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Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation

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A B S T R A C T

This study presents the first appraisal of the socio-economic impacts of river floods in the European Union in view of climate and socio-economic changes. The assessment is based on two trajectories: (a) *no adaptation*, where the current levels of protection are kept constant, and (b) *adaptation*, where the level of protection is increased to defend against future flooding events. As a basis for our analysis we use an ensemble-based pan-European flood hazard assessment for present and future conditions. Socio-economic impacts are estimated by combining flood inundation maps with information on assets exposure and vulnerability. Ensemble-based results indicate that current expected annual population affected of ca. 200,000 is projected to increase up to 360,000 due to the effects of socio-economic development and climate change. Under the *no adaptation* trajectory current expected annual damages of €5.5 billion/year are projected to reach €98 billion/year by the 2080s due to the combined effects of socio-economic and climate change. Under the adaptation trajectory the avoided damages (benefits) amount to €53 billion/year by the 2080s. An analysis of the potential costs of adaptation associated with the increase in protection suggests that adaptation could be highly cost-effective. There is, however, a wide range around these central numbers reflecting the variability in projected climate. Analysis at the country level shows high damages, and by association high costs of adaptation, in the United Kingdom, France, Italy, Romania, Hungary and Czech Republic. At the country level, there is an even wider range around these central values, thus, pointing to a need to consider climate uncertainty in formulating practical adaptation strategies.

1. Introduction and scope

In the last decade, major flooding events have occurred in Europe including, for example, the catastrophic floods along the Elbe and Danube (August 2002, March/April 2006); flooding in Romania and the Alpine countries (August 2005); the severe summertime flooding in Britain in 2007; several events in Czech Republic, Italy, and Poland in 2009; and very recently the devastating floods that hit central and Eastern Europe in June 2013. Between 1998 and 2009 alone, the European Environment Agency estimated that 213 flood events in Europe caused about 1126 fatalities, affected more than 3 million people and caused at least €52 billion in losses out of which €12 billion were insured economic losses (EEA, 2010).

Albeit some recent studies suggest that there may be an increase in the number of extreme floods in Europe in the last decades (see, e.g., Kundzewicz et al., 2013) there is still no conclusive evidence of a climate signal in the occurrence and severity of floods. Detecting a possible trend is hampered by the interaction between the climate-driven physical causes and socio-economic factors such as urban development in flood-prone areas (Barredo, 2009; Feyen et al., 2009; Elmer et al., 2012). Moreover, the statistical analysis of extreme river discharges, which serve as the basis to assess trends in floods, is an inherently difficult process plagued with uncertainties given the natural variability of extreme events (see, e.g., Mudelsee et al., 2003; Kundzewicz et al., 2005; Wilby et al., 2008).

The current knowledge on climate modelling suggests that climate change will be a determining factor in intensifying the hydrological cycle (Christensen and Christensen, 2007; van der Linden and Mitchell, 2009). This will most likely lead to an increase

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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; Fowler and Ekström, 2009; 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). Non-linear relationships between temperature and snow/rainfall and changes therein might also trigger alterations in flood hazard, especially in northern Europe. Due to increased temperatures, early spring snowmelt floods are likely to reduce (Kundzewicz et al., 2006) but compensation effects between rainfall- and snow-driven river floods in currently snow-dominated areas make projections of future flood hazard in these regions highly uncertain (Dankers and Feyen, 2009; Rojas et al., 2012). Using a 12-member ensemble of bias-corrected climate simulations based on the SRES-A1B emission scenario (Nakicenovic and Swart, 2000) to drive a pan-European hydrological model, Rojas et al. (2012) further observed a strong increase (>40%) in future flood hazard for the United Kingdom, northwest and southeast of France, and northern Italy, whereas less pronounced increases (10–30%) were projected for central Europe and the upper reaches of the River Danube and its main tributaries. A significant variability in future flood hazard was reported by Rojas et al. (2012), which was explained by the diverse signals in the magnitude of climate changes simulated by the climate models used in the analysis.

Traditionally, flood damage assessments have been limited to basin (e.g., de Kok and Grossmann, 2010; te Linde et al., 2011) or national (e.g., Hall et al., 2005; EA, 2009) scales and, up to date, only few studies have assessed current and/or future damages at global or continental scales. Lugeri et al. (2010) assessed the current damages at pan-European scale on the basis of a topography-based flood hazard map where no hydrological modelling was involved. Feyen et al. (2012) performed current and future damage assessment at pan-European scale for a small multi-scenario (A2 and B2) ensemble of four (non-corrected for bias) climate simulations. Recently, Jongman et al. (2012) presented global yearly damage estimates until 2050 due to river and coastal flooding using a purely data-driven approach. From these studies, only the work by Feyen et al. (2012) considered large-scale hydrological modelling driven by future climate simulations forced by IPCC-based emission scenarios (Nakicenovic and Swart, 2000). At the same time, none of the aforementioned studies considered adaptation scenarios, the quantification of avoided damages and/or costs of adaptation measures, or the uncertainty in damage estimates arising from different climate projections for the 21st century.

Besides changes in climate also dynamics in the socio-economic system may alter the consequences of floods in the future. In practice, the accumulation of wealth and urban development in flood-prone areas as well as the expansion of residential areas may significantly contribute to rise the damages from flooding events (see, e.g., Mitchell, 2003; Barredo, 2009; Feyen et al., 2009; Elmer et al., 2012). In this work the socio-economic dimension is accounted for by using high-resolution land use and population density maps as well as socio-economic developments projected for the future which are in line with the SRES-A1B scenario defined by Nakicenovic and Swart (2000). This scenario projects a fast economic growth, global population peaking in mid-century, rapid introduction of new and more efficient technologies, and a balance across all energy sources. The objective of our assessment is to evaluate how future climate and socio-economic developments will affect future flood risk in Europe, and at what cost the negative impacts could potentially be abated through adaptation.

This article builds upon the works of Rojas et al. (2012) and Feyen et al. (2012). First, we use flood hazard estimates under the SRES-A1B emission scenario (Nakicenovic and Swart, 2000) obtained from Rojas et al. (2012) to calculate the expected damages and population affected at pan-European scale following the methodological framework presented in Feyen et al. (2012). This work provides the first pan-European assessment of flood risks and potential costs and benefits of adaptation explicitly accounting for uncertainty arising from the definition of an ensemble of climate simulations. In particular, our work shows several innovative aspects which overcome some of the limitations identified in previous works (e.g., Feyen et al., 2012): (a) a very large ensemble of high-resolution (25 km) climate simulations considering 12 members is used, (b) biases in the precipitation and (min, avg, and max) temperature fields are corrected using a Quantile Mapping technique (see Rojas et al., 2011; Dosio et al., 2012, (c) more than twice the number of gauging stations (554 stations across Europe) are used for the validation of extreme discharges, (d) impacts are estimated throughout the 21st century and compared with current conditions, (e) socio-economic dynamics are taken into account through the use of GDP and population projections in line with the SRES-A1B scenario, and (f) an exploration of the possible costs and benefits of adaptation to increase protection against future flood hazard is provided.

We note that a flood is defined here as the temporary covering of land by water outside its normal confines. There exist different types of floods, such as large-scale river floods, flash floods, ice-jam or snowmelt induced floods, and coastal floods due to sea level rise/storm surges. This work focuses on river flooding, which is mainly linked with prolonged or heavy precipitation events as well as with snowmelt. Furthermore, we limit the analysis to estimating the direct tangible damages derived from the physical contact of flooding waters with the exposed assets and population. Theoretically, indirect damages can be estimated and there exist several methods to achieve this (see, e.g., Jonkman et al., 2008; Merz et al., 2010). In practice, however, they are hardly ever estimated given the current data and model limitations, and the dependence of the magnitude of the indirect damages on the boundaries in space and time of the damage assessment. Moreover, in a national or international setting, indirect economic damages at the regional scale tend to disappear as they are often compensated by production gains in regions outside the flooded area (Merz et al., 2010). Some methods include a fixed share of the total costs to account for indirect damages in a flood risk assessment: for example, the Damage Scanner used in the Netherlands adds about 5% of indirect damages (mainly reflecting business interruption) to the total damage, hence suggesting that direct damages dominate the total damage figures (e.g., Ward et al., 2011; te Linde et al., 2011).

In Section 2, we describe the methodological framework, including the details of the climate simulations, hydrological modelling, the depth-damage functions used to estimate damages as well as the assessment of cost/benefits of adaptation. Results are reported in Section 3, whereas a comprehensive discussion and main conclusion of this work can be found in Section 4.

2. Methodology

Fig. 1 shows the methodological approach used in this work. In a first step, a series of bias-corrected climate simulations (Dosio et al., 2012) were used to force the hydrological model LISFLOOD (van der Knijff et al., 2010). Subsequently, by using extreme value analysis techniques we obtained river discharge and water levels for return periods ranging between 2 and 500 years (see Rojas et al., 2012). A planar approximation approach following Bates and de Roo (2000) was then employed in which the flood wave is considered as a plane that is intersected with a high resolution digital elevation model to estimate flood inundation extent and water depth, resulting in inundation maps at a 100 m × 100 m

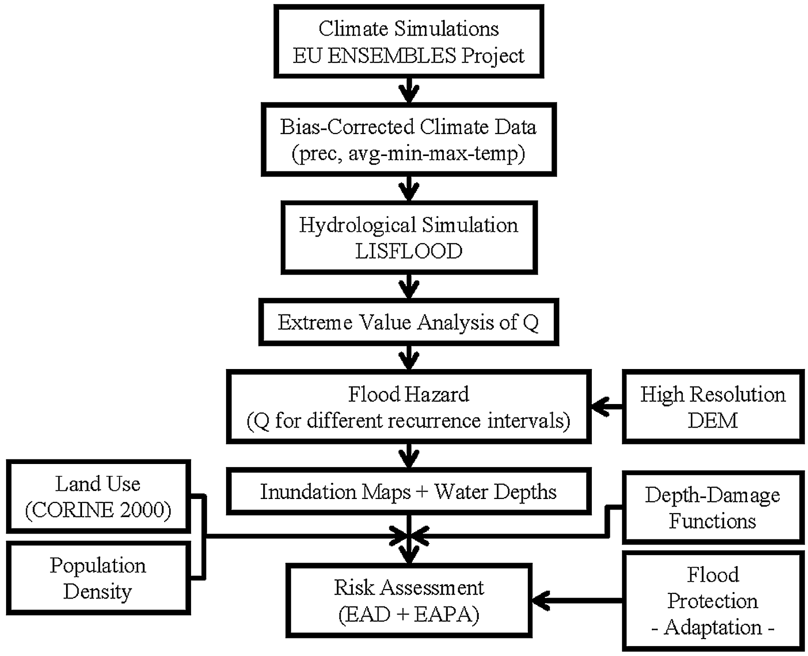

Fig. 1. Schematic overview of the methodological approach (adapted from Feyen et al., 2012). Risk due to river flooding is expressed as the expected annual damage and the expected annual population affected.

horizontal resolution. A quantification of the risk associated with river flooding was then obtained by combining inundation maps (flood hazard) for different return periods with information on population density, exposed assets (land use), and country specific depth-damage functions relating water depths and potential damages for each land use class. The risk was obtained from damage-probability curves and further expressed as expected annual damages and expected annual population affected. Finally, by implementing two scenarios of flood risk mitigation an estimation of the avoided damages (benefits) and the corresponding costs of adaptation were assessed. In this case, flood protection is accounted for by truncating the damage-probability function at the corresponding protection level. The data and methods used in the steps discussed above are further described in the following sections.

2.1. Data

2.1.1. Climate simulations

To effectively model flood generation processes it is important to capture fine-scale climatic features. The climate simulations used in this work (see Table 1) have been obtained from the EU FP6 ENSEMBLES project (van der Linden and Mitchell, 2009), which constitutes the largest high-resolution ensemble of climate simulations available for Europe. Other datasets driven by different scenarios are available (e.g., from FP6 PRUDENCE project) but these are at a coarser resolution (50 km), not continuous in time, and fewer model runs are available to sample climate uncertainty. From the ensemble of climate runs performed in ENSEMBLES we retained those that included all the required variables to run the hydrological model LISFLOOD. In total, 12 climate experiments derived from a combination of 4 GCMs and 7 RCMs, and covering the period 1961–2100, were used. These nested GCM–RCM simulations have a horizontal resolution of ca. 25 km, a daily temporal resolution, and were forced by the SRES-A1B scenario (Nakicenovic and Swart, 2000). Prior to running LISFLOOD, the precipitation and minimum, average, and maximum temperature fields were corrected for bias using a Quantile Mapping (QM) method (Rojas et al., 2011; Dosio et al., 2012).

2.1.2. Hydrological simulation and extreme value analysis

River discharge simulations for different climate experiments (see Table 1) were obtained using the LISFLOOD model (van der Knijff et al., 2010). LISFLOOD is a GIS-based hydrological model where processes such as infiltration, water consumption by plants, snowmelt, freezing of soils, surface runoff and groundwater storage are explicitly accounted for at the grid level. Being a fully distributed and physically based hydrological model developed for large-scale flood forecasting and impact assessment studies, LISFLOOD simulates the spatial–temporal patterns of catchment responses as a function of spatial information on meteorology, topography, soils, and land cover. Properties for soils, vegetation types, land uses, and river channels constitute the basic input to set up a LISFLOOD run, whereas data on precipitation, air temperature, potential evapotranspiration, and evaporation from water bodies and bare soil surfaces, are the main meteorological drivers. For a detailed description of the processes and equations included in LISFLOOD as well as its calibration we refer the reader to van der Knijff et al. (2010) and Feyen et al. (2007, 2008).

For this work, LISFLOOD was configured using a 5 km grid, a daily time step, and a simulation period between 1961 and 2100. For time windows of 30 years (control represents 1961–1990, the 2000s 1981–2010, the 2020s 2011–2040, the 2050s 2041–2070, and the 2080s 2071–2100), a Gumbel distribution was fitted to the annual maximum discharges simulated by LISFLOOD in every grid cell of the modelled domain. From the fitted Gumbel distributions, the discharge return levels were derived for every river pixel for return periods of 2, 5, 10, 20, 50, 100, 250 and 500 years. For further details on the flood hazard assessment employed in this work we refer the reader to Rojas et al. (2012).

2.1.3. Land use and population data

Land use information reflecting the assets exposed to the flood hazard was obtained from the CORINE Land Cover 2000 (EEA, 2002). CORINE is one of the most complete and accurate European databases containing 44 land use classes at a horizontal resolution

Table 1
Climate experiments forced by the A1B scenario and used to drive LISFLOOD in the period 1961–2100.

Model no.	Driving GCM	RCM	Institute	Acronyms
1	HadCM3Q16[a]	RCA3.0	The Community Climate Change Consortium for Ireland	C4I-RCA-HadCM3
2	ARPEGE	ALADIN-RM5.1	Centre National de Recherches Météorologiques, Meteo France	CNRM-ALADIN-ARPEGE
3	ARPEGE	HIRHAM5	Danish Meteorological Institute	DMI-HIRHAM5-ARPEGE
4	BCM	HIRHAM5	Danish Meteorological Institute	DMI-HIRHAM5-BCM
5	ECHAM5-r3[b]	HIRHAM5	Danish Meteorological Institute	DMI-HIRHAM5-ECHAM5
6	HadCM3Q0[a]	CLM	Swiss Federal Institute of Technology	ETHZ-CLM-HadCM3
7	ECHAM5-r3[b]	RACMO2	The Royal Netherlands Meteorological Institute	KNMI-RACMO2-ECHAM5
8	HadCM3Q0[a]	HadRM3Q0	UK Met Office, Hadley Centre for Climate Prediction and Research	METO-HadRM3-HadCM3
9	ECHAM5-r3[b]	REMO	Max-Planck-Institute for Meteorology, Germany	MPI-REMO-ECHAM5
10	BCM	RCA3.0	Swedish Meteorological and Hydrological Institute	SMHI-RCA-BCM
11	ECHAM5-r3[b]	RCA3.0	Swedish Meteorological and Hydrological Institute	SMHI-RCA-ECHAM5
12	HadCM3Q3[a]	RCA3.0	Swedish Meteorological and Hydrological Institute	SMHI-RCA-HadCM3

[a] Represent three versions of the HadCM3 model with perturbed parametrization impacting the simulated climate response sensitivities: Q0 (reference), Q3 (low-sensitivity) and Q16 (high-sensitivity) (see Collins et al., 2006).
[b] Represent one run of the ECHAM5 model using three different sets of initial conditions defined as "-r1", "-r2", and "-r3" (see Kendon et al., 2010)..

of 100 m. Out of the 44 land use classes defined in CORINE, approximately one-third was excluded from the analysis. These correspond to different types of forest, beaches, dunes, sands, bare rocks, burnt areas, glaciers, wetlands and inland water bodies. As these classes have a negligible impact on the damage estimates, they were not considered in the damage calculations. The remaining CORINE land use classes were merged into 5 dominant uses, namely, residential, agriculture, transport, commerce, and industry.

We should note that land use changes or a possible spatial expansion of the exposed assets is not accounted for in the calculation of the flood risk and, therefore, all damages are calculated on the basis of the current spatial patterns of exposed assets. This implies that our damage estimates might underestimate future flood impacts in some regions where substantial land development/urbanization in flood-prone areas is projected. Instead, to account for changes in wealth and the value of assets in flood-prone areas we scale current exposed asset values by the projected changes in GDP.

In the absence of high-resolution socio-economic projections, downscaled country-level GDP (in 1990 US$) projections for the SRES-A1 scenario (see Nakicenovic and Swart, 2000) were used in this work to adjust the value of the exposed assets in future time windows. These data were obtained from the Center for International Earth Science Information Network (CIESIN) (http://ciesin.columbia.edu/datasets/downscaled/). To adjust future exposed assets the ratio between the future period GDP and the baseline asset values used in Control and 2000s was applied. As such, the absolute GDP figures were not used in the analysis presented herein, but only the changes with respect to the baseline were used to rescale current exposed asset values.

To evaluate the population affected by river flooding we used a dataset of gridded population density for Europe at 100 m horizontal resolution from 2001 (Gallego and Peedell, 2001). Downscaled country-level population projections for the SRES-A1 (see Nakicenovic and Swart, 2000) were used in this work to adjust the (spatially distributed) values of people affected in future time windows. These data were obtained as well from the CIESIN website (http://ciesin.columbia.edu/datasets/downscaled/). To rescale the future numbers of people exposed to floods the ratio between the future and the baseline population values used in Control and 2000s was applied. Similar to the scaling of the exposed assets by GDP, the absolute numbers of the population projections were not used in the analysis presented herein, but only the changes with respect to the baseline to adjust the baseline gridded population.

2.1.4. Depth-damage functions

In this work a set of country specific depth-damage functions was used derived from empirical flood damage data and damage relations from 11 countries across Europe (see Huizinga, 2007). For countries without historic flood data, the "GDP per capita PPS (Purchasing Power Standards)" obtained from EUROSTAT was used to scale the average maximum damages (derived from countries for which information was available) over the different exposure categories. More detailed information on the derivation of the damage functions and maximum damages can be found in Huizinga (2007). The depth-damage functions represent, for each country and for each aggregated land use class (i.e. 27 $\times$ 5 depth-damage functions), the absolute amount of damage per unit area as a function of the water depth. In particular, these functions are used to appraise the vulnerability of the exposed assets to flood inundation and are considered as the standard approach for large-scale damage assessments (Messner et al., 2007; Merz et al., 2010). Jongman et al. (2012) evaluated several depth-damage models for catchments in Germany and the United Kingdom and showed that the functions used herein (Huizinga, 2007) produce estimates that are relatively close to the reported damage in both case studies.

As suggested by some authors (see, e.g., de Moel and Aerts, 2011; Jongman et al., 2012), uncertainties related to the construction of depth-damage functions could be significant. There is also a large degree of uncertainty in the value of the elements at risk and it is essential to adjust asset values to the regional economic situation. To account for large regional differences in the values of exposed assets for a given land use class within a country, we therefore further rescale the specific depth-damage functions by the GDP/capita of the administrative level NUTS2 regions (see http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction). Given the limited availability of spatially detailed empirical information on flood losses for specific exposed assets across Europe, a detailed uncertainty analysis at pan-European scale of the construction of the damage curves, the asset values connected to these curves, and the larger methodological framework is not feasible. Therefore, we acknowledge our results might provide biased damage estimates in regions of the EU where the damage curves and assets used herein not fully reflect true conditions.

2.2. Flood risk assessment

Flood damage assessment integrates information about the frequency and magnitude of floods with inundation characteristics and damage evaluation to construct damage-probability curves. These damage-probability curves represent flood damages as a function of the probability of occurrence (or recurrence interval) of a flood. Estimations of direct damages were obtained by combining inundation water depth with land use classes, further linked with specific depth-damage functions. For all the recurrence intervals considered (i.e. 2, 5, 10, 20, 50, 100, 250 and 500 years), a damage map (100 m × 100 m) was produced. Damage-probability curves were obtained at the grid cell by interpolating the damage estimates between the different recurrence intervals considered. The expected annual damages at a given grid cell due to river flooding are thus the integral of the damage-probability curve. Individual grid cell values can then be aggregated to catchment, NUTS2 or country level to evaluate changes in flood damage at large scales.

To assess the number of people directly affected by river floods, a European population density map at 100 m resolution (Gallego and Peedell, 2001) was overlain by the flood inundation maps for the different return maps. Similar to flood damages, population exposure probability functions were derived for each grid cell within the modelled domain.

In practice, defence measures are implemented in most European countries to protect up to a certain design flood. Flood protection can be included in the expected annual damages estimation by truncating the damage-probability curves at the corresponding protection level (e.g. design flood = Q_{100}). The integral of the remaining part after truncation quantifies the expected annual damages and expected annual population affected caused by river flooding considering flood protection up to the design flood.

In order to assess the potential impacts from flooding in the EU a common pan-European scenario for flood risk assessment and management is required. This is provided by the EU Flood Directive (EC, 2007). Even though this directive does not enforce EU member states to take immediate actions to reduce flood risk, by the year 2013 all member states should develop flood hazard and flood risk maps in areas where potential significant flood risk exists. These maps must be based on a medium likelihood of flooding defined by a 100-year event. Taking into consideration that information on flood protection measures as well as their probability of failure is barely available at the country or European level, we therefore assumed a uniform flood protection level up to the medium probability scenario stipulated in the EU Flood Directive (EC, 2007). We acknowledge that in different regions of Europe actual protection levels may deviate strongly (in both directions) from the 100-year flood protection level assumed here, which may locally result in biased estimates of expected annual damages and expected annual population affected. We therefore also provide impact estimates at EU and country level for protection levels up to the 50- and 250-year flood event.

While several authors report that different socio-economic factors may play a significant role in damage estimates due to river floods (see, e.g., Barredo, 2009; Feyen et al., 2009; Elmer et al., 2012), the risk assessment implemented in this work only accounts for the change in wealth in flood-prone areas based on changes in country-level GDP as derived from the socio-economic scenarios (see Section 2.1.3). Changes in land use, which may increase or decrease flood risk in the future (see, e.g., de Moel and Aerts, 2011), are not accounted for. We further note that no discounting has been applied to future damages as they are calculated using 2006 prices on the basis of Huizinga (2007) thus the valuation results are presented in terms of constant 2006 prices for the three time periods considered (i.e. the 2020s, 2050s and 2080s). The results are presented in this way to facilitate direct comparison over time.

2.3. Flood protection – adaptation scenarios

In this work, two scenarios of risk mitigation against flooding events were considered: first, *no adaptation*, i.e. current levels of flood protection, assumed to be up to the current 100-year flood (medium probability event according to the EU Flood Directive), are kept constant for future analysis, i.e. there are no upgrades in response to changing risks; second, *adaptation*, i.e. levels of acceptable risk are adjusted to account for future changes in flood hazard, so that future protection levels are increased to provide protection up to the corresponding 100-year flood event obtained in future time windows (e.g., a future 100-year event may correspond to a current 150-year, in which case future protection is against a current 150-year event). The difference between these two management scenarios provides an estimation of the avoided damages (benefits).

Local implementation of adaptation measures depends on site-specific hydro-morphological characteristics as well as on socio-economic conditions. Within the current modelling framework, it is not possible to undertake a detailed analysis of the costs of this increased level of protection. However, in order to provide some analysis of the relative costs of adaptation, the available literature on adaptation benefit-to-cost ratios (BCR) was surveyed.

Several studies have reported diverse figures about benefits and costs of different flood mitigation strategies across Europe, covering different regions, types of floods, flood protection measures, accounting and cost-benefit approaches (see, e.g., Petrascheck, 2003; Förster et al., 2005; Fošumpaur, 2005; Lamothe et al., 2005; Satrapa et al., 2006; Johnson et al., 2007; Zevenbergen et al., 2007; Dehnhardt et al., 2008; EA, 2009, 2010; UNFCCC, 2009; Broekx et al., 2011). These studies indicate that the current flood protection schemes typically have high benefits when compared to costs, although capital investments can be large. The studies reviewed provided a range of BCR between 8 and 1.5, with an average value of 4. These results have been used to provide indicative estimates (order of magnitude) of the potential costs of the adaptation scenario. However, the costs of protection are likely to rise disproportionately – and the BC ratios likely to fall – as ever higher levels of protection are set (Parry et al., 2009), in this case in response to the intensification of the hydrological cycle. The available literature does not provide sufficient detail to know whether this applies for the case of river floods, but there is information to suggest this is the case for coastal floods (Brown et al., 2011).

2.4. Definition of scenarios

We defined four alternative scenarios in order to differentiate the effects of climate change, socio-economic development, the combined impact of these two, and the benefits of adaptation. In the "climate change" scenario, the values of exposed assets and the population density are assumed static over time (through to 2100) and are thus representative of present conditions (2006). In this case, only climate change derived from the climate experiments listed in Table 1 changes. In the second scenario (socio-economic change), the exposed asset values and population density change according to country GDP and population projections obtained from the CIESIN data portal (see Section 2.1.3). For this scenario, the climate of the control period (1961–1990) is assumed static for future estimations (through to 2100). In the third and more realistic scenario, both climate and socio-economic change is accounted for. In the last scenario, also both climate and socio-economic change is accounted for, but, whereas in the first three scenarios the protection level is assumed static and equal to the current 100-year flood event, this scenario assumes upgraded defence levels to maintain protection against the corresponding 100-year flood event in the future time window (see Section 2.2).

3. Results

3.1. Expected annual population affected in the European Union (EU)

Ensemble-based estimates of the impact of river flooding on population are depicted in Fig. 2 for a constant protection level against the current 100-year flood event. In general, under a medium–high emission scenario (A1B), the current EU expected annual population affected (ensemble mean) of ca. 200,000 aligns reasonably well with an average expected annual population affected of 250,000 reported by the European Environment Agency (EEA, 2010). Due to the effect of climate change alone the current people affected is projected to reach 300,000 by the 2050s, rising up to 390,000 by the 2080s (ensemble mean).

If socio-economic growth alone is considered (i.e. future projections of population with no change in climate), expected annual population affected (ensemble mean) remains relatively stable up to the 2020s but then decreases to ca. 160,000 by the 2080s. Lower values of people affected in the 2050s and 2080s reflect the projected decline in Europe's population for the second half of this century. This partly offsets the increase in people affected due to climate change, resulting in approximately 360,000 people affected in the EU by the 2080s due to the combined effect of climate and demographic changes.

The variability amongst the climate experiments used to force LISFLOOD is clearly reflected by the significant range of values observed for the 2080s, shown also in Fig. 2. Here, we see that by considering the combined effects of climate and socio-economic change, most expected annual population affected estimates are concentrated between 269,000 and 407,000, with a maximum range spanning from 180,000 to 780,000. The upper end of this interval is largely dominated by the high values for France (203,000), the United Kingdom (192,000), Italy (77,000), Germany (69,000) and The Netherlands (53,000) obtained from the C4I-RCA-HadCM3 climate experiment (see Table 1). We should note that this particular climate simulation shows a much stronger warming (average warming over Europe of 5.2 °C compared to an ensemble-average warming of 3.2 °C over the 11 remaining models), especially towards the end of this century. Despite this, it is worth noting that maximum expected annual population affected estimates for other time windows are driven by other climate experiments (e.g. for 2000s by ETHZ-CLM-HadCM3, whereas for 2020s and 2050s by DMI-HIRHAM-ARPEGE).

Fig. 3 shows the ensemble-based expected annual population affected estimates at country level for the combined effects of socio-economic and climate change when assuming a current 100-year protection level that remains constant in time. A clear trend towards a higher number of people affected by river floods over time is observed for the United Kingdom, Ireland, Belgium, Luxembourg, France, the Netherlands, Austria, Finland and Italy, even if for the latter a substantial decrease in population (ca. 19%) with respect to present conditions is projected by the 2080s. Smaller (Portugal, −10% by 2080s), comparable (Spain, −17% by 2080s) or more pronounced reductions in projected population (Slovenia, −23% by 2080s; Bulgaria, −45% by 2080s) reverse the climate-change induced trend of increasing population affected by the 2080s. Such climate-cancelling effect induced by negative population growth can be observed already earlier (2050s) in the Czech Republic, Slovakia, Romania and Hungary, which are characterized by moderate, spatially sometimes opposite changes in the magnitude of floods (see Rojas et al., 2012). The strongest decrease in people affected is projected for Poland (−25% by 2080s) and Estonia (−65% by 2080s), due to both a reduction in flood

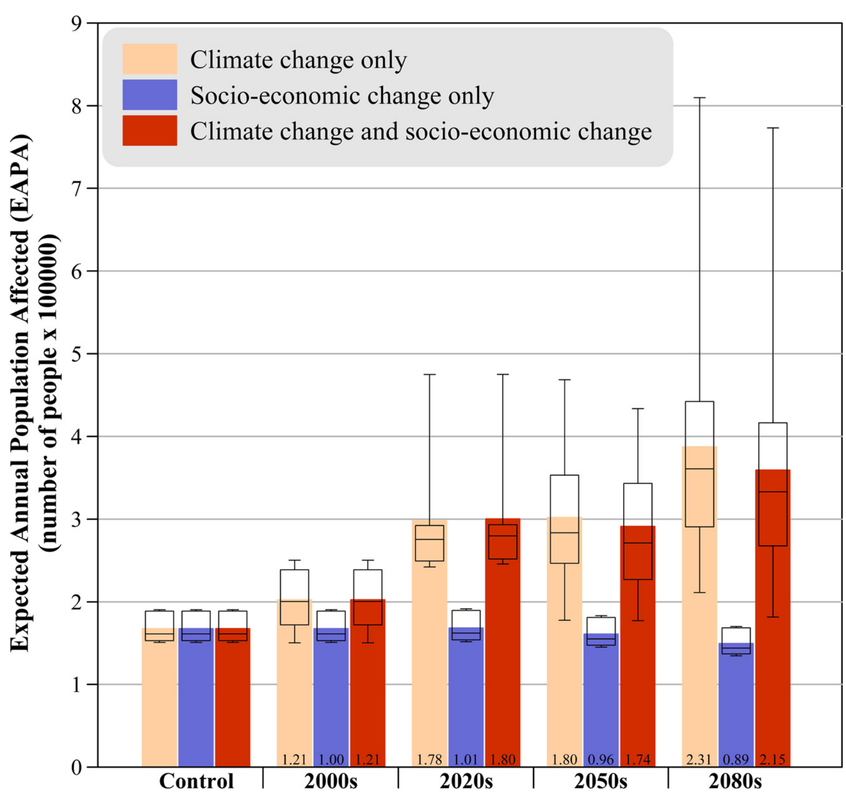

Fig. 2. EU expected annual population affected (people/year) for the control period, 2000s, 2020s, 2050s, and 2080s. Flood protection up to the current 100-year flood event is assumed constant in time. Ensemble-based average estimates and five-number summaries based on 12-member climate ensemble for the A1B scenario. Numbers at the bottom of the bars represent the ratio with respect to the control period.

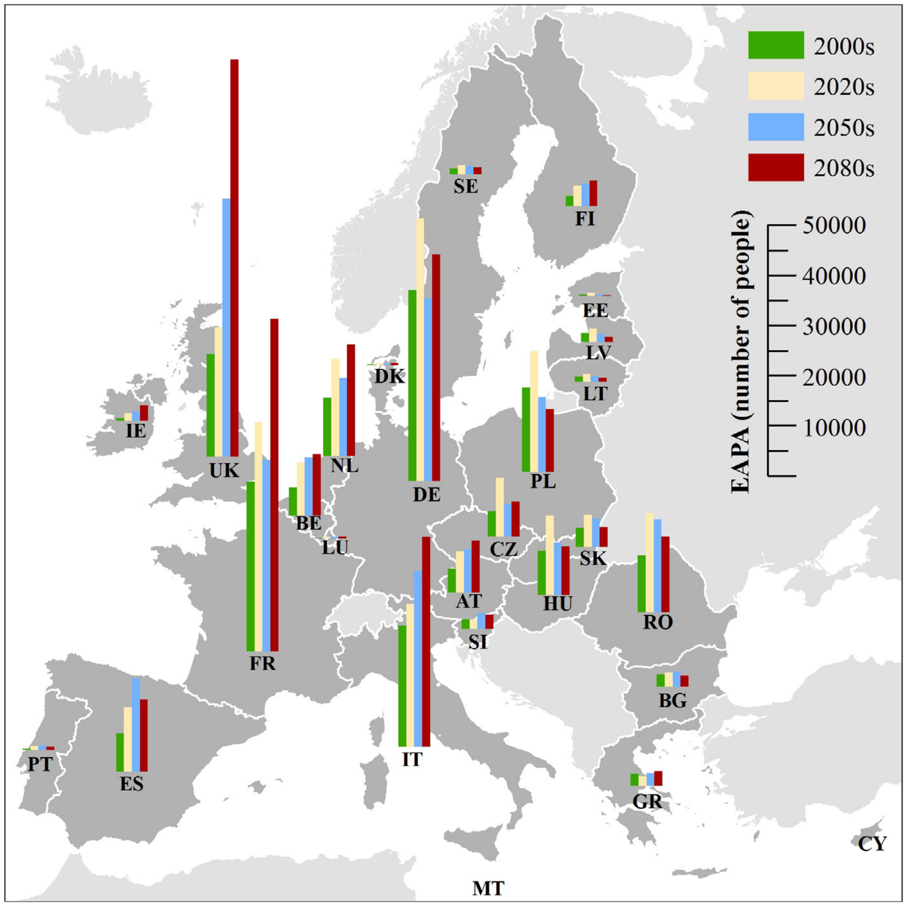

Fig. 3. EU expected annual population affected (people/year) by country for the 2020s, 2050s, and 2080s. Flood protection up to the current 100-year flood event is assumed constant in time. Ensemble-based average estimates based on 12-member climate ensemble for the A1B scenario.

hazard and negative population growth (−20% for Poland and −40% for Estonia). We further note that discontinuities in the trends of people affected, e.g., for France and the Netherlands, can be explained by the interaction between projections of future population at country level and flood hazard fluctuations caused by inter-decadal climate variability.

In order to understand the relative impacts across EU countries, Fig. 4 shows the expected annual population affected expressed as a percentage of the corresponding country population for the current situation and the end of this century. All countries presently (see Fig. 4a) have less than 0.1% of their population that is annually affected by floods, although that for some countries (in particular Hungary, Slovenia and Latvia) some climate ensemble members yield estimates above 0.2% of the country population. Denmark and Portugal show the lowest share of population affected by flooding. By the end of this century (see Fig. 4b), the highest average relative impact on population is projected for Austria (0.15%), Hungary (0.13%), the Netherlands (0.13%), Slovenia (0.18%) and the UK (0.13%). In the Netherlands, however, protection standards by far outweigh the assumed protection level in our analysis; hence our estimates likely overestimate the true number of people affected in the Netherlands. Also note that for some countries (e.g., Bulgaria and Poland) the declining trend in absolute population affected (see Fig. 3) not necessarily implies a reduction in the relative impact on the projected population in the future. The variation in population affected across the climate models rises considerably for nearly all countries by the 2080s (see Fig. 4b), with maximum relative impacts above 0.3% for Belgium (0.32%), Finland (0.49%), France (0.31%), the Netherlands (0.33%), Slovenia (0.60%) and the UK (0.31%).

3.2. Expected annual damages in the European Union (EU)

Assuming a uniform protection level across the EU up to flood events with a current recurrence interval of 100 years, the estimated EU expected annual damages for the control period (1961–1990) and the 2000s (1981–2010) are between €5.5 and €6.9 billion, respectively. These figures are similar to the €5.5–7 billion reported by the Association of British Insurers (ABI, 2005), and to the €5.2 billion (on average) reported by the European Environment Agency (EEA, 2010). As discussed earlier, flood defence levels across Europe may considerably deviate from the assumed protection standard. Table 2 shows at country and EU level how different protection levels yield different damage estimates. Imposing a protection level up to the current 50-year event would result in EU aggregated damages for the baseline and current period that are nearly twice as large, whereas protection up to a 250-year flood would more than halve the EU damages estimate for these periods.

Fig. 5 shows the progression in time of the ensemble-average expected annual damages under the *no adaptation* scenario, i.e. assuming protection against river floods up to a current 100-year event that is kept constant in the future. Due to the combined effect of climate and socio-economic change, current EU damages (€6.9 billion/year) is projected to reach €20.4 billion/year by the 2020s, €45.9 billion/year by the 2050s, and € 97.9 billion/year by the 2080s (constant 2006 prices, undiscounted). The largest share of these damages arises from socio-economic development, indicating the relevance of the socio-economic dimension in the estimation of future damages. Assuming less stringent protection up to the current 50-year event (see Table 2), EU damages amount

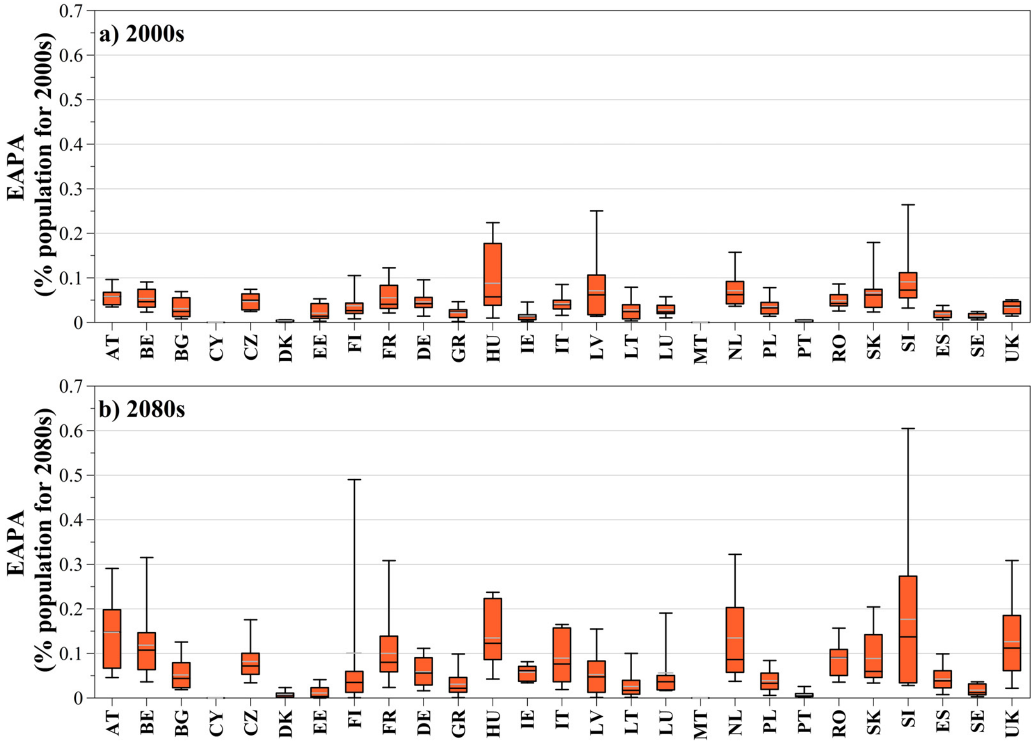

Fig. 4. Expected annual population affected (percentage of country population) by country for the (a) 2000s and (b) 2080s under the scenario with combined effects of climate change and socio-economic development. Flood protection up to the current 100-year flood event is assumed constant in time. Ensemble-based average estimates and five-number summaries based on 12-member climate ensemble for the A1B scenario.

Table 2
Expected annual damages for different protection levels (assumed constant in time) at country and EU level. Monetary values are in €Millions, constant 2006 prices, undiscounted.

Time period and protection level																
Country	Code	Control			2000s			2020s			2050s			2080s		
		50y	100y	250y	50y	100y	250y	50y	100y	250y	50y	100y	250y	50y	100y	250y
Austria	AT	557	297	125	632	309	97	1725	892	332	3184	1695	655	6269	3452	1402
Belgium	BE	240	129	55	390	198	71	985	575	263	1801	1019	437	3303	1828	749
Bulgaria	BG	79	42	18	94	50	20	481	275	122	1897	1191	594	3497	2138	1062
Cyprus	CY	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
Czech Republic	CZ	337	179	74	345	164	54	2789	1504	602	5797	3065	1182	13,037	7007	2773
Denmark	DK	36	19	8	31	14	4	81	42	16	87	40	13	273	140	52
Estonia	EE	22	12	5	25	13	4	194	119	58	353	192	79	384	200	79
Finland	FI	400	218	92	454	228	75	1306	752	329	2491	1451	644	4609	2917	1454
France	FR	1862	1011	424	3037	1559	570	5623	2937	1109	7592	3902	1444	20,872	11,436	4618
Germany	DE	924	502	214	1087	540	189	2176	1142	432	2756	1378	489	5729	2920	1061
Greece	GR	59	32	14	113	63	27	143	81	35	329	205	100	672	410	193
Hungary	HU	708	390	158	607	289	99	4191	2235	865	10,092	5444	2199	20,730	11,163	4368
Ireland	IE	66	35	15	62	30	9	208	109	42	356	182	67	971	522	205
Italy	IT	922	499	211	1662	912	343	3109	1733	726	7223	4197	1864	14,708	8720	3929
Latvia	LV	48	26	11	70	37	14	393	225	99	862	450	170	1215	612	228
Lithuania	LT	37	20	8	55	29	11	310	175	76	720	382	151	1079	593	248
Luxembourg	LU	16	9	4	21	10	3	48	24	9	70	36	14	152	80	31
Malta	MT	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
Netherlands	NL	439	225	104	849	424	221	1404	859	423	1965	1155	526	4722	2746	1248
Poland	PL	432	239	102	381	191	68	2359	1322	559	4647	2505	997	8282	4512	1822
Portugal	PT	16	9	4	11	5	1	38	20	8	72	39	16	105	58	24
Romania	RO	296	164	69	320	166	55	2331	1257	498	7474	4294	1853	13,384	7561	3197
Slovakia	SK	231	125	51	213	100	35	1400	745	290	3963	2171	895	6373	3352	1309
Slovenia	SI	58	32	14	104	55	21	438	225	81	2239	1305	571	4359	2559	1134
Spain	ES	374	200	85	339	181	62	934	528	232	2204	1333	635	3149	1884	878
Sweden	SE	227	122	51	229	112	35	522	275	107	853	448	174	1316	710	288
United Kingdom	UK	1712	904	376	2514	1247	419	4600	2326	843	14,143	7804	3210	34,994	20,413	8941
EU		10,098	5,439	2,291	13,647	6,924	2,509	37,789	20,378	8,157	83,168	45,883	18,979	174,184	97,934	41,293

[a] No results are reported as Cyprus (CY) was not included in the modelled domain and Malta (MT) did not include relevant river cells with upstream areas larger than 1000 km^2.

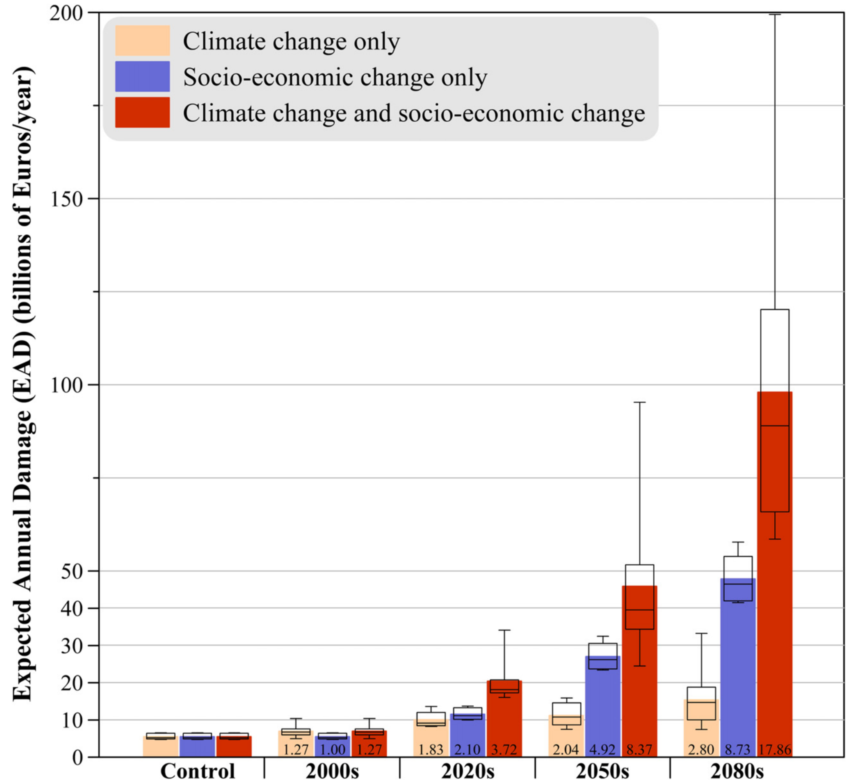

Fig. 5. EU expected annual damages (billions €/year) for the control period, 2000s, 2020s, 2050s, and 2080s. Ensemble-based average estimates and five-number summaries based on 12-member climate ensemble for the A1B scenario. Flood protection up to the current 100-year flood event is assumed constant in time. Monetary values are in constant 2006 prices, undiscounted. Numbers at the bottom of the bars represent the ratio with respect to the control period. Note that no difference for the "socio-economic change" only scenario between control period and 2000s is observed as these two are based on the exposed assets for year 2006.

to € 174.2 billion/year by the end of this century. For a protection level equal to the current 250-year event, on the other hand, EU damages would total € 41.3 billion/year by the 2080s.

A large range of variability for the future damage estimates arises from the climate experiments. Accounting for both the effect of climate and socio-economic change and assuming a constant protection up to the current 1-in-100 year flood event the EU expected annual damages vary between € 16.0 and € 34.1 billion/year by the 2020s, € 24.5 and € 95.3 billion/year by the 2050s, and € 58.6 and ca. € 200 billion/year by the 2080s (constant 2006 prices, undiscounted). Even though at this scale of aggregation the majority of damage estimates across the climate models fall within a reasonable range of the central estimates, some damage estimates seriously deviate from those of the other ensemble members. We see, for example, that for the 2080s damage estimates are concentrated between € 65.9 and € 120 billion/year, with the second highest damage estimate amounting to € 126 billion/year but a maximum damage estimate of nearly € 200 billion/year (obtained for the C4I-RCA-HadCM3 climate experiment). These results clearly illustrate the risk of selecting a single climate experiment (GCM/RCM combination) as the basis for the risk assessment.

Table 2 summarizes the evolution in time of the absolute ensemble-averaged damages at the country (and EU) level for the three different protection levels assumed. In general, all countries will experience an increase in future damages due to the combined effect of socio-economic and climate change, irrespective of the protection level in place. Actually, the relative changes in country and EU damages between the different time windows are fairly robust across the alternative defence standards. Currently, the highest damage values are observed for France, Italy and the UK. Also in future time windows these countries will face the largest absolute economic impacts from flooding. However, also the Czech Republic, Romania and especially Hungary will likely experience large flood damages by the end of this century. Note that the rise in wealth in these countries is projected to be nearly 5 times larger than for West-European countries. This partly explains the large increases in absolute expected annual damages seen for these countries, as well as for neighbouring countries such as Slovenia and Bulgaria.

Fig. 6 presents for the 2000s and 2080s the expected annual damages as a fraction of the country GDP for the scenario with climate and economic changes and constant protection up to the current 100-year flood event. For most countries present damages are well below 0.5% of the national GDP (Fig. 6a). In general, higher relative impacts are observed in Eastern European countries, especially in Hungary and Slovakia (0.8% and 0.6%, respectively). Note also that in these countries protection levels may likely not comply (everywhere) with the standard imposed here, hence true damages may actually represent a larger share of the national GDP. By the end of this century (Fig. 6b), relative economic impacts are projected to increase for all EU countries except Poland and the Baltic States. In relative terms, Eastern European countries will still be most severely affected by flooding, especially Hungary (1.36%), but also Slovakia (0.87%), the Czech Republic (0.81%), and Romania (0.79%). The spread in relative impacts from climate variability considerably increases with time for most countries, with upper estimates reaching 2.75% for Hungary and nearly 2% for Slovenia, Slovakia and Finland. It is worth noting that Finland shows a small interquartile range but an extreme upper damages estimate. Contrary to most other countries, where the upper (damage) values are obtained for the C4I-RCA-HadCM3 climate experiment, in Finland the upper extreme estimate is driven by the ETHZ-CLM-HadCM3 climate

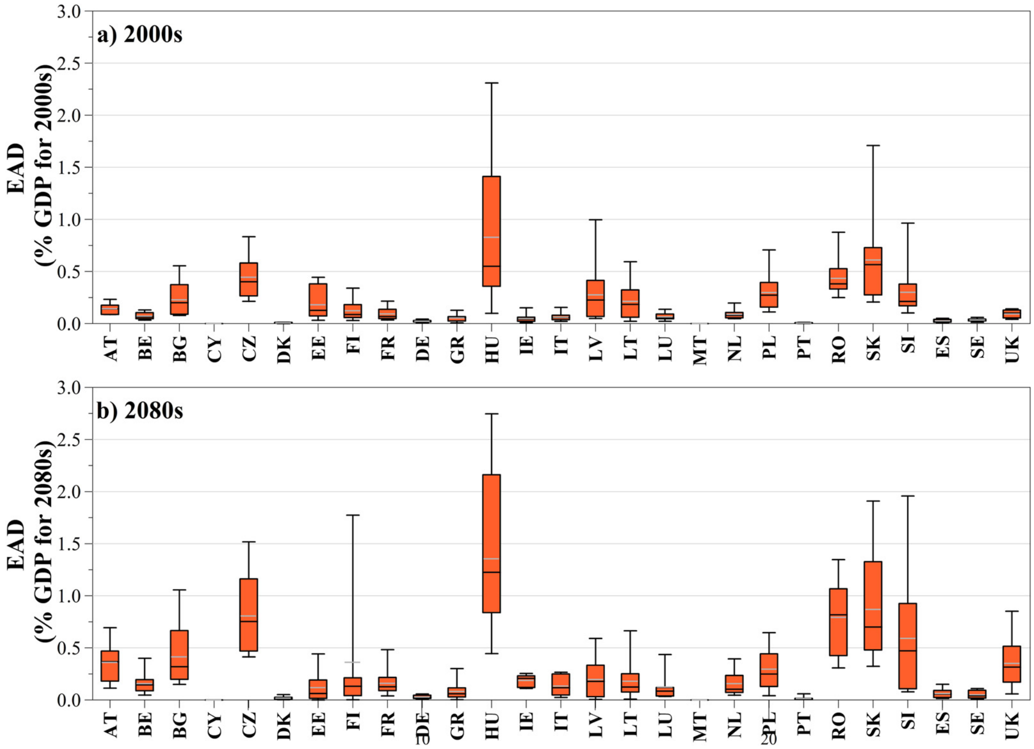

Fig. 6. Expected annual damage (percentage of GDP) by country for the (a) 2000s and (b) 2080s under scenario with combined effects of climate change and socio-economic development. Flood protection up to the current 100-year flood event is assumed constant in time. Ensemble-based average estimates and five-number summaries based on 12-member climate ensemble for the A1B scenario.

experiment. This reinforces the idea of potentially obtaining biased damage estimates when relying on a single climate experiment.

Fig. 7 shows a map with the relative change in ensemble-averaged expected annual damages with respect to the control period across the EU accounting only for the effects of climate change. These changes are based assuming a constant protection up to the current 100-year flood event. As noted earlier, however, the relative changes in damages are fairly constant irrespective of the protection level assumed, hence this map is also informative should regionally another protection level be in place. For illustrative purposes the damages have been aggregated over the administrative level NUTS2 as a compromise between the pixel-scale (which would show a very erratic pattern due to large differences in damages between individual pixels) and the coarse country-level. The patterns in damages changes reflect largely those observed in the changes in flood hazard (see Rojas et al., 2012), but local differences can be noted especially in the magnitude of change. These differences may originate from several reasons. Firstly, due to the spatial aggregation over NUTS2 regions, some of the small-scale spatial variability in the changes in flood hazard is filtered out. In some regions, an increase (or decrease) in flood hazard may be offset by a stronger decrease (or increase) in other parts of the same NUTS2 region. In the lower reaches of the Danube (Romania and Bulgaria), for example, the projected decrease in floods in many of the smaller tributaries is offset by the increase in floods projected for the main river reach. This results in an overall increase of expected annual damages for these regions (blue in Fig. 7), even though most small tributaries in this areas show a decrease in flood hazard. At the same time, small changes in flood magnitude (i.e. Q_{100}) can result in considerable changes in flood recurrence period and, thus, in the expected annual damages. A strong (mostly positive) change in flood magnitude for a particular model will therefore more strongly impact the ensemble-average damages than the ensemble-average flood magnitude. Finally, damages are largely determined by the exposed assets. Hence, changes in expected annual damages are largely determined by the changes in floods in the areas with high exposure such as urban zones, whereas changes in floods in rural and agricultural areas, which may differ from those in the high-exposed areas, are less important in the overall damage figures.

In general, from Fig. 7 a strong increase in expected annual damages from climate change can be observed particularly in Western Europe, including the United Kingdom, Ireland, the Netherlands, Belgium, (western parts of) France, as well as in Italy, along the Mediterranean coasts of France and Spain, and in Finland and northern parts of Sweden. Areas showing a consistent decrease in damages values are the middle and downstream parts of the Vistula, Odra and Elbe catchments (Poland and Eastern Germany). In these regions snow-driven floods are projected to decline due to rising temperatures, offsetting the increase in summer and autumn rainfall floods (see Rojas et al., 2012). Other regions that will likely see a reduction in flood damage are the northern parts of Spain and the southernmost regions of Sweden. These changes in flood risk become more pronounced towards the end of the century.

3.2.1. Expected annual damages by land use class

Table 3 shows the aggregation of the expected annual damages into five dominant land use classes, namely, residential properties, agriculture, transport, commerce and industry. About 82.3% of the damages relate to residential areas, 6.8% to industry, 4.9% to commerce, 4.7% to agriculture and only 1.3% to industry. As a static spatial distribution of the land use and hence exposed assets is assumed in this work, the distribution of the damages remains fairly constant over time in the analysis. These percentages, however, will most likely change due to land use dynamics. Feyen

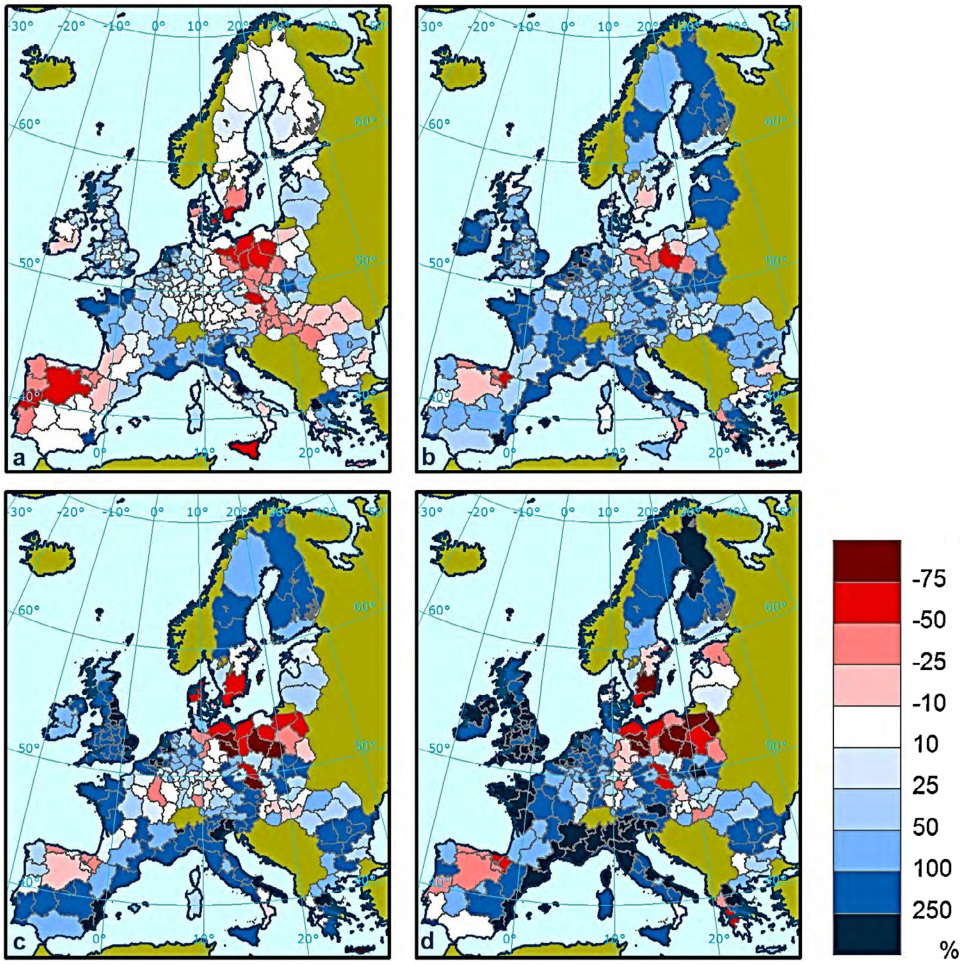

Fig. 7. Changes in expected annual damages compared to the control period (1961–1990) for the (a) 2000s, (b) 2020s, (c) 2050s, and (d) 2080s. Scenario with only climate change, with flood protection up to the current 100-year flood event assumed constant in time. Ensemble-based average estimates based on 12-member climate ensemble for the A1B scenario. Values are aggregated at administrative level NUTS2 regions. (For interpretation of the references to colour in the text, the reader is referred to the web version of the article.)

et al. (2009), for example, showed that the effect of increased exposure due to urban expansion of the Madrid region could outweigh the effect of climate change. Note that the assumption of a uniform protection level implies that protection is the same irrespective of the land use behind the protection measure. In agricultural areas protection is typically much lower than in urban areas. However, such "over-protection" of agricultural land has a negligible impact on the overall damage estimates, as reflected by the share of agriculture damages to the total damage (see Table 3), which is below 5%.

Table 3
EU expected annual damages (billions €/year) by land use class. Ensemble-based average from LISFLOOD simulations driven by the A1B scenario for the control (1961–1990) and 2000s (1981–2010) (in parenthesis) periods. Monetary values are in constant 2006 prices, undiscounted.

Land use class	Expected annual damage	%
Residential	4.50 (5.70)	82.3%
Agriculture	0.26 (0.32)	4.7%
Transport	0.07 (0.09)	1.3%
Commerce	0.27 (0.36)	4.9%
Industry	0.37 (0.48)	6.8%
Total	5.47 (6.95)	100.0

3.3. *Avoided damages (benefits) and indicative costs of adaptation in the European Union (EU)*

Avoided damages (benefits) are estimated on the basis of the risk management options described in Section 2.3. Here, we define the avoided damages, i.e. benefits, as the difference between damage estimates from the *no adaptation* scenario, i.e. constant protection levels consistent with a current 100-year event, and damage estimates from the *adaptation* scenario, i.e. protecting against the future 100-year event obtained for each time window analyzed.

EU ensemble-based avoided damages under the SRES-A1B scenario are shown in Fig. 8. Ensemble-average avoided damages for EU are estimated at € 9.2 billion/year by the 2020s, € 21.8 billion/year by the 2050s, and € 53.1 billion/year by the 2080s (constant 2006 prices, undiscounted), whereas for the "climate change only" scenario these estimates are below € 10 billion/year by the 2080s. At the country level (not shown here) we have identified significant benefits for the United Kingdom, France, Italy and Hungary from upgrading protection levels to the future 100-year flood event. However, also Romania, the Czech Republic, Slovakia, Slovenia and Bulgaria would see large benefits relative to their GDP. Similar as the damage estimates, the benefits vary strongly with the climate simulations used to force LISFLOOD. For the 2080s, the interquartile range for the EU avoided damage

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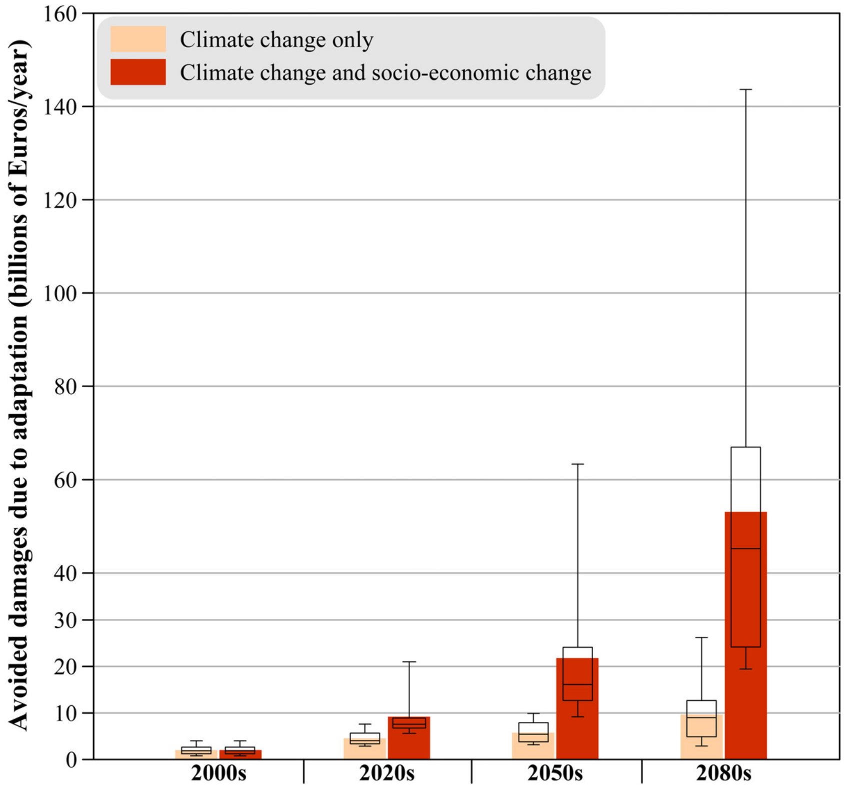

Fig. 8. EU potential benefits (avoided damages) due to adaptation (billions €/year) to maintain 1 in 100-year levels of flood protection. Ensemble-based average estimates and five-number summary from LISFLOOD simulations driven by the A1B scenario. Monetary values are in constant 2006 prices, undiscounted.

estimates spans from € 24.1 up to € 67 billion/year, with an upper maximum close to € 144 billion/year. When moving to the country level, the variations across the models become even more important for some countries, especially for the UK and France.

It should be noted that even after implementing the *adaptation* measures, i.e. protecting against the future 100-year flood event, there are still "residual damages". Under the scenario accounting for climate change only, these damages are kept similar to current levels, i.e. ca. € 6 billion/year, along time. For the scenario considering climate and socio-economic change, however, the residual damages are estimated at € 11.2 billion/year by the 2020s, € 24.1 billion/year by the 2050s, and € 44.8 billion/year by the 2080s (constant 2006 prices, undiscounted). For this scenario, residual damages are much higher since damages would rise even if minimum protection levels are maintained due to socio-economic growth. This suggests that higher levels of protection may be justified in the future.

The reduction in future damages by implementing the risk management option *adaptation*, however, will come at a cost. To derive indicative costs of adaptation, the literature-based BCR values discussed in Section 2.3 were combined with the projected benefits. This suggests that ensemble-averaged adaptation costs (per year) for the EU under the SRES-A1B scenario – for the combined impact of socio-economic and climate change – might be of the order of € 1.7 billion by the 2020s, € 3.4 billion by the 2050s, and € 7.9 billion by the 2080s (constant 2006 prices and undiscounted). It is stressed that these indicative costs are subject to many factors, such as the shape of the marginal cost curve for increasing protection levels against increasing hydrological intensity, the balance between soft and hard options, and the balance of capital and operating costs, among others. Nonetheless, they suggest that adaptation (i.e. enhanced protection) could be a highly cost-effective strategy.

Table 4
Total costs of adaptation in millions €/year and as a percentage of the current GDP for EU and member states assuming flood protection upgrade from current to future 100-year flood event and average BCR of 4:1. Figures represent ensemble-based averages based on 12-member climate ensemble for A1B scenario. Monetary values are in constant 2006 prices, undiscounted.

Country	Code	Costs of adaptation	% GDP
Austria	AT	314.5	0.12
Belgium	BE	178.1	0.06
Bulgaria	BG	153.6	0.58
Cyprus	CY	[a]	–
Czech Republic	CZ	368.6	0.31
Denmark	DK	11.2	0.01
Estonia	EE	10.4	0.08
Finland	FI	323.4	0.20
France	FR	1019.9	0.06
Germany	DE	169.8	0.01
Greece	GR	43.6	0.02
Hungary	HU	424.6	0.47
Ireland	IE	52.4	0.03
Italy	IT	921.0	0.06
Latvia	LV	29.5	0.18
Lithuania	LT	33.7	0.14
Luxembourg	LU	6.8	0.02
Malta	MT	[a]	–
Netherlands	NL	256.9	0.05
Poland	PL	126.7	0.05
Portugal	PT	3.4	0.002
Romania	RO	443.6	0.45
Slovakia	SK	126.3	0.28
Slovenia	SI	220.7	0.71
Spain	ES	158.1	0.02
Sweden	SE	46.2	0.01
United Kingdom	UK	2439.2	0.12
EU		7882.1	0.07

[a] No results are reported as Cyprus (CY) was not included in the modelled domain and Malta (MT) did not include relevant river cells with upstream areas larger than 1000 km^2..

While these estimates are only indicative, they do highlight some important issues. Countries with high expected annual damages are expected to have higher adaptation costs and for some countries (notably the United Kingdom) there would therefore be significant additional levels of investment required (see Table 4). While it is obvious that adaptation costs will not fall equally across Europe, this does have important implications. The analysis of indicative adaptation costs (if incurred now) by country shown in Table 4 indicates that some countries in Eastern Europe would potentially have to spend a significant share of their current GDP to abate the future impacts from flooding in view of socio-economic and climate changes – notably Slovenia (0.7%), Bulgaria (0.6%), Romania and Hungary (both close to 0.45% of current GDP).

4. Discussion and conclusions

EU ensemble-based damage estimates for present conditions obtained in this work are in agreement with independent damage figures obtained from ABI (2005) and EEA (2010). In addition, our damage estimates for the United Kingdom for present conditions (ca. € 900 million) compare reasonably well to country-scale damages for the United Kingdom by Hall et al. (2005) and Evans et al. (2004) (€ 617–894 million). At the same time, our estimates for the expected annual population affected are in line with the 250,000 people annually affected (on average) for the period 1998–2009 reported by the EEA (2010). These aspects suggest that our framework for risk assessment is robust and tenable for appraising the current flood risk.

When interpreting the results obtained in this work, several notes on the large-scale approach employed in this study should be considered. The climate-related uncertainty may still be under-sampled, even though we used the largest consistent ensemble of high-resolution climate simulations currently available for Europe. Correcting for biases in the main meteorological drivers used to force LISFLOOD drastically improved the quality of the extreme discharge simulations during the validation period 1961–1990 (see Rojas et al., 2011), however, after bias-correction there is no guarantee that the energy balance will be preserved. Uncertainty arising from the fitting of extreme value distributions used to obtain flood return levels, as well as hydrological uncertainty, has not been accounted for. For the first, Rojas et al. (2012) suggest this uncertainty might be relevant, especially for high return periods, whereas the second layer of uncertainty is recognized to be of secondary importance by some authors (see, e.g., Wilby, 2005; Najafi et al., 2011), while others regard it as important (see, e.g., Bastola et al., 2011). Relevant factors such as flow velocity and content of sediments are not included in the damage assessment. Such factors can be incorporated in local-scale studies, however, for a large-scale approach the level of detail and information required renders the implementation not feasible. Analyzing the Elbe catchment flood in Germany in 2002, Kreibich et al. (2009) found, however, only a strong influence of flow velocity on structural damages of road infrastructure, whereas monetary losses to residential buildings, companies and business interruption were weak to non-existent. Moreover, only direct and tangible damages have been considered in this analysis; hence monetary estimates obtained here might be relatively conservative. There is also uncertainty associated to the value of the exposed assets as well as with depth-damage functions used for quantifying flood risks. On this regard, de Moel and Aerts (2011) found for a small case study in the Netherlands that uncertainty in land-use data has a modest effect on the resulting damage estimate (about a factor 1.2), whereas the main source of uncertainty relates to the value of the elements at risk and the depth-damage curves, which can jointly account for about a factor 4 in the total damage variation. A lack of information on these aspects at pan-European or country scale, however, renders it very difficult to include these factors in a robust uncertainty analysis. Finally, there is also a wide cascade of uncertainty associated with the socio-economic projections. This wider uncertainty has not been considered, but would substantially widen the ranges reported here.

It may also be argued that land use dynamics can contribute to changes in future flood risk, thus contributing to increase uncertainty in our results. We are aware that there exist a number of land use projections for Europe (e.g. SCENAR I and II, EU-RURALIS, ETC-LUCI). These projections, however, show several discrepancies with the CORINE base map such as spatial resolution and number and types of land use classes. Moreover, these projections have a limited temporal horizon (typically up to 2020s or 2030s) and are driven by land use scenarios not fully compatible with the scenario (SRES-A1B) used in this analysis. It is worth noting that depth-damage relations used in this work are linked to CORINE land use classes and there is no straightforward procedure to link them with land use classes used by other classifications. All these issues rendered the inclusion of alternative land use scenarios not feasible in the present study.

Despite the limitations listed above, our study provides estimates of damages and population affected by river flooding in the EU over the 21st century. Additionally, a first European-wide estimation of the avoided damages incurred to adapt to climate change is obtained by defining a risk management scenario in line with the EU Flood Directive (EC, 2007), which requires all member states to take adequate and coordinated measures to reduce flood risk. At the same time, the ensemble-based approach used in this work allowed for the first time to explicitly account for the large variability in the climate signals (i.e. projected changes) simulated by different climate models and their impacts on the damage estimates. We acknowledge, however, that our results can deviate from those obtained by local flood risk assessments as they are typically based on more detailed information and physical process representation compared to large-scale approaches as the one used in this work. Therefore, there is room for conflicting results when large-scale approaches are compared against catchment-scale studies. This highlights the need to define clear objectives for analyses at specific scales. Large-scale studies might be limited in representing small-scale processes; however, they prove to be useful in guiding European policies (e.g. EU Climate Adaptation Strategy) or the allocation of funding to cope with climate change impacts (e.g., Lung et al., 2012). Our estimates provide an indication of the potential future developments of flood risk under a changing climate and, through an indicative based analysis, of the possible costs faced to adapt to future flood hazard in the EU. Furthermore, we identified "hot spots" across Europe where a significant to mild increase in flood risk is expected. The latter could guide in-depth studies at national/catchment-scale accounting, for instance, for local mitigation/adaptation measures.

Our estimates for annual damages and people affected show a large variability around the ensemble-mean values, thus, highlighting two important aspects. First, there is a high probability of obtaining biased damage estimates when only a single climate simulation is used as driver for the impact assessment; and second, an ensemble-based framework using as many GCM/RCM combinations seems the most reliable approach to account for this variability and provide robust damage estimates.

Adaptation strategies to mitigate future flood risk can be defined depending on whether an economic efficiency criterion (i.e. benefits vs. costs) or risk based criterion based around an acceptable level of protection is sought. The *adaptation* scenario implemented in this work is in line with a risk-based strategy and, as such, costs will be determined by the level of flood risk protection defined, in our case, the future 100-year flood event. This highlights an obvious but important point that the costs of adaptation depend on the framework and objectives set. Thus, countries/regions setting higher levels of flood risk protection will incur higher adaptation costs. Given the large climate variability, benefits and costs of adaptation also show a large variability across different countries/regions, highlighting the strong distributional patterns across the EU. The variability in the benefits – and by implication the costs of adaptation – across the ensemble-based results highlight the inherently unknown future, and suggests there is potential for mal-adaptation, i.e. under- or over-designing to provide adequate flood protection. Therefore, recognizing and adapting to this uncertainty requires an approach for adaptation that considers hard and soft measures, as well as integrated flood and land management. Ultimately, the move towards such adaptation approach must be framed in a site- and context-specific response, preferably one that is based on iterative adaptive (risk) management.

Our results suggest that future damages and people affected by river floods in the EU are expected to considerably increase due to the combined impact of climate and socio-economic change. This finding is in agreement with the results by Feyen et al. (2012) and Jongman et al. (2012). Our estimates suggest that by the end of the 21st century (2071–2100) ensemble-based EU damages could reach € 98 billion/year (constant 2006 prices, undiscounted). Increasing protection levels to the future 100-year flood event could lead to avoided damages (benefits) of € 53 billion/year. At the country level, the United Kingdom, France and Italy in Western Europe as well as Romania, Hungary, and Czech Republic in Eastern Europe, show the highest absolute damage estimates, and by association, are likely to bear the highest costs of adaptation. These results are in line with the current flood risk assessment performed for Europe by Lugeri et al. (2010), where the same regions appeared to be under significant threat. Residual damages, i.e. damages remaining after implementing adaptation measures, amount to ca. € 45 billion/year for the EU, suggesting that even higher levels of risk protection could be justified and needed in the future.

In terms of population, people affected by floods could reach 360,000 inhabitants/year, again with the same countries as above dominating the impacts.

These results indicate that increasing flood risks could be one of the major impacts of climate change across Europe. Future changes in the socio-economic dimension could be as relevant as climate change in increasing future flood risks. Therefore, any action to address future flood risks needs to consider these two dimensions in the analysis and the responses. At the policy level, the high degree of variability derived from the climate simulations seems to reinforce the idea of stimulating flexible, soft non-structural measures of adaptation (e.g. spatial planning and watershed management, flood forecast and warning systems), which could be implemented through an adaptive management and with portfolios of strategies. Across Europe, regions where future risks will be considerably higher might require external funding to bear the increasing costs that potential adaptation strategies might demand.

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