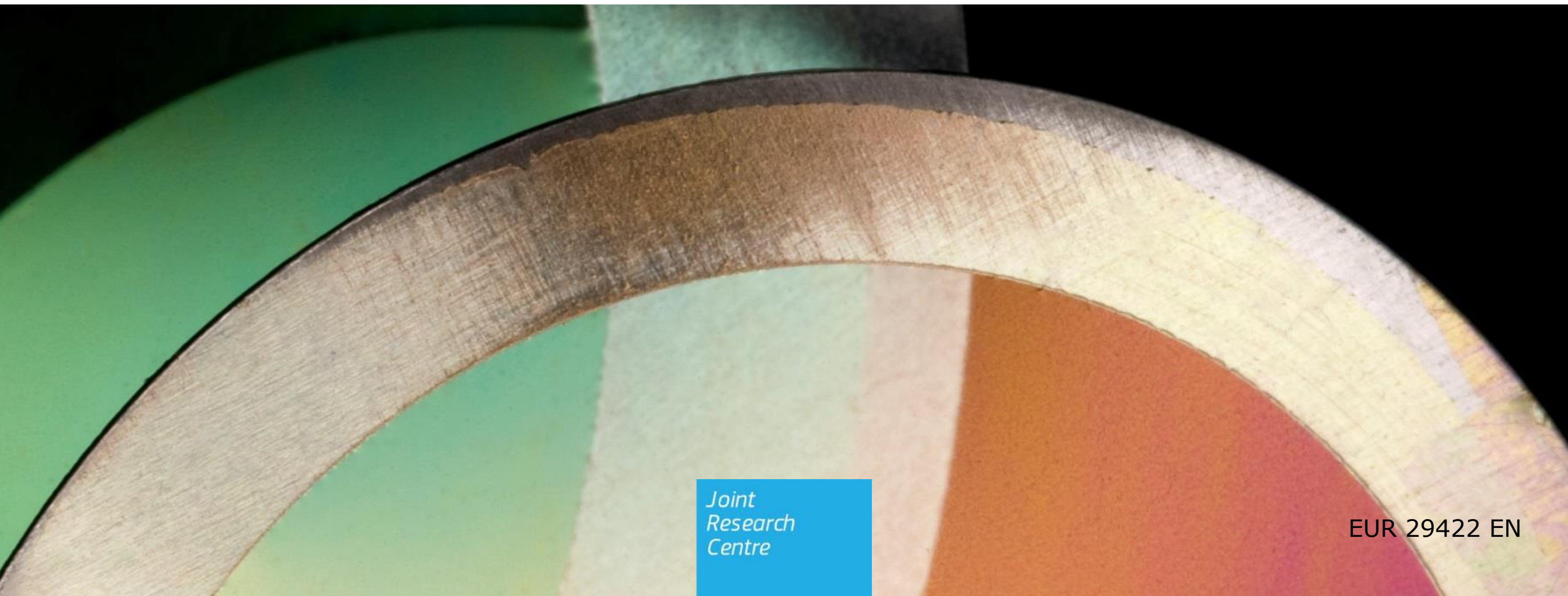
JRC TECHNICAL REPORTS

Task 7 – River floods

JRC PESETA III project

Lorenzo Alfieri, Francesco Dottori and
Luc Feyen

2018



Joint
Research
Centre

EUR 29422 EN

Contact information
Name: Lorenzo Alfieri
Email: lorenzo.alfieri@ec.europa.eu
Tel.: +390332783835

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

JRC110308

EUR 29422 EN

ISBN 978-92-79-96911-9 ISSN 1831-9424 doi:10.2760/849948

Luxembourg: Publications Office of the European Union, 2018

How to cite this report: Alfieri L., Dottori F., and Feyen L., PESETA III – Task 7: River floods, EUR 29422 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-96911-9, doi:10.2760/849948, JRC110308.

Contents

Executive Summary

Since 1980 river floods in Europe have resulted in over 4,700 fatalities and caused direct economic losses of more than €150 billion (2013 values), and future risk is likely to increase due to the combination of climatic and socio-economic drivers. As such, reliable research works are needed to investigate river flood risk under future climate scenarios, and to evaluate adaptation strategies able to limit the impacts of river flooding.

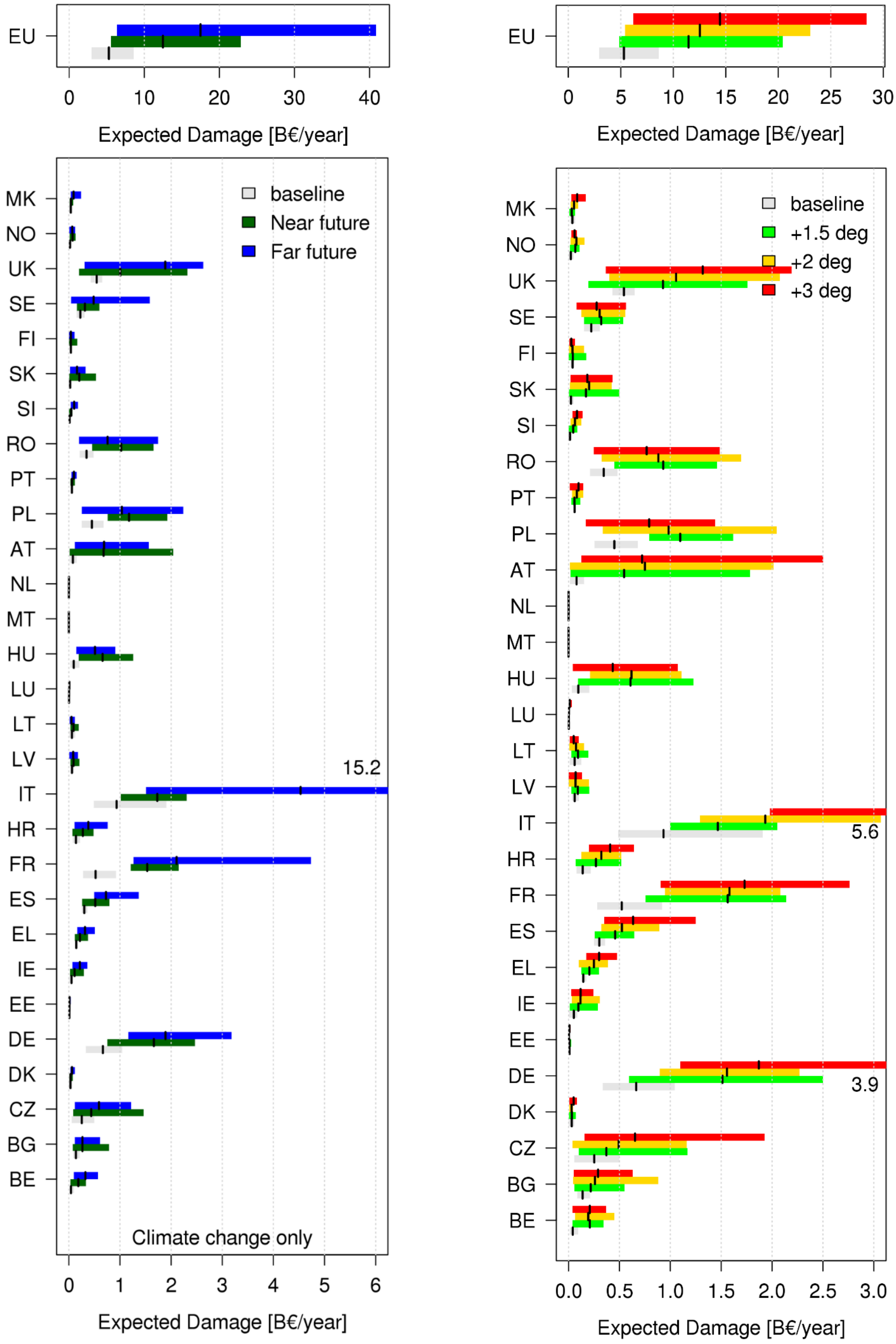
In this report, we present results of the PESETA III river flood risk assessment based on an ensemble of high-resolution regional climate scenarios and suitable socio-economic pathways. We evaluated river flood risk in Europe throughout the 21st century by comparing flood impacts under baseline (1976-2005) climate with those in the near (2021–2050) and far (2071–2100) future and under specific warming levels (SWLs) of 1.5, 2 and 3°C global warming above preindustrial levels. Simulated flood risk scenarios are representative for high levels of greenhouse gas concentrations in the atmosphere, and considering both time-based and warming-based scenarios allows to evaluate the influence of the speed of warming on flood impacts.

Our analysis includes all EU member states plus a number of neighbouring countries, most of which include parts of European river basins like the Danube. The neighbour countries considered are Bosnia – Herzegovina, Belarus, Iceland, Kosovo, Moldova, Montenegro, the Former Yugoslav Republic of Macedonia (FYROM), Norway, Serbia and Switzerland.

An ensemble of seven regional climate projections from 1970 to 2100 forced by the Representative Concentration Pathway (RCP) 8.5 scenario were run through a distributed hydrological model and resulting streamflow was analysed statistically to estimate future changes in the river flood hazard in Europe. Note that the analysis does not consider other flood processes such as coastal floods (due to storm surges and waves), nor pluvial and flash floods (caused by localized, high-intensity rainfall events). Impacts of river floods in Europe were evaluated by combining the occurrence and magnitude of future discharge peaks with present exposure maps (population, landuse) and information on flood defences. Estimates of expected economic damage and population affected were produced considering first only climatic drivers (static economic analysis) and then including the effects of socio-economic development coherent with the considered climate scenarios (dynamic economic analysis). Furthermore, the risk assessment framework was applied to qualitatively evaluate the risk reduction potential of a number of flood adaptation strategies. Measures taken into account include the rise of flood protection, reduction of the peak flows through water retention, reduction of vulnerability and relocation to safer areas.

Under baseline climate, in Europe around 216,000 people are exposed each year to river flooding and annual flood damage amounts to €5.3 billion. In most regions of Europe we see an increase of flood risk due to global warming (see Figure 1). Under a 2°C global warming scenario, which under the RCP8.5 pathway will occur in the early 2040s, and considering current socio-economic conditions, flood impacts could more than double, with 525,000 people annually exposed to floods and €13 billion of expected annual losses. If near term (2021-2050) climate conditions are considered, approximately 450,000 people could be exposed annually to river flooding and direct flood damages could reach €12 billion. Longer term climate conditions (2071-2100) imposed on present society could result in over 700,000 people annually exposed to floods while direct flood damages could see a more than three-fold increase with respect to current conditions, reaching €17 billion of average annual losses.

Figure 1. Expected annual damage for baseline, near (2021-2050) and far future (2071-2100) (left graph) and different levels of warming (right graph). Figures show flood impacts under future climate conditions on present European society. Note that some countries are not included in the graphs because impacts are negligible compared to other countries.



Projections of flood impacts show an even more pronounced increase when socio-economic scenarios are considered in the projections. Depending on the socio-economic scenario, average estimates of population annually affected by floods could range between 500,000 and 550,000 in the 2021-2050 period, and between 530,000 and 975,000 in the 2071-2100 period. A larger increase is foreseen in expected annual flood damage, which is projected to rise to €19-26 billion in 2021-2050 and €29-112 billion in 2071-2100. This shows that flood risk is amplified by economic growth. However, the projected socio-economic conditions imply a wealthier society hence also an increase in the capacity to absorb the increase in flood risk. As for the evaluation of risk adaptation options, results suggest that the future increase in expected damage and population affected by river floods can be compensated through different configurations of adaptation measures. The adaptation efforts should favour measures targeted at reducing the impacts of floods (such as relocation and vulnerability reduction), rather than trying to avoid them. Conversely, adaptation plans only based on rising flood protections have the effect of reducing the frequency of small floods and exposing the society to less-frequent but catastrophic floods and potentially long recovery processes.

1 Introduction

Flood risk is the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event (EU Floods Directive, European Commission, 2007). A key component of flood risk assessment is the accurate estimation of the flood hazard (i.e. magnitude and frequency, or probability, of floods) and of the potential impact on human activities. The latter is usually quantified as the product of exposure, that is, "people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses", and of vulnerability, that is, "the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard" (UNISDR, 2009). All components of flood risk are subject to changes in time due to socio-economic development and the possible influence of a changing climate. This makes the assessment of present and future flood risk a particularly challenging task.

Since 1980 river floods in Europe have resulted in over 4,700 fatalities and caused direct economic losses of more than €150 billion (based on 2013 values), which is almost one-third of the damage caused by all natural hazards (EEA, 2017). Moreover, the current knowledge suggests that climate change will be a determining factor in intensifying the hydrological cycle and most likely lead to an increase in the magnitude and frequency of intense precipitation events in many parts of Europe (see, e.g., Frei et al., 2006; Christensen and Christensen, 2007; van der Linden and Mitchell, 2009; Nikulin et al., 2011), which may lead to an increase in future flood hazard in those regions (e.g., Dankers and Feyen, 2009; Whitfield, 2012).

The objective of the river flood analysis in PESETA III is to evaluate flood impacts in Europe throughout the 21st century. To this end, this work makes use of the pan-European flood hazard mapping procedure by Alfieri et al. (2014), which is for the first time fully integrated into a high resolution flood risk assessment at continental scale. This is combined with projections of future flood hazard (Alfieri et al., 2015) driven by an ensemble of climate projections for RCP8.5. Climate projections from 1970 to 2100 are run through a distributed hydrological model and resulting streamflow is analysed statistically to estimate future changes in the flood hazard in Europe. Note that such analysis complements the evaluation of future changes in river flow and water resources performed in Task 12. Specifically, while Task 12 considers changes in magnitude and frequency of high-flow and low-flow conditions, the focus is on frequent and low-intensity river floods. Conversely, here we analyze the full range of possible flood events, including less frequent and more severe floods, and we evaluate their consequences through simulating floodplain inundation processes and evaluating flood impacts.

Note that in the present work we analyse only river flooding, that is, flood events caused by overflowing of water from rivers above a specific size (i.e. upstream drainage area above 500 km^2). We do not consider flash floods (due to localized, high-intensity rainfall events involving the minor river network) and coastal floods, which are the main topic of Task 8. From now on in the text, for reasons of conciseness we use the term "flood" to refer to river flooding.

We quantify the future impact of floods in Europe by combining the occurrence and magnitude of future discharge peaks with present exposure maps and information on flood defences. Future estimates of expected economic damage and population affected are produced considering first only climatic drivers (static economic analysis) and then including the effect of possible socio-economic development (dynamic economic analysis) coherent with the considered climate scenarios.

In addition to flood risk evaluation, adaptation plans are a vital component of current and future disaster risk reduction strategies (Adger et al. 2005; Brandimarte et al. 2009). Flood risk reduction may be tackled through structural and non-structural measures involving flood zoning, land-use planning and private precautionary measures, with notable differences in the approach from country to country, even within Europe (Kreibich et al. 2015). While the number of coordinated flood reduction plans is steadily growing, particularly at community level (e.g., Stahre 2008; Reinhardt et al. 2011), most flood risk prevention actions performed in the past decades focused on corrective rather than preventive measures. After a flood had hit, a recurrent case of flood management was to reinforce and rise flood protections up to a level that would safely confine the peak flow of the river in case a similar event occurred again in the future (see e.g., Fenn et al. 2014). Yet, more and more research studies based on past events acknowledge dykes heightening as measures of last resort or even examples of maladaptation (Hallegatte 2009; Zurich 2014; Wenger 2015), as they give a misleading impression of complete safety which is at odds with the catastrophic consequences in case of failure during flood events (e.g., Di Baldassarre et al. 2015). The last two decades have seen a progressive policy shift towards programs to give "room for rivers" (Rohde et al. 2006; Opperman et al. 2009), aimed to increase the storage space of rivers by restoring floodplains and thus reducing the flood depth by spreading floodwaters over wider areas. Other adaptation options such as relocation to safer areas or flood proofing of buildings require deeper commitment of homeowners and have thus found limited applications in practice (McLeman and Smit 2006; Bichard and Kazmierczak 2012). Yet, insurance programs and disaster financing schemes have large potential in steering the flood risk management in the private and public sectors (Keskitalo et al. 2014; Jongman et al. 2014).

Quantifying the benefits of adaptation measures is crucial for planning nation-wide coordinated actions for flood risk reduction in view of future socio-economic dynamics and the potential intensification of the hydrological cycle and of its extremes (Alfieri et al. 2015a). In the frame of PESETA III we perform a sensitivity analysis to understand the potential of different adaptation measures to reduce flood risk. To this end we consider four different adaptation options in our flood risk assessment framework and evaluate their risk reduction effectiveness. Each adaptation option is therefore simulated in 8 to 12 different configurations to assess the sensitivity of its implementation on the resulting flood risk. Risk reduction estimates are obtained by aggregating the results of seven ensemble simulations in space, over 28 European countries, and in time, through two 30-year time slices, to strengthen the robustness of the analysis.

2 Methodology

The risk assessment framework applied for the present study combines hydrological modelling driven by historical climate scenarios and future projections, statistical extreme value analysis and inundation modelling with the vulnerability of assets and people to floods in order to estimate direct impacts of floods. The risk assessment framework is also applied to evaluate the risk reduction potential of a number of strategies for flood adaptation.

Statistical and quantitative analyses shown in this report are performed over 30-year time periods. The historical scenario spans the period 1976–2005, hereinafter referred to as "baseline", after the median year of the time slice. Similarly, future time slices span over the windows 2021–2050 and 2071–2100 are referred to as "near future" and "far future", respectively. In addition, we compare impacts for the historical scenario with those over 30-year time slices centred on the year that the specific warming levels (SWLs) of 1.5, 2 and 3°C global warming above preindustrial levels are reached (see Table 1). Note that the 1.5°C and 2°C warming scenarios are explicitly considered in the recent 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.

Both time-based and warming-based time windows are driven by the same scenario of greenhouse gases emission, to evaluate the influence of the speed of warming on flood impacts.

Table 1. Regional climate projections used in the flood analysis and corresponding year of exceeding 1.5, 2 and 3°C warming.

Institute	GCM	RCM	Driving ens member	SWL:1.5	SWL:2	SWL:3
KNMI	EC-EARTH	RACMO22E	r1i1p1	2031	2046	2069
SMHI	HadGEM2-ES	RCA4	r1i1p1	2025	2037	2055
SMHI	EC-EARTH	RCA4	r12i1p1	2028	2042	2067
MPI-CSC	MPI-ESM-LR	REMO2009	r1i1p1	2031	2045	2068
CLMcom	MPI-ESM-LR	CCLM4-8-17	r1i1p1	2031	2045	2068
SMHI	MPI-ESM-LR	RCA4	r1i1p1	2031	2045	2068
CLMcom	EC-EARTH	CCLM4-8-17	r12i1p1	2028	2042	2067

2.1 Flood risk analysis

2.1.1 Data and models

EURO-CORDEX historical climate scenarios and future projections with the Representative Concentration Pathway (RCP) 8.5 in Europe (Jacob et al. 2014) are used as input to simulate river streamflow over the period 1970-2100. RCP8.5 is representative of high level greenhouse gas concentrations in the atmosphere. We selected seven models (see Table 1) giving priority to driving Global Circulation Models (GCMs) with high ranking in the performance evaluation of CMIP5 models carried out by Perez et al. (2014). Continuous daily streamflow simulations are computed with Lisflood, a distributed, physically based hydrological model, run at 5km grid resolution (Burek et al., 2013a; van der Knijff et al., 2010). We used the following variables from the climate models to force Lisflood: daily precipitation, average, minimum and maximum temperature, incoming solar radiation, surface air pressure, specific humidity and wind speed. Lisflood is also used in Task 12 to evaluate future changes in river flow and water resources. However, in task 12 the analysis of high-flow conditions is limited to frequent and low-intensity river floods (Q99.9, i.e. flows occurring approximately once every 3 years). Conversely, here we perform a full analysis of high-flow conditions including less frequent and more severe flows, which are more 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, which are not simulated in Task 12.

Exposure information is given by the European population density map by Batista e Silva et al. (2013) and by the refined version of the CORINE Land Cover proposed by Batista e Silva et al. (2012). Both maps are consistent with official statistical data at European scale. Moreover, they are available at the same resolution of flood hazard maps (100m) and are consistent with the data used by other Tasks of PESETA III (e.g. Task 5 – Energy). Vulnerability to floods is included in the form of damage functions and through a flood protection map. Country specific depth-damage functions from Huizinga (2007) are used to link flood depth with the corresponding direct economic damage, considering CORINE 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 the 5 km resolution map produced by Jongman et al. (2014).

To disentangle the effects of climate change and socio-economic development flood risk scenarios are obtained assuming static exposure values (static economic analysis, only accounts for the effects of climate change) and by including socio-economic dynamics (dynamic economic analysis) defined by two Shared Socioeconomic Pathways (SSP, O'Neill et al., 2014) in the model chain. We considered scenarios of socio-economic development driven by mitigation challenges (SSP5) or both mitigation and adaptation challenges (SSP3), which are both compatible with the RCP 8.5 scenario (van Vuuren and Carter 2014). In addition, we evaluated impacts for the socio-economic scenario developed in Task 2 of the PESETA III project (Peseta SP in the following) and based on the ECFIN Ageing report. The coupling of climate scenarios with coherent projections of socio-economic growth allows an overall evaluation of the future flood risk and the related uncertainty.

Gross domestic product (GDP) and population projections from the Organisation for Economic Co-operation and Development (OECD) for SSP5 and SSP3 were acquired in the form of 5-years national multipliers and applied to the exposure layers (i.e. population density and damage functions) to include socioeconomic features in the future population affected and expected damage estimation. A similar procedure has been applied to evaluate the socio-economic scenario developed in Task 2.

2.1.2 Modelling approach

In a first step, we used the Lisflood-FP model fed with hydrological input from Lisflood to produce 100 m resolution maps of flood extent and flood depth in Europe for the observed climate and return periods 10, 20, 50, 100, 200, 500 years (for more details see Alfieri et al., 2014). Flood hazard maps were then combined with depth-damage functions and population density maps described in Section 2.1.1 to derive expected economic damage (ED) and population affected (PA) by floods for each of the return periods, assuming no flood protection. Finally, 100 m resolution maps of ED and PA were aggregated to 5 km resolution and linked with the river network used in Lisflood.

As a second step, streamflow simulations run with Lisflood over the period 1970-2100 were used to determine magnitude and recurrence of projected discharge peaks. Extreme value statistical distributions were fitted on the simulated annual maxima of the control period (1976–2005), to derive analytical relations between extreme streamflow and probability of occurrence (and consequently of their return period), in each point of the European river network. In this step, a Gumbel extreme value distribution was assumed for annual maximum discharges, as described by Alfieri et al. (2015). Finally, for each of the seven climate scenarios, flow peaks exceeding the local flood protection levels are assigned an impact (PA and ED) through linear interpolation among the return periods estimated for the current climate. Finally, impact estimates are aggregated in space and time, to produce country-wide and Europe-wide estimates of expected annual damage (EAD) and expected annual population affected (EAPA) over 30-year time slices of the baseline and future scenarios. Maps refer to population estimates of 2006 and to GDP Purchasing Power Standards of 2007.

2.2 Adaptation measures for flood risk reduction

Four types of adaptation measures were considered and implemented to different extents, to assess their sensitivity to the corresponding risk reduction. In the figures and the related discussions presented in Section 3.3, multiplicative and reduction rates associated to each adaptation option defined below are referred to as "sensitivity factors". Each adaptation option targets the reduction of flood risk by acting on one of the three components of the risk formula, namely hazard, exposure and vulnerability. Note that adaptation options have been evaluated considering future socio-economic developments based on SSP5 scenario.

2.2.1 Increase of flood protection levels

It aims at reducing the vulnerability of people and assets to extreme streamflow conditions. It requires limited space as it normally 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. This keeps flood storage to minimum levels hence the magnitude of the flood peak remains unchanged for long river reaches. As a consequence, its implementation (and maintenance) need be homogeneous within each river basin as local weaknesses would represent preferential triggering points for flooding. In the simulation framework, the return period of current flood protections in Europe, expressed in years, was increased by a set of 12 constant rates ranging between 5 % and 2500 %, where the upper bound was set to 10,000 years.

2.2.2 Reduction of the peak flows

This adaptation option aims at reducing the flood hazard through a reduction and a delaying of peak flows during extreme events. Peak reduction 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. In addition, peak flows are reduced by reservoirs, sustainable urban drainage systems (SUDS, e.g., Pasche et al. 2008), retarding basins, infiltration basins, and through targeted land management plans such as afforestation and river renaturation (Reinhardt et al. 2011). In this study, we run the impact model with a set of 11 different reduction factors between 5 % and 95 % applied to the return period (i.e., the average recurrence interval) of simulated discharge peaks.

2.2.3 Reduction of vulnerability

This measure includes all adaptation options which can be modelled through a progressive reduction of the vulnerability, including the implementation of early warning systems, dry and wet flood proofing, and floating buildings, among others (see Kreibich et al. 2015;

Pappenberger et al., 2015). In the impact model, the adaptive measure is implemented through a multiplicative factor, ranging between 0 and 1, applied to the damage curves and to the population density layer. One should note that this measure does not reduce the frequency of flooding events but rather the consequences of the flooding, hence the reduction in population affected is to be seen as a reduction of the degree of disruption to the population and their activities

2.2.4 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). Here, we define a relocation mask as the set of areas with 3 or more meters of flood depth following an event with return period of 20 years, assuming no flood protections in place. By definition, in these areas, flooding has a 50 % probability to occur in a 13.5 year period, so it is likely to be experienced by permanent residents once or more in their lifetime. In the impact assessment, we tested 8 different relocation ratios between 5 % and 100 %, to be applied as multiplicative factors to people and assets located within the area defined by the relocation mask. These modified exposure layers are then used within the risk assessment framework to estimate the impact of future flood peaks and their corresponding inundation depths.

3 Results

3.1 Flood hazard in Europe

We report in Table 2 the results of the frequency analysis of extreme peak flow events above a 100-year return period (referred to as f100), aggregated at country level. Such an analysis is of particular interest, given that the average protection level of the European river network is of the same magnitude (Rojas et al., 2013), with some obvious differences among different countries and river basins (Jongman et al., 2014). In other words, a substantial increase in the frequency of peak flows below the protection level is likely to have a lower impact, in terms of population affected and economic losses, in comparison to a small but significant change in extreme events causing settled areas to be inundated by the flood flow. A summary of country-aggregated estimates of f100 and the relative changes from the baseline in future time slices is shown in Table 2. Values are obtained by counting the average frequency of occurrence in all grid points of the river network within each country. The statistical significance of the estimated change in the ensemble mean was tested with a two-proportion z test. A stringent p value of 1‰ is chosen as threshold for significance, to compensate for the autocorrelation of extreme events in neighbouring grid points along the drainage direction. In addition, this issue is mitigated by the use of an ensemble of seven independent models. Note that no flood damages are computed for Cyprus and Malta because the river network in these countries is below the minimum threshold considered in the analysis.

The first striking outcome of Table 2 is the predominance of positive changes in f100 since the "near future" time slice, with most of the countries experiencing an increase of more than 100% and several exceeding 200% and more like Iceland (390%), Kosovo (405%) and the Netherlands (296%). In the "far future" time slice, projected changes show a further increase above 200% in most countries, with values ranging between 11% in Finland and up to 1050% in Iceland. This means that in all countries there will be an increase in frequency of severe flood events.

Table 2. Mean annual exceedance frequency of the 100-year return period peak flow for different European countries and percentage change between the baseline and the future time slices. Changes in italic are not significant at 1‰.

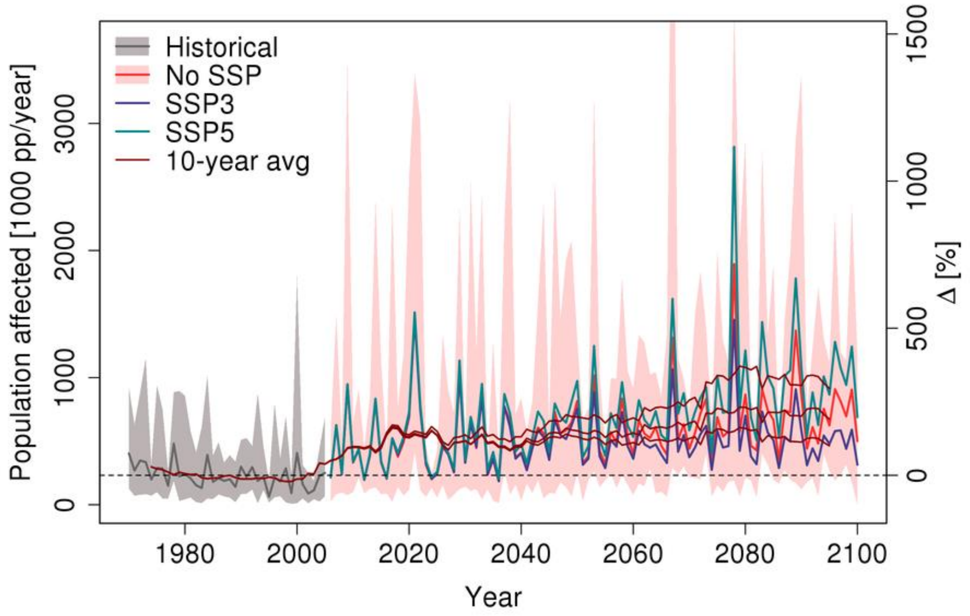
Country	f_{100}			Δf_{100}	
	baseline	2021-2050	2071-2100	2021-2050	2071-2100
Austria	0.0067	0.0223	0.0316	231%	369%
Belgium	0.0102	0.0344	0.0519	235%	407%
Belarus	0.0083	0.0152	0.0157	83%	90%
Bosnia - Herzegovina	0.0096	0.0211	0.0302	121%	216%
Bulgaria	0.0159	0.0292	0.0324	84%	104%
Croatia	0.0062	0.0165	0.0267	165%	328%
Cyprus	0.0000	0.0000	0.0000	0%	0%
Czech Republic	0.0140	0.0199	0.0246	42%	76%
Denmark	0.0179	0.0228	0.0377	*28%*	111%
Estonia	0.0025	0.0069	0.0118	179%	379%
Finland	0.0031	0.0030	0.0034	*-4%*	*11%*
France	0.0094	0.0235	0.0334	150%	256%
FYROM	0.0120	0.0204	0.0464	69%	285%
Germany	0.0115	0.0235	0.0282	105%	146%
Greece	0.0113	0.0242	0.0410	113%	262%
Hungary	0.0087	0.0222	0.0236	153%	170%
Ireland	0.0086	0.0211	0.0494	147%	477%
Iceland	0.0020	0.0100	0.0235	390%	1050%
Italy	0.0126	0.0241	0.0483	92%	284%
Kosovo	0.0088	0.0443	0.0512	405%	484%
Lithuania	0.0078	0.0131	0.0122	66%	55%
Luxemburg	0.0058	0.0201	0.0194	247%	235%
Latvia	0.0054	0.0163	0.0192	202%	255%
Malta	0.0000	0.0000	0.0000	0%	0%
Moldova	0.0203	0.0402	0.0310	98%	53%
Montenegro	0.0089	0.0200	0.0388	125%	335%
The Netherlands	0.0090	0.0358	0.0511	296%	465%
Norway	0.0027	0.0086	0.0091	215%	233%
Poland	0.0125	0.0268	0.0261	114%	109%
Portugal	0.0074	0.0115	0.0237	55%	220%
Romania	0.0088	0.0224	0.0266	154%	201%
Serbia	0.0091	0.0275	0.0374	203%	313%
Slovenia	0.0061	0.0230	0.0365	279%	501%
Slovakia	0.0050	0.0153	0.0144	206%	190%
Sweden	0.0029	0.0062	0.0093	118%	224%
Spain	0.0090	0.0185	0.0286	106%	218%
Switzerland	0.0036	0.0122	0.0223	238%	517%
United Kingdom	0.0120	0.0216	0.0410	81%	242%
Europe	0.0080	0.0204	0.0320	113%	234%

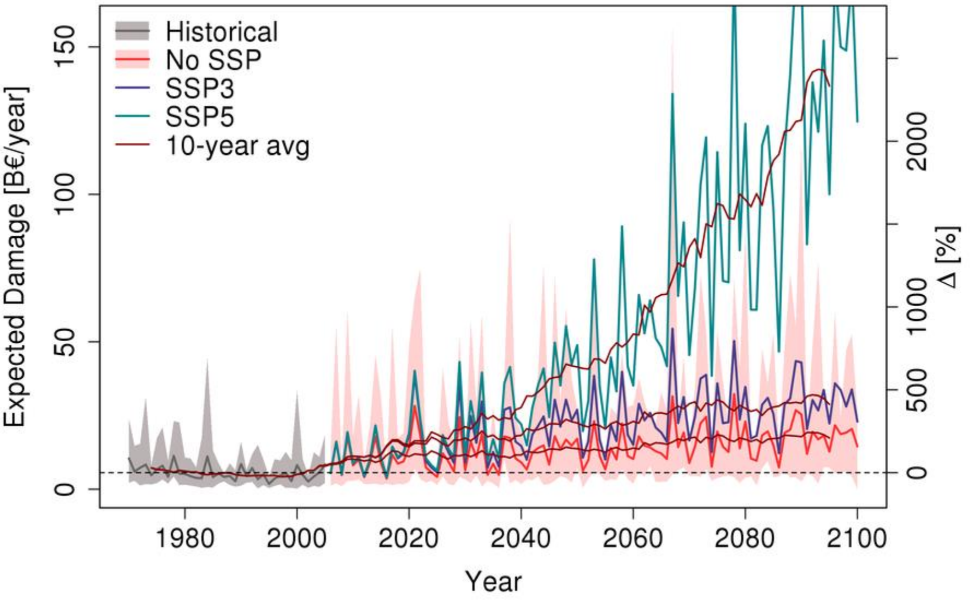
3.2 Flood risk in Europe

Spatially aggregated mean values of Expected Annual Damage (EAD) and Expected Annual People Affected (EAPA) per year are shown in Figures 2 and 3, together with the ensemble spread given by the seven model realizations. Relative changes from the baseline average values can be read in the y-axis on the right. Projections of EAD and EAPA considering

SSP3 and SSP5 are shown in Figure 2, while impact projections considering PESETA socioeconomic scenario (Peseta SP) are displayed in Figure 3.

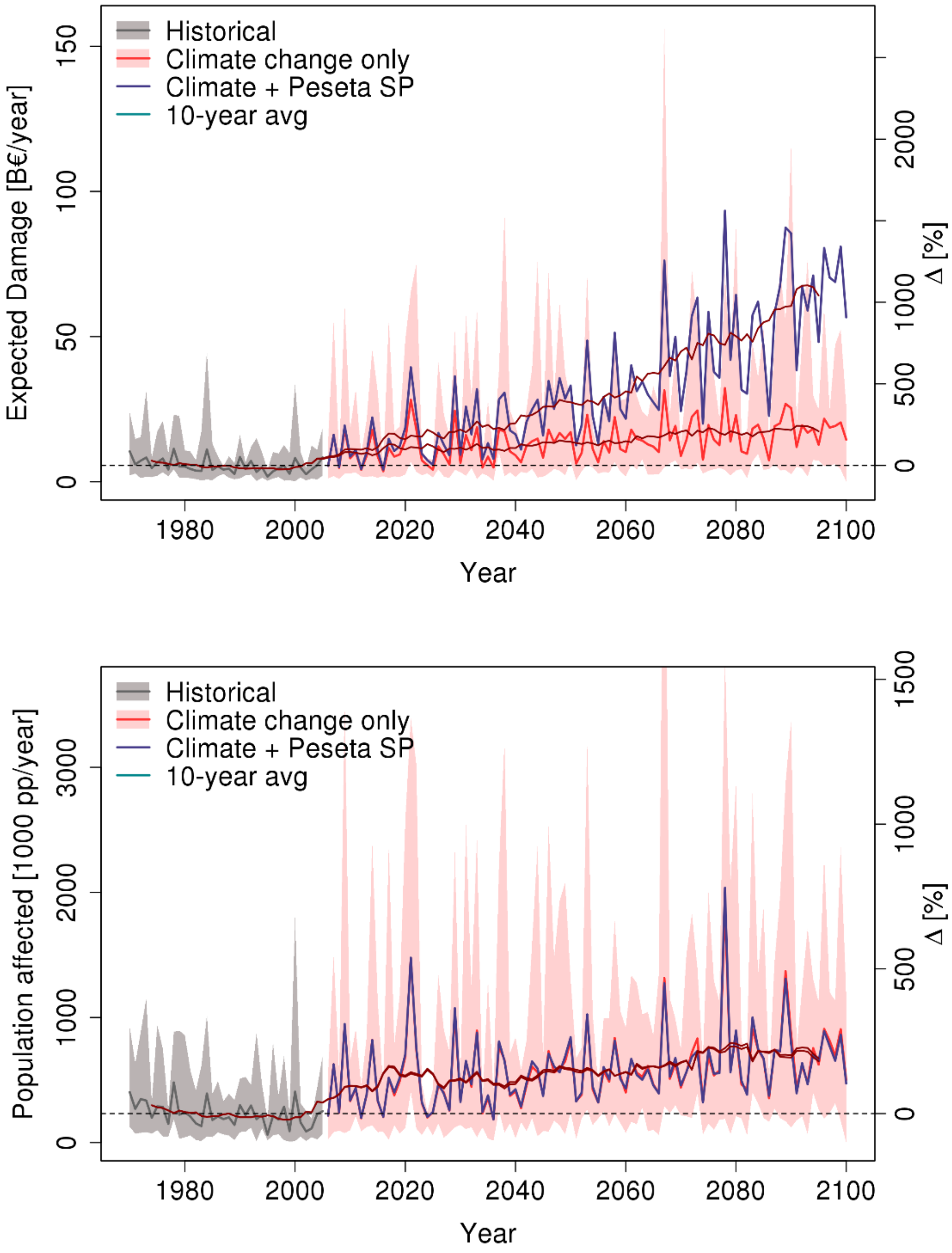
Figure 2. Simulated damage and population affected per year and relative change from the baseline scenario (Europe-wide aggregated figures). Future scenarios include no SSP (with ensemble spread in pink), SSP3, and SSP5, together with their 10-years moving average.





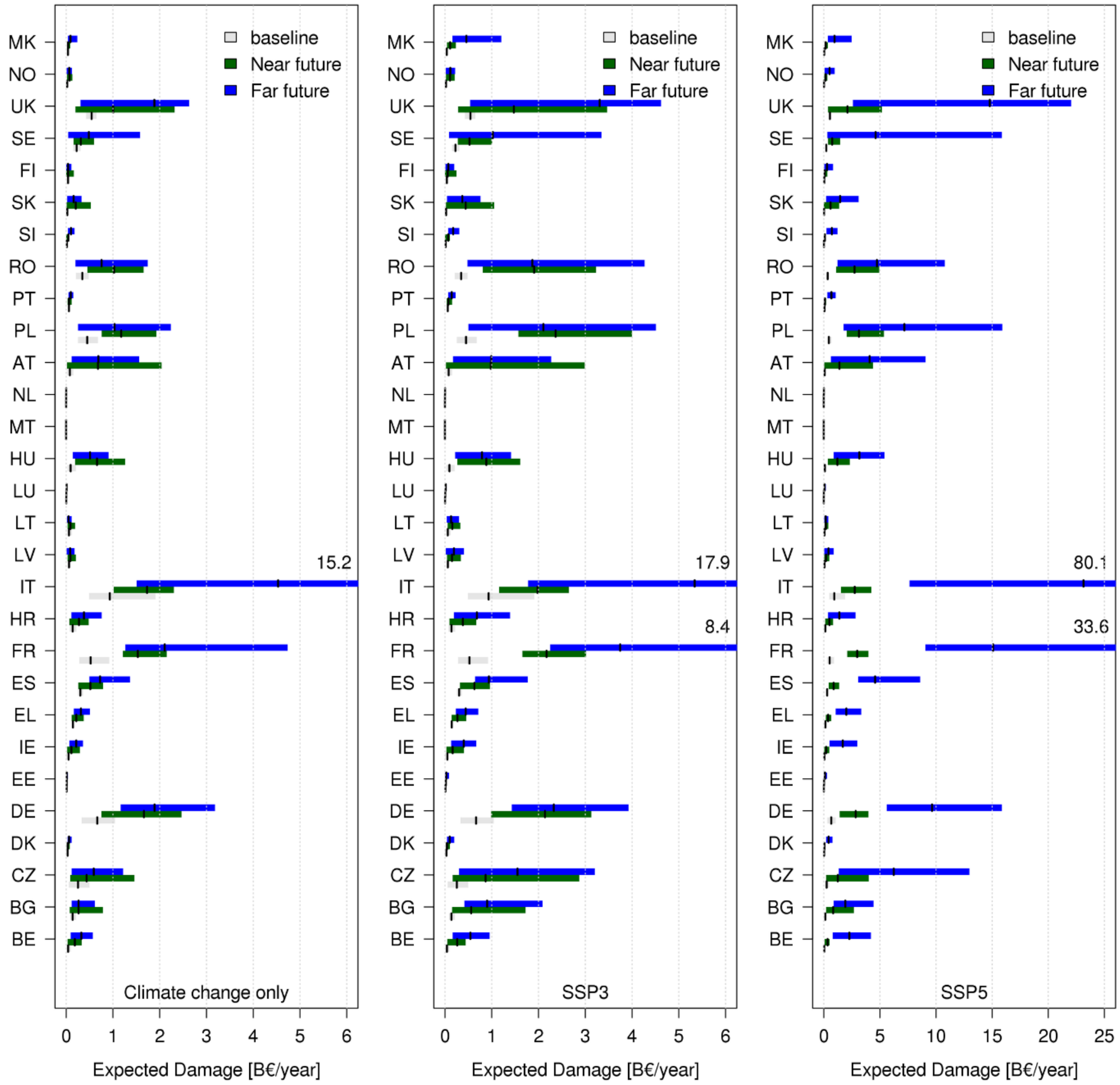
Overall mean impact in Europe for the baseline scenario amounts to €5.3 billion of damage and 216,000 people affected per year. This compares well with estimates by the Association of British Insurers (ABI, 2005) and by the European Environment Agency (EEA, 2010), reporting figures of annual losses between €4.3 and 8 billion and 262,000 people affected each year by flood events in Europe. If SSPs are not considered, this means when only accounting for the effects of climate change, overall mean projections of annual population affected by floods are estimated to increase to 530,000 for the "near future" time slice and to further rise to 720,000 for the "far future". Conversely, the expected annual damage is projected to rise to €12.5 billion (+108%) and €17.5 billion (+227%) through the future time slices. When SSPs are accounted for, EAPA remains comparable to the "No SSP" scenario for the "near future" time slice, and increases for the "far future" to reach 530,000 and 975,000 for SSP3 and SSP5, respectively. Under the Peseta SP scenario EAPA remains always close to the "No SSP" scenario (Figure 3). The increases are much larger for EAD, which is projected to reach 29 B€ under SSP3, and a stunning €112 billion under SSP5, while under the Peseta SP scenario the projected value exceeds €50 billion.

Figure 3. Simulated damage and population affected per year and relative change from the baseline scenario (Europe-wide aggregated figures). Future scenarios include no SSP (with ensemble spread in pink) and Peseta scenario, together with their 10-years moving average.



Future risk projections for each time slice are then broken down at country level for the three socioeconomic pathways as shown in Figures 4, 5 and 6. These figures highlight countries that contribute the most to the overall change in flood risk through the current century, together with the associated uncertainty of the ensemble and their mean value.

Figure 4. Country aggregated expected annual damage for the baseline and future time slices of 2021-2050 (near future) and 2071-2100 (far future) (mean value and ensemble spread) for the three cases of no SSP (left), SSP3 (centre), and SSP5 (right). Some countries are not included in the graphs because impacts are negligible compared to other countries.



Results clearly show an increasing spread of the model ensemble in time, though with some exceptions, notably in the near future time slice (i.e. 2021-2050). When only the climate forcing is considered (i.e. "No SSP" scenario), countries with mean EAD larger than €1 billion by the end of the century are Italy (€4.6 billion), France (€2.1 billion), UK (€1.9 billion) and Germany (€1.8 billion), though Poland is projected to reach €1.2 billion by the time slice 2020, later decreasing at about €1 billion by the end of the century. Where SSPs or Peseta SP are included, EAD is projected to rise further in all countries, reaching an average five-fold increase for the SSP5 in the "far future" time slice as compared to the "No SSP" scenario, which becomes seven-fold for UK and France. Considering projections of average annual population affected driven only by climate forcing, the most affected countries by the end of the century will be Germany (110,000), Italy (95,000) and France (90,000). Under SSP3 scenario, EAPA is comparable or lower with respect to the "No SSP", while in the SSP5 scenario the impacts for all countries are projected to be larger, with an increasing spread of the model ensemble. Under Peseta SP scenario, the increase of future impacts is generally in between SSP3 and SSP5 values (Figure 6).

Figure 5. Country aggregated affected population for the baseline and future time slices of 2021-2050 (near future) and 2071-2100 (far future) (mean value and ensemble spread) for the three cases of no SSP (left), SSP3 (centre), and SSP5 (right). Some countries are not included in the graphs because impacts are negligible compared to other countries.

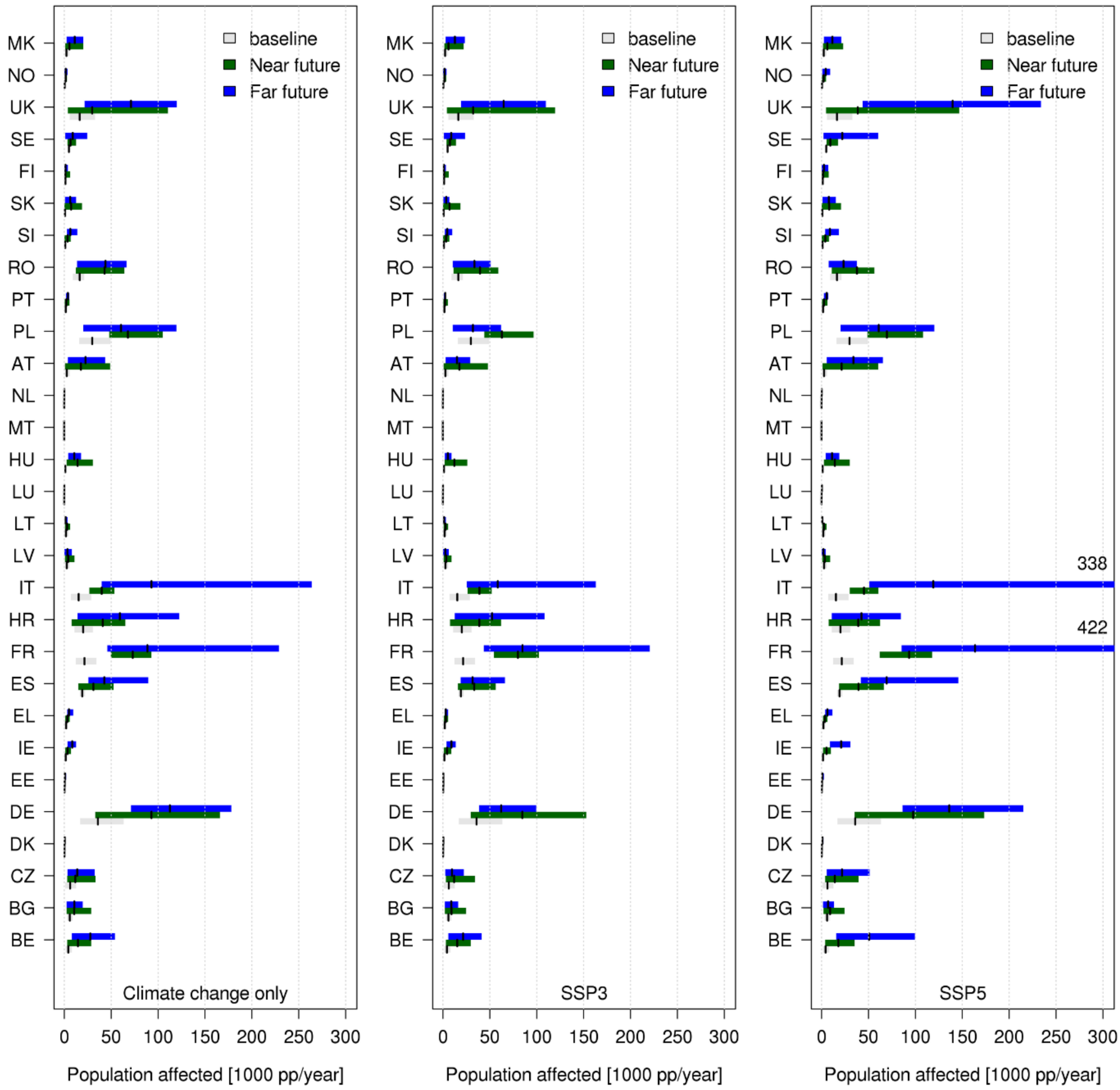


Figure 6. Country aggregated affected population (right) and economic damage (left) for the baseline and future time slices of 2021-2050 (near future) and 2071-2100 (far future) (mean value and ensemble spread) for the Peseta SP scenario. Some countries are not included in the graphs because impacts are negligible compared to other countries.

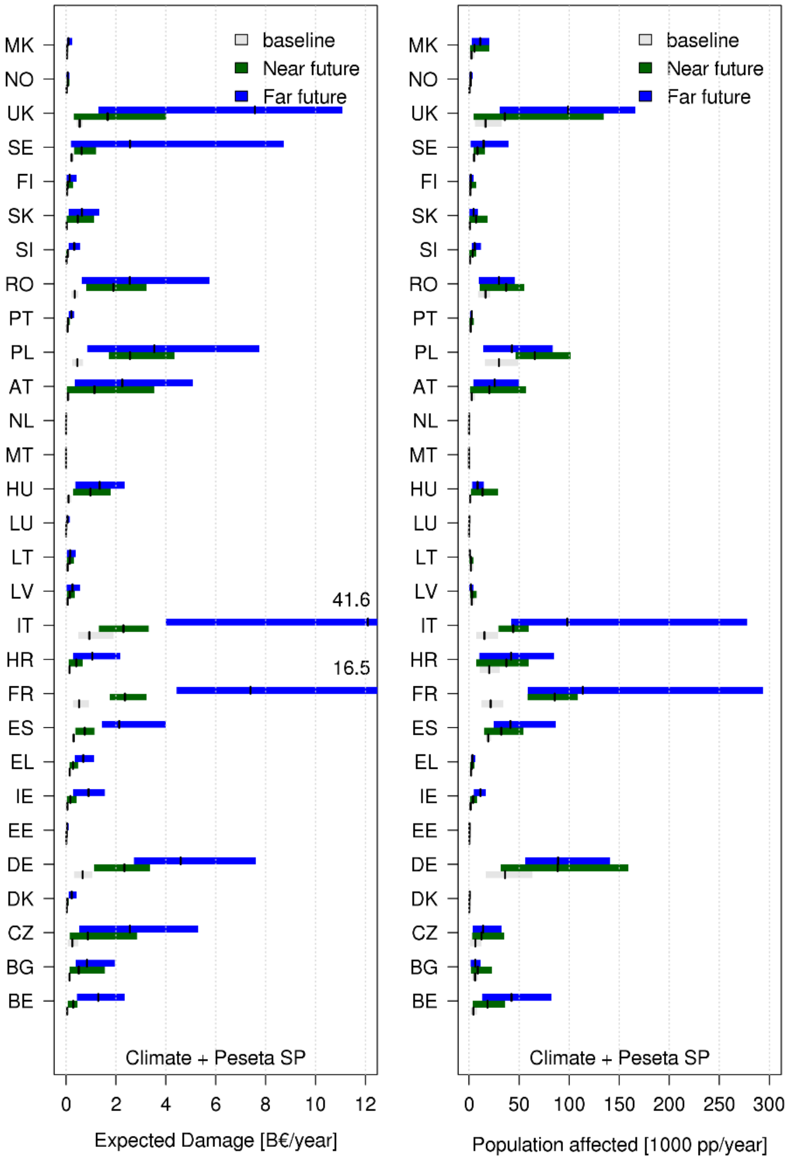
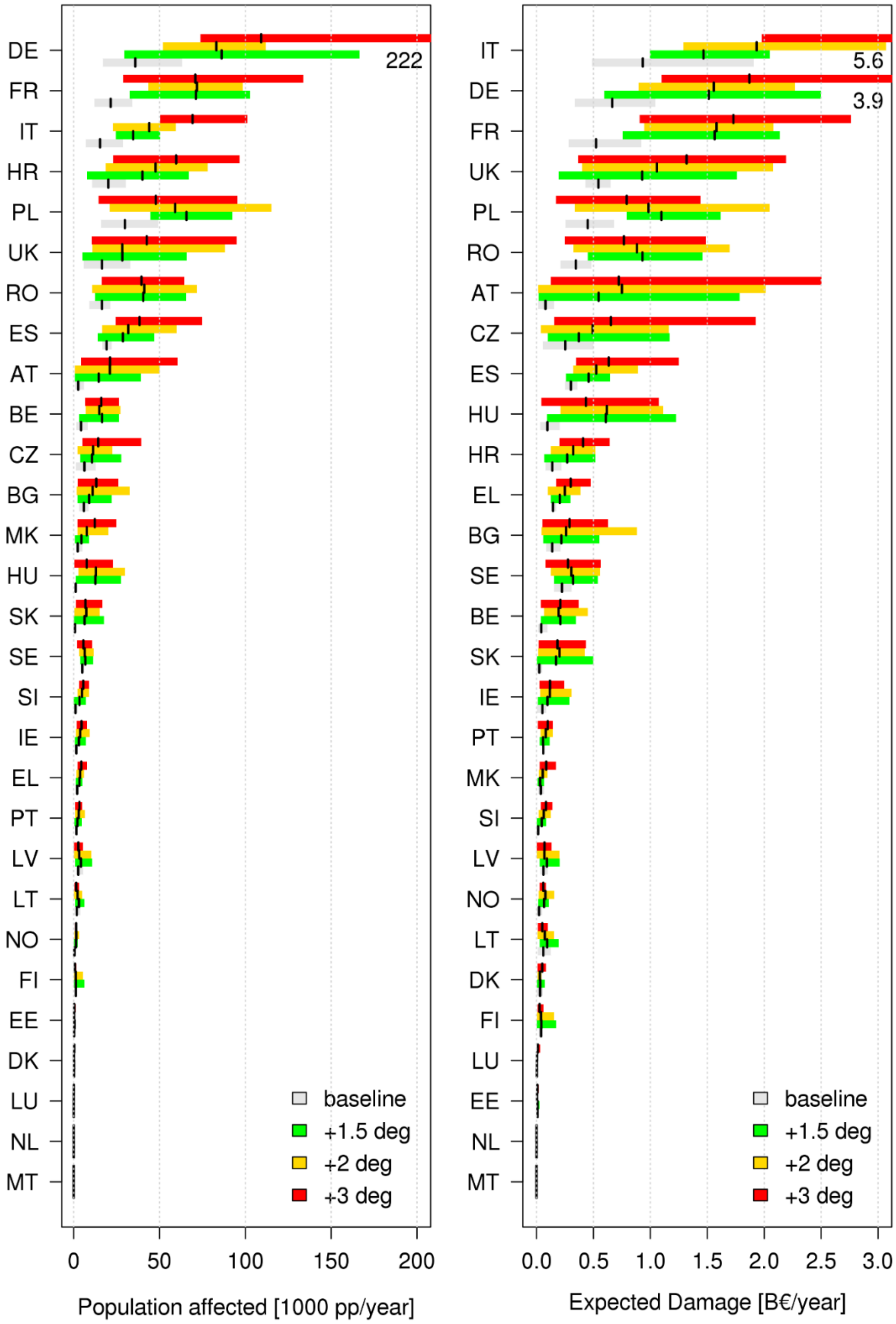


Figure 7 shows the annual ED and PA for the baseline and specific warming levels (SWLs) of 1.5, 2 and 3°C. Note that no SSPs have been considered in this case.

Figure 7. Country aggregated EAD and EAPA for the baseline and 3 specific warming levels (1.5, 2 and 3°C warming) based on a static economic analysis. Some countries are not included in the graphs because flood damages are negligible compared to other countries.



Results show a general trend of rising flood losses with increasing warming level. At present about 220,000 people are flooded annually, which rises to 480,000 under 1.5°C global warming. With 2°C warming this amount is slightly higher to equal 510,000, whereas under 3°C warming more than 600,000 people will be annually under risk of flooding. Direct economic losses from flooding show a similar trend, with expected annual damages projected to rise from €5.3 billion/year at present to €11 billion/year, €12 billion/year and €14.5 billion/year respectively under 1.5, 2, and 3°C warming. In a 3°C warmer world, the four largest European countries in terms of population (i.e., Germany, France, United Kingdom and Italy) are projected to suffer a considerable increase in population affected and direct damage by river floods, reaching a total (ensemble mean) of 290,000 people affected and €8 billion damage per year, as compared to 90,000 people and €2.7 billion damage per year in the present climate.

When evaluating the results, it is important to remember that the proposed approach is focused on the flood risk due to riverine floods in river basins with upstream area larger than 500 km^2 (see Alfieri et al., 2014). Hence, the impact due to flash floods, surface water flooding and coastal floods is not accounted for. In addition, despite our effort to characterize and possibly minimize the climatic uncertainty, one should be aware of other sources of uncertainty (e.g., in the hydrological and hydraulic modelling, in the space-time discretization, in the impact model, among others) which affect complex modelling framework such as the one presented in this work.

3.3 Strategies for flood risk reduction

The effect of the four adaptation strategies described in Sect. 2.2 on annual estimates of population affected and expected damage in Europe is shown in Fig. 8. Each graph includes the corresponding average impact of the same set of simulations over the baseline window 1976–2005. Graphs in Fig. 8 clearly indicate increasing flood risk and ensemble spread for time slices further in time, as a combination of increasing hazard due to climatic change and of socio-economic drivers. Also, the graphs indicate a non-linear behaviour in the risk reduction of the first two adaptation options, as opposed to a linear trend in the latter two, which leave the flood depth and extent unchanged while acting on measures to reduce the disruption to population and assets. Past levels of flood impact are unlikely to be retained by the end of the century if only one adaptation option is implemented.

Risk reduction estimates were then aggregated for each of the 28 countries. Figures 9 and 10 show the results for Germany, France, UK and Italy, which together contribute to more than 50 % of the European population considered in this study. Note that we considered here three future time slices centred respectively at 2020, 2050 and 2080, to illustrate better the development in time. Each graph shows, with a horizontal dashed line, the risk reduction needed to retain the relative flood impact of the baseline window 1976–2005. Differently from Fig. 8, the horizontal line referring to historical impact data do not include the socio-economic development but only the effect of climate change. In practice, it represents the risk reduction needed to keep the historical ratio of population affected and economic damage as compared to the country population and GDP. In most countries, the required risk reduction grows in time due to the increasing flood risk, which implies a continuous effort to improve the adaptation strategy. For instance, in Germany (DE) in the TS 2020, historical values of flood impact can be retained as long as adaptation measures are implemented to achieve a risk reduction of 65 % (PA, Fig. 9) and 61 % (ED, Fig. 10), as compared to the no-adaptation scenario. Regarding population affected, the risk reduction can be achieved on average with 65 % reduction of vulnerability, 80 % reduction of the return period of peak flows, or a 5 to 10-fold increase in the return period of flood protections. One can note that a complete relocation of people living in the relocation mask would reduce the population affected by only 12 %, which is far less than the target risk reduction. On the other hand, the reduction in expected damage through relocation was always found larger (e.g., 59 % in Germany), suggesting that a considerable proportion of assets is currently located in areas at risk of flooding. Also, it is noteworthy that vulnerability reduction measures do not depend on the climate scenarios and consequently on the frequency of flooding, hence no spread of the climate scenarios can be seen in Figs. 9 and 10.

Figure 8. Benefits of four adaptation strategies on ensemble annual estimates of population affected (left) and expected damage (right) in Europe in future time slices 2021-2050 (Near Future) and 2071-2100 (Far Future), as compared with baseline period (1976-2005).

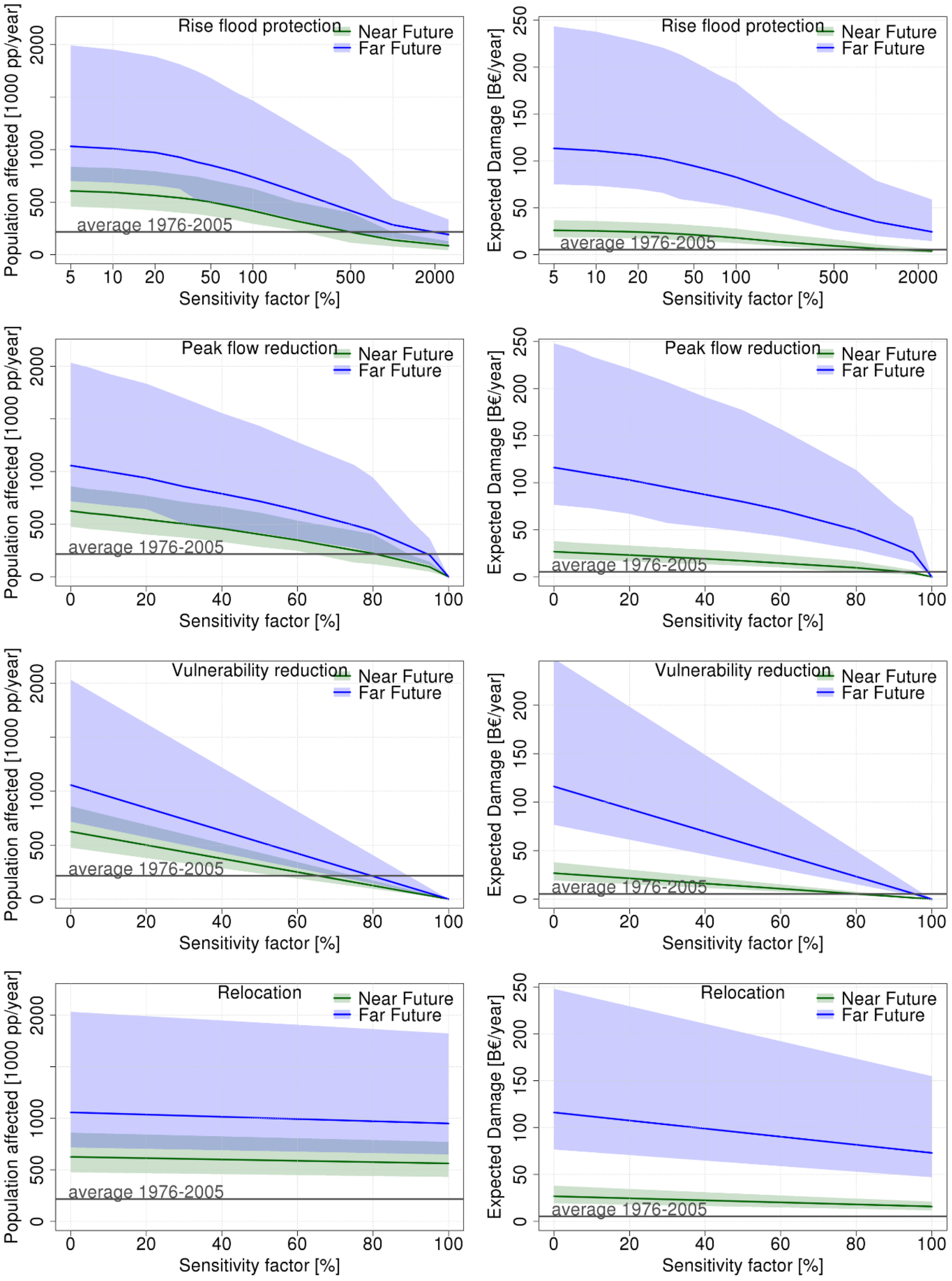
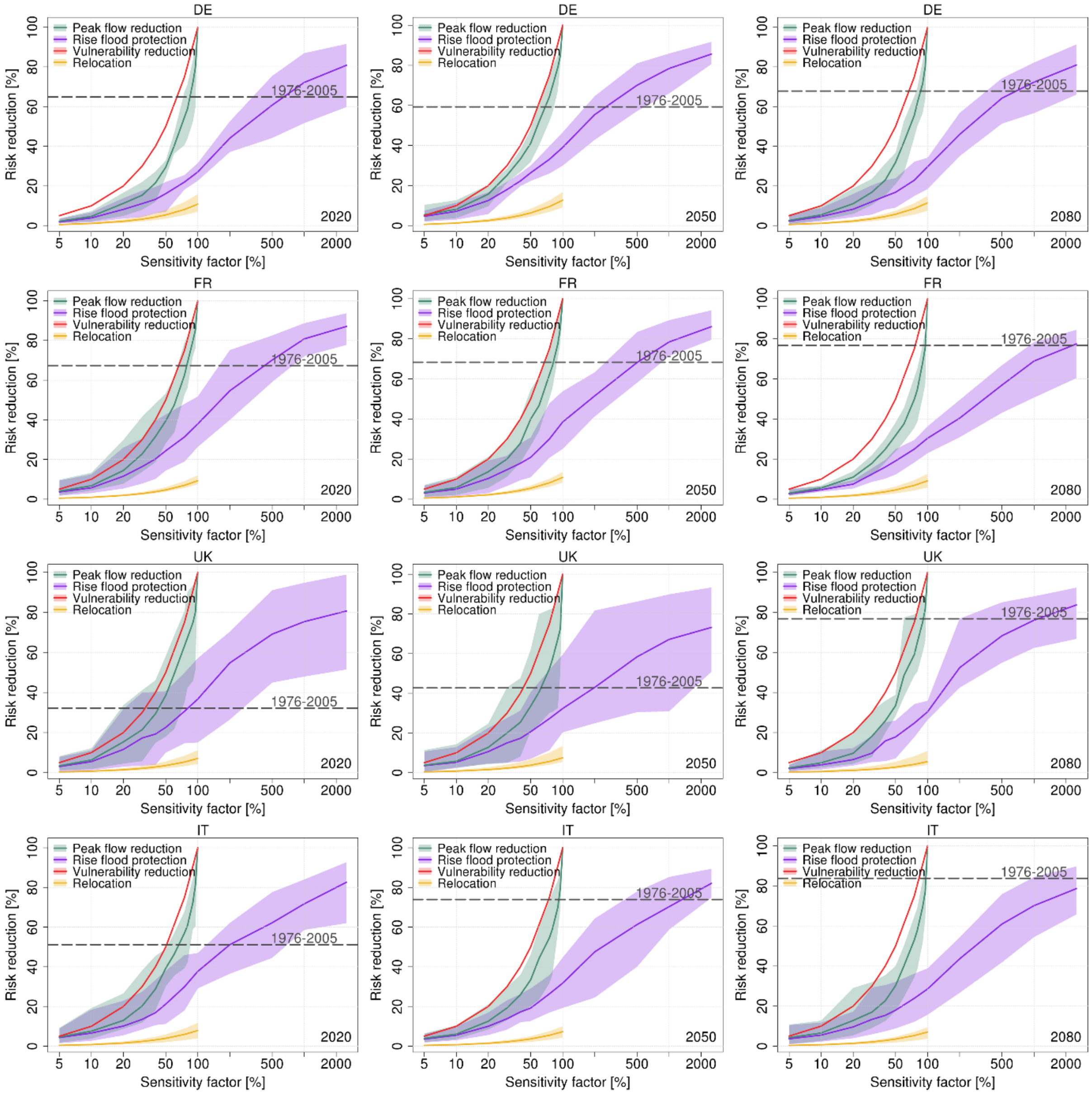
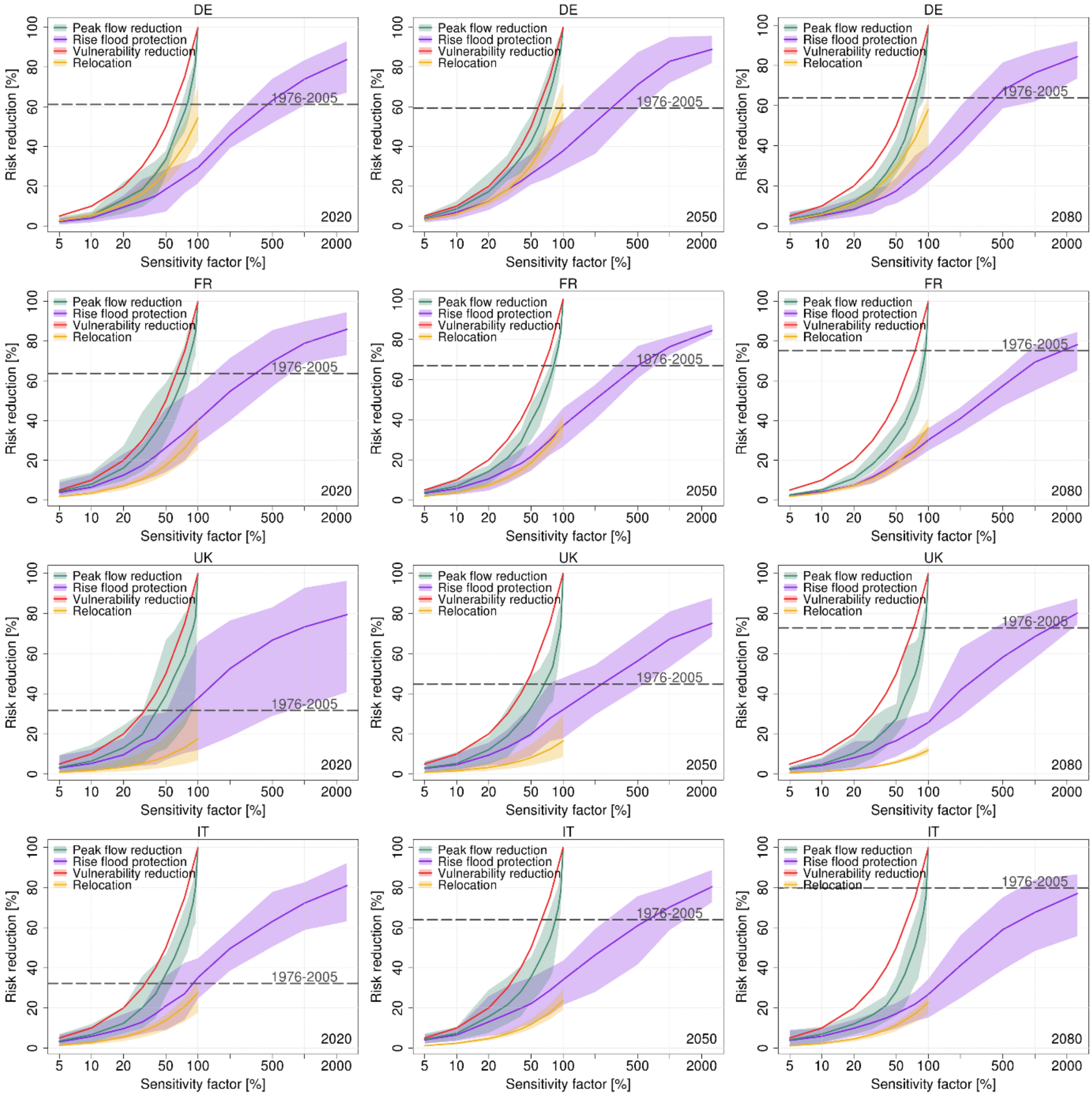


Figure 9. Risk reduction in population affected through different adaptation options. Ensemble projections over 3 time slices are shown for Germany, France, UK and Italy



When evaluating the results, it should be considered that sensitivity factors approaching 100 % reduction of the peak flow and of the vulnerability are unrealistic with technologies currently available. Simulations in the upper range of sensitivity are shown for completeness of the analysis as well as to show the effect of the climate uncertainty at different sensitivity levels. In real world applications, peak flow reduction rates rarely exceed 50 % (Pasche et al. 2008; Reinhardt et al. 2011) and tend to decrease with the event magnitude and with the catchment area. With regard to vulnerability reduction, early warning systems are known to yield profitable cost-benefit ratios (Pappenberger et al. 2015), though with relatively low risk reduction ratios (Meyer et al. 2012). On the other hand, structural measures for vulnerability reduction lead to higher risk reduction rates, at the expense of more considerable investments.

Figure 10. Risk reduction in expected damage through different adaptation options. Ensemble projections over 3 time slices are shown for Germany, France, UK and Italy



From a numerical viewpoint, it appears that rising flood protections is the only adaptation option that can compensate for any increase in the flood risk. It has relatively high cost-effectiveness (Fenn et al. 2014) and often finds little societal resistance in its implementation as it is mostly not associated with land-use changes. However, a comprehensive analysis of costs and benefits of this adaptation measure should include the following issues:

- An additional risk component is due to the probability of failure of the flood protections for event magnitudes lower than the design standards, as often occurs in flood events (Zurich 2014).
- Heightening river dykes reduces the probability of overflowing thus minimizing the floodplain storage and increasing the magnitude of peak flows downstream.
- Rising flood protections and the consequent reduction in the frequency of flooding events favours the loss of flood memory, leading to increasing exposure in flood-prone areas (Di Baldassarre et al. 2015). This dynamic, usually referred to as "levee

effect", is characterized by potentially long flood-free periods followed by catastrophic events and large flood losses.

On the other hand, empirical evidence suggests that recurrent flooding is usually associated with decreasing vulnerability (e.g., Jongman et al. 2015), due to the enhanced resilience and coping capacity acquired by the society during previous events (so-called "adaptation effect").

Finally, the benefits of methods relying on reducing the exceedance of flood thresholds (i.e., rising flood protections, reducing peak flow) heavily depend on the future climate scenario. In some cases, the magnitude of future climate extremes is within a relatively wide range around that of local flood protections, so that the consequent ensemble range of estimated risk reduction can be large. Uncertainty in risk reduction consistently decreases in the case of relocation and disappear altogether in vulnerability reduction, as these measures rely on reducing the consequences of a flooding event, rather than trying to avoid it.

4 Conclusions

Results from this work suggest that future river flood risk in Europe will largely increase compared to present levels, due to both climate change and socio-economic developments.

According to the models applied, impacts under current socio-economic conditions and for baseline climate amount to €5.3 billion of damage and 216,000 people affected by river floods every year, well within the range of the observed values found in the literature. By forcing the model with high end climatic projections, the socio-economic impact of river floods is projected to increase by an average of 220% by the end of the century, due to climate change only.

Estimates of population annually affected in 2021-2050 are within 500,000 and 640,000 and within 540,000 and 950,000 in 2071-2100. Larger variability is foreseen in the future economic growth and consequently in the expected damage of flooding, with central estimates at 10–30 B€ in 2021-2050 and 30–100 B€ in 2071-2100. Under a 2°C global warming scenario and considering current socio-economic conditions, flood impacts could more than double, with 520,000 people annually exposed to floods and 12.5 B€ of annual losses.

High-end climate scenarios are hereby shown to be linked with a significantly larger impact of future river floods on the European economy and society. In addition, we showed how four different classes of adaptation options can reduce the future flood risk to compensate for the impact of climate change. Research findings suggest that current relative flood impact levels can be retained or even decreased in the future decades, provided that coordinated and effective adaptation plans are promptly prepared and put into action. Under the projected increase in frequency and magnitude of river floods, traditional approaches based only on rising indefinitely local flood protections are not sustainable in the long term. The combined effect of these two dynamics is likely to exacerbate the "levee effect" by reducing the frequency of moderate events and exposing the society to few catastrophic floods, followed by potentially long and painful post-event recovery. We recommend future adaptation strategies to be based on a combination of different measures working in synergy and optimized at the level of river basins, rather than through independent actions over selected river reaches.

References

Alfieri, L., Burek, P., Feyen, L., Forzieri, G., 2015a. **Global warming increases the frequency of river floods in Europe**, *Hydrol. Earth Syst. Sci.* 19, 2247-2260.

Alfieri, L., Feyen, L., Dottori, F., Bianchi, A., 2015b. **Ensemble flood risk assessment in Europe under high end climate scenarios,** *Glob. Environ. Change 35*, 199–212, doi:10.1016/j.gloenvcha.2015.09.004

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

ABI, 2005. **Financial Risks of Climate Change - Summary Report**, *Association of British Insurers*.

Adger, W.N., Arnell, N.W., Tompkins, E.L., 2005. **Successful adaptation to climate change across scales.** *Glob. Environ. Chang*e 15, 77–86. doi:10.1016/j.gloenvcha.2004.12.005

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**. *J. Hydrol.* 387, 33-45.

Batista e Silva, F., Lavalle, C., Koomen, E., 2012. **A procedure to obtain a refined European land use/cover map**. *J. Land Use Sci*. 1–29. doi:http://dx.doi.org/ 10.1080/1747423X.2012.667450.

Batista e Silva, F., Gallego, J., Lavalle, C., 2013. **A high-resolution population grid map for Europe**. *J. Maps* 9, 16–28. doi:http://dx.doi.org/10.1080/ 17445647.2013.764830.

Brandimarte, L., Brath, A., Castellarin, A., Di Baldassarre, G. 2009. **Isla Hispaniola: A trans-boundary flood risk mitigation plan**. *Phys Chem Earth* 34, 209–218. doi:10.1016/j.pce.2008.03.002

Bichard, E., Kazmierczak, A., 2012. **Are homeowners willing to adapt to and mitigate the effects of climate change?** *Clim. Chang*e 112, 633–654. doi:10.1007/s10584-011-0257-8

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

Christensen, J. H., & Christensen, O. B., 2007. **A summary of the PRUDENCE model projections of changes in European climate by the end of this century**. *Clim. change*, 81, 7-30.

Dankers, R., Feyen, L., 2009. **Flood hazard in Europe in an ensemble of regional climate scenarios**. *J. Geophys. Res. Atmos.* 114, doi:http://dx.doi.org/10.1029/ 2008jd011523.

Di Baldassarre, G., Viglione, A., Carr, G., et al., 2015. **Debates—perspectives on sociohydrology: capturing feedbacks between physical and social processes**. *Water Resour Res* 51, 4770–4781, doi:10.1002/2014WR016416

EEA, **Mapping the Impacts of Natural Hazards and Technological Accidents In Europe - An Overview of the Last Decade**. European Environment Agency, ISBN 978-92-9213-168-5 No. EEA Technical report No. 13/2010, 2010.

EEA, 2017. **Climate change, impacts and vulnerability in Europe** 2016. EEA Report No 1/2017.

European Commission, 2007. **Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks.**

Fenn, T., Fleet, D., Hartman, M., et al., 2014. **Study on economic and social benefits of environmental protection and resource efficiency related to the European semester final report.**

Frei, C., Schöll, R., Fukutome, S., Schmidli, J., Vidale, P.L., 2006. **Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models**. *Journal of Geophysical Research: Atmospheres*, 111(D6).

Hallegatte, S., 2009. **Strategies to adapt to an uncertain climate change**. *Glob Environ Chang* 19, 240–247. doi:10.1016/j.gloenvcha.2008.12.003

Huizinga, H.J., 2007. **Flood Damage Functions for EU Member States**. *HKV Lijn in water*, Lelystad, the Netherlands.

Jacob, D., Petersen, J., Eggert, B., et al., 2014. **EURO-CORDEX: new high-resolution climate change projections for european impact research**. *Reg Environ Chang* 14, 563–578. doi:10.1007/s10113-013-0499-2

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**. *Nat. Clim. Change* 4, 264–268, doi:10.1038/nclimate2124.

Keskitalo, E.C.H., Vulturius, G., Scholten, P., 2014. **Adaptation to climate change in the insurance sector: examples from the UK, Germany and the Netherlands**. *Nat Hazards* 71, 315–334. doi:10.1007/s11069-013-0912-7.

King D, Bird D, Haynes K, et al. (2014) **Voluntary relocation as an adaptation strategy to extreme weather events**. *Int J Disaster Risk Reduct* 8, 83–90. doi:10.1016/j.ijdrr.2014.02.006

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**.

Opperman, J.J., Galloway, G.E., Fargione, J., et al., 2009. **Sustainable floodplains through large-scale reconnection to rivers**. *Science* 326, 1487–1488. doi:10.1126/science.1178256

McLeman, R., Smit, B., 2006 **Migration as an adaptation to climate change**. *Clim Chang* 76, 31–53 doi:10.1007/s10584-005-9000-7.

Nikulin, G., et al., 2011. **Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations**. *Tellus A* 63.1, 41-55.

Pasche, E., Manojlovic, N., Behzadnia, N., 2008. **Floods in small urban catchments: hydrological sensitivity, risk assessment and efficient integrative strategies of mitigation**. In: *Proceedings of the 11th International Conference on Urban Drainage*, Edinburgh.

Reinhardt, C., Bölscher, J., Schulte, A., Wenzel, R., 2011. **Decentralised water retention along the river channels in a mesoscale catchment in South-Eastern Germany**. *Physics and Chemistry of the Earth* 36, 309–318. doi:10.1016/j.pce.2011.01.012

Pappenberger F, Cloke HL, Parker DJ, et al., 2015. **The monetary benefit of early flood warnings in Europe**. *Environ Sci Pol* 51:278–291. doi:10.1016/j.envsci.2015.04.016

Perez, J., Menendez, M., Mendez, F. J., Losada, I. J., 2014 **Evaluating the performance of CMIP3 and CMIP5 global climate models over the north-east Atlantic region**, *Clim. Dynam*. 43, 2663-2680, doi:10.1007/s00382-014-2078-8.

Rojas, R., Feyen, L., and Watkiss, P., **Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation**, *Global Environ. Change*, 23, 1737–1751, doi:10.1016/j.gloenvcha.2013.08.006.

UNISDR, 2009. **UNISDR Terminology on Disaster Risk Reduction**.

Reinhardt, C., Bölscher, J., Schulte, A., Wenzel, R., 2011. **Decentralised water retention along the river channels in a mesoscale catchment in South-Eastern Germany**. *Physics and Chemistry of the Earth* 36, 309–318, doi:10.1016/j.pce.2011.01.012

Rohde, S., Hostmann, M., Peter, A., Ewald, K.C., 2006. **Room for rivers: An integrative search strategy for floodplain restoration**. *Landsc Urban Plan* 78, 50–70. doi:10.1016/j.landurbplan.2005.05.006

van der Linden, P., & Mitchell, J. E., 2009. **ENSEMBLES: Climate change and its impacts-Summary of research and results from the ENSEMBLES project**.

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**. *Int. J. Geogr. Inf. Sci*. 24, 189–212.

van Vuuren, D.P., Carter, T.R., 2014. **Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old**. *Clim. Change* 122, 415–429. doi:http://dx.doi.org/10.1007/s10584-013-0974-2.

Zurich, 2014. **Risk Nexus, Central European floods 2013: a retrospective.**

Wenger, C., 2015. **Better use and management of levees: reducing flood risk in a changing climate**. *Environ Rev* 23, 240–255, doi:10.1139/er-2014-0060.

Whitfield, P.H., 2012. **Floods in future climates: a review**. *Journal of Flood Risk Management* 5(4), 336-365.

List of abbreviations and definitions

AL	Albania
AT	Austria
B€	EUR billion
BA	Bosnia and Herzegovina
BE	Belgium
BG	Bulgaria
BY	Belarus
CH	Switzerland
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
EAD	Expected Annual Damage
EAPA	Expected Annual Population Affected
ES	Spain
FI	Finland
FR	France
GDP	Gross Domestic Product
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IS	Iceland
IT	Italy
KS	Kosovo
LT	Lithuania
LU	Luxemburg
LV	Latvia
MT	Malta
MD	Moldova
ME	Montenegro
MK	FYROM (Former Yugoslav Republic of Macedonia)
NL	The Netherlands
NO	Norway
PL	Poland
PT	Portugal

RO	Romania
RS	Serbia
RCP	Representative Concentration Pathway
SE	Sweden
SI	Slovenia
SK	Slovakia
SSPs	Shared Socioeconomic Pathways
SWLs	Specific Warming Levels
UK	United Kingdom

List of figures

List of tables

KJ-NA-29422-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub
EU Science Hub - Joint Research Centre
Joint Research Centre
EU Science Hub

Publications Office

doi:10.2760/849948

ISBN 978-92-79-96911-9