An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe

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Abstract
The **C**oastal **F**luvial **Flood** (**CFFlood**) model for assessing coastal and fluvial flood impacts under current and future climate and socio-economic conditions is presented and applied at the European scale. Flood frequency is estimated as a function of river flows, extreme sea levels and estimated defence standards to determine the flood extent and depth. Flood consequences are estimated by combining the latter with information on urban areas, population density and Gross Domestic Product (GDP). Climate and socio-economic scenarios and possible adaptation choices are included to analyse future conditions. In 2010, almost 6% of the European population is estimated to live in the 100 year flood area. The corresponding economic loss is €236 billion, assuming no defences. Estimated flood protection reduces economic damage substantially by 67% to 99% and the number of people flooded is reduced by 37% to 99% for the 100 year event. Impact simulations show that future climate and socio-economic conditions may increase flood impacts, especially in coastal areas due to sea-level rise. In contrast, impacts caused by fluvial flooding sometimes decrease, especially in southern and western regions of Europe due to decreases in precipitation and consequent run-off. Under high-end scenarios, flood impacts increase substantially unless there are corresponding adaptation efforts.

Keywords: climate change, flood impact, integrated impact assessment, sea-level rise, adaptation

1. Introduction

Floods have significant socio-economic impacts in Europe. Between 1998 and 2009 they caused 1126 deaths and at least €52 billion in insured economic losses (EEA 2010). These impacts are expected to be exacerbated by future changes in climate and sea-level rise (IPCC 2007; 2013). Understanding future flood risk in order to plan adaptation requires an approach that is capable of estimating impacts by accounting for both coastal and fluvial flooding and investigating the effects due to changes in future climate and socio-economic pressures.

A number of studies have developed assessment methods to quantify flood risks and to understand the implications of future climate and socio-economic changes at global (e.g., Jongman et al. 2014; Hinkel et al. 2014; Hallegatte et al. 2013; Hirabayashi et al. 2013), continental (e.g., Rojas et al. 2013; Meyer et al. 2013; Jongman et al. 2012; Feyen et al. 2012; Hinkel et al. 2010) and national/sub-national scales (e.g., Dawson et al. 2009; Goulby et al. 2008). Most of these studies have focused on either coastal or fluvial flood assessment. For example, Hallegatte et al. (2013) explored flood exposure in the 136 largest coastal cities under current and future climate and socio-economic conditions. At a sub-regional scale, the coastal programme at the Tyndall Centre for Climate Change Research investigated future changes in flood risk due to changes in marine climate as well as in socio-economic conditions in North Norfolk, UK (Dawson et al. 2009; Mokrech et al. 2011). At the global scale, Hirabayashi et al. (2013) employed a global routing model to investigate fluvial flood exposure under multiple climate models.

At the European scale, studies such as Feyen et al. (2012) and Rojas et al. (2013) investigated the implications of future climate on fluvial flooding under current socio-economic conditions and changes in population. On the other hand, the Dynamic Interactive Vulnerability Assessment (DIVA) integrated model was used by Hinkel et al. (2010) to investigate flood impacts and adaptation in the European Union due to sea-level rise and storm surges for selected IPCC SRES scenarios. To date, no studies have yet assessed the combined impacts of coastal and inland flooding at the continental scale in view of climate and socio-economic changes and adaptation.

Integrating coastal and fluvial flooding at national or larger scales within an integrated assessment methodology is a significant challenge as coastal and fluvial flooding follow different hydrological mechanisms. In addition, projecting future climate and socio-economic conditions can generate considerable uncertainty. Investigating flood impacts under uncertain conditions can be more effective when using a dynamic and interactive model using predefined and/or user defined scenarios. This allows flexibility which is not available with many modelling systems. Holman et al. (2008) have suggested integrated assessment methodologies to achieve this goal, in which the concept of meta-modelling, whereby computationally efficient or reduced form models that emulate the performance of more complex models, can be used to allow dynamic links between sectors and user interactions. This approach has been used to develop the Regional Impact Simulator (RegIS) using the Driver-Pressure-State-Impact-Response (DPSIR) framework to establish links and interactions between meta-models. In this context, Mokrech et al. (2008) developed a flood meta-model for assessing socio-economic impacts under future climate and socio-economic conditions in East Anglia and North West England, UK. This effort has been significantly extended in the CLIMSAVE project (Harrison et al. 2012) to develop a broad-scale model that combines coastal and fluvial flood impact assessments for Europe within the CLIMSAVE Integrated Assessment Platform (IAP), allowing users to interactively examine flood impacts under varying climate and socio-economic conditions and adaptation options.

In this paper, we present the new CFFlood model that integrates coastal flooding with fluvial flooding at the European scale and estimates current and future flood impacts for user-defined levels of climate and socio-economic conditions. The methodology section introduces the coastal and fluvial impact sub-models, datasets, flood damage estimation method, future climate and socio-economic scenarios and the range of designed adaptation options. The results section presents a selected number of simulation outputs including the socio-economic impacts at the baseline year, future trends in impacts due to coastal flooding, impacts of fluvial flooding under predefined socio-economic scenarios, and the benefit of adaptation measures in reducing impacts. Finally, key findings and limitations are presented in the conclusion.

2. Methodology

The CFFlood model is designed to be integrated within the CLIMSAVE IAP (www.CLIMSAVE.eu), which provides a holistic approach for evaluating the effects of future climate and socio-economic changes on six sectors: agriculture, forestry, water, coasts, biodiversity and urban (Harrison et al. 2012; Harrison et al. this volume (a)). The IAP is a web-based interactive tool and as such rapid simulations are needed for effective user engagement. Holman et al. (2008) have found that the use of computationally simpler modelling techniques, so called ‘meta-models’ (Carmichael et al. 2004) can be effective in allowing much greater complexity of model linkages and feedbacks. In this context, the CFFlood model has been developed using a GIS approach based on overlay analysis to create detailed databases that can be used in computational algorithms. The model has been developed around the DSPIR integrated assessment framework to establish dynamic links between the different sectoral models within the CLIMSAVE IAP (Harrison et al. 2012) and to build a consistent structure for the modelling elements.

2.1 The CFFlood model

The CFFlood model consists of coastal and fluvial sub-model components for estimating socio-economic impacts of flood events, including area at risk of flooding, people in flood zones, people affected and economic damages. These components are integrated and coupled with a range of adaptation measures to allow the analysis of possible responses that aim to reduce impacts under current/future conditions (see section 2.5). The model simulates flood impacts for the 2010 baseline year and interacts within the IAP with the Regional Urban Growth (RUG) model (Rickebusch 2010) and the WaterGAP meta-model (Wimmer et al. this volume) to simulate impacts for the 2020s and 2050s time slices (Figures 1 and 2). The input data is resampled from high resolution data sets (e.g. 100 m resolution CORINE land use data and 100 m fluvial flood maps) and the results are communicated to the IAP at a 10’ resolution (which is the agreed spatial resolution of the CLIMSAVE IAP) for swift data display. The 10’ grid cells mostly have heterogeneous physical and social characteristics such as topography, geomorphology, land use and population density. Thus, highly processed data inputs based on overlay analysis of flood zones, land use, climate data and sea-level rise, and socio-economic data have been constructed and integrated. This enables the model to produce the rapid dynamic simulations that are required for an interactive user engagement within the CLIMSAVE IAP. The estimates of socio-economic flood impacts can be inherently uncertain due to model and scenario assumptions at the European scale and are difficult to validate. Similar validation difficulties have been highlighted in comparable studies (e.g. Feyen et al. 2012; Mokrech et al. 2008). Thus, validated datasets (e.g. fluvial flood maps) have been used and model results (e.g. WaterGAP meta-model) have been validated and compared with other studies, where possible.

2.1.1 Coastal flood sub-model

The main steps for estimating the impacts of coastal flooding are illustrated in Figure 1. The concept of overlay analysis is used to outline flood zones by examining the regional extreme sea level relative to topography. Future regional extreme sea levels are obtained by combining present-day extreme sea levels and future relative sea-level rise (i.e. absolute rise in sea level and varying vertical land movement around the European coastline), as appropriate. The outlined flood zones are compared with selected sites using available UK floodplain maps; the outlines of these zones are consistent with the floodplains despite the difference in spatial resolution. Thus, flood zones are calculated and estimates of the people living in these zones are calculated using local population density. The method uses the Standard of Protection (SoP) parameter for analysing the effect of relative sea-level rise on the protection level provided by flood defences. It assumes that SoP decreases and flood frequency increases with a rise of extreme sea level (e.g., Hinkel et al. 2014; Mokrech et al. 2008). For example, the 100 year flood event becomes a 21 year flood event along the Portsmouth coastline in the UK due to a 25cm climate-induced sea-level rise combined with land subsidence in the 2050s. This effect will vary along the European coastline as the vertical land movement and the slope of the exceedance curve varies spatially. By comparing the investigated flood event with the SoP, the model determines if flooding occurs. Hence, people affected by flooding are estimated and flood damages are calculated following the method presented in section 2.3. Considering the 10’ cell size and the meta-modeling approach, the failing mechanisms of flood defences (e.g. breaching and overtopping) are not investigated – the explicit assumption here is that the flood zones will be flooded if the flood defence’s SoP is exceeded.

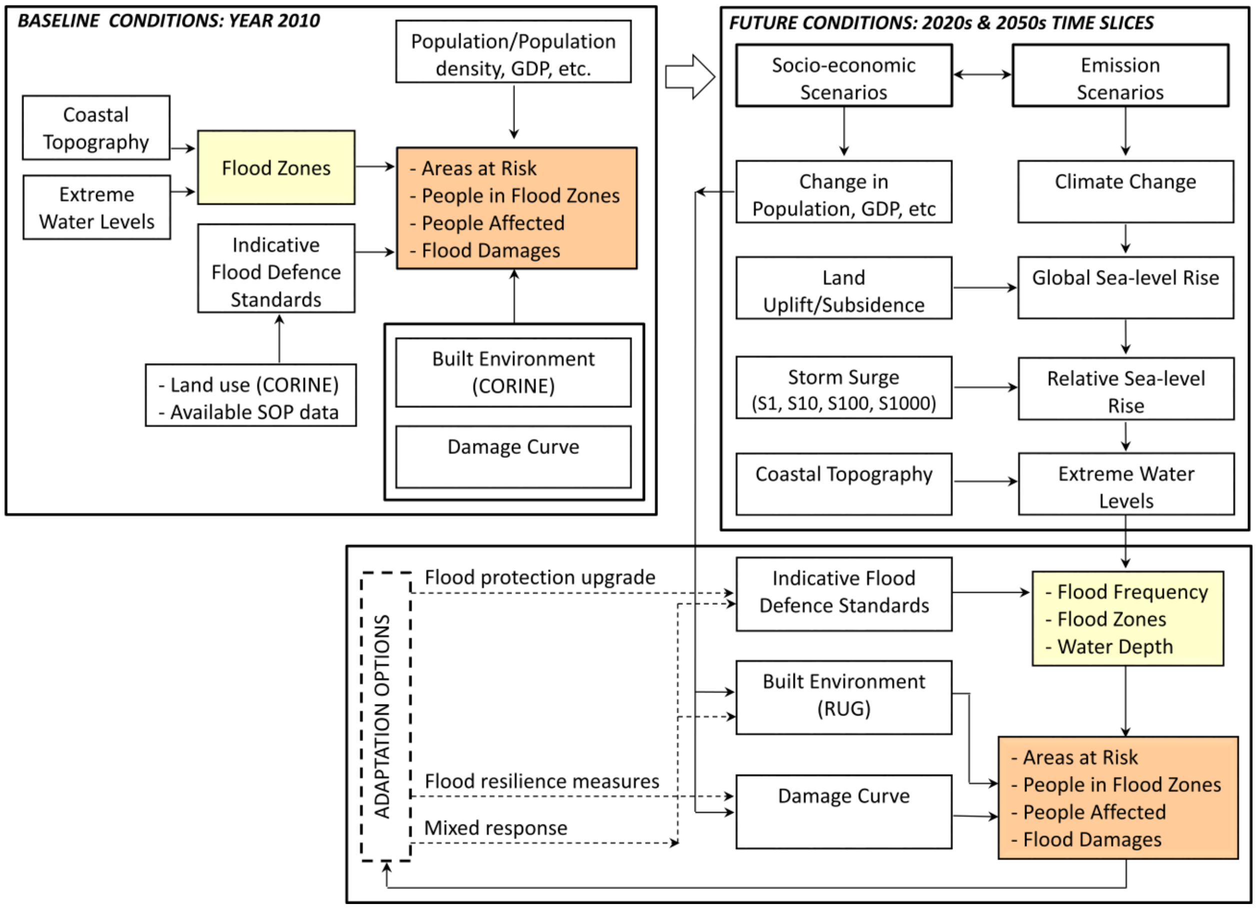

Figure 1. Overview of the coastal flood sub-model, steps, data inputs and model outputs.

2.1.2 Fluvial flood sub-model

The fluvial flood sub-model is implemented as illustrated in Figure 2 to estimate the outputs of area at risk, people living in flood zones, people affected and flood damages. The model uses fluvial flood maps for Europe that are produced at a 100 m resolution with a planar approximation approach based on LISFLOOD extreme river water level simulations (Feyen et al. 2012). The flood maps represent fluvial catchments across Europe, including extent and water depth at 2, 5, 10, 20, 50, 100, 250 and 500 year return periods, assuming no flood defences. These maps have been used to define the fluvial flood zones in the CLIMSAVE project. They are analysed in conjunction with the CORINE land use data and the socio-economic data (i.e. population and GDP) from the NUTS3 statistical datasets. The estimated SoP parameter is used to analyse the effect of changes in peak river flows on flood protection following Mokrech et al. (2008). Thus, protection levels of flood defences are degraded with increases in peak river flows and vice versa (e.g. 10% increase in peak river flow degrades the 100 year flood defence to the 53.5 year level in the London basin, UK).

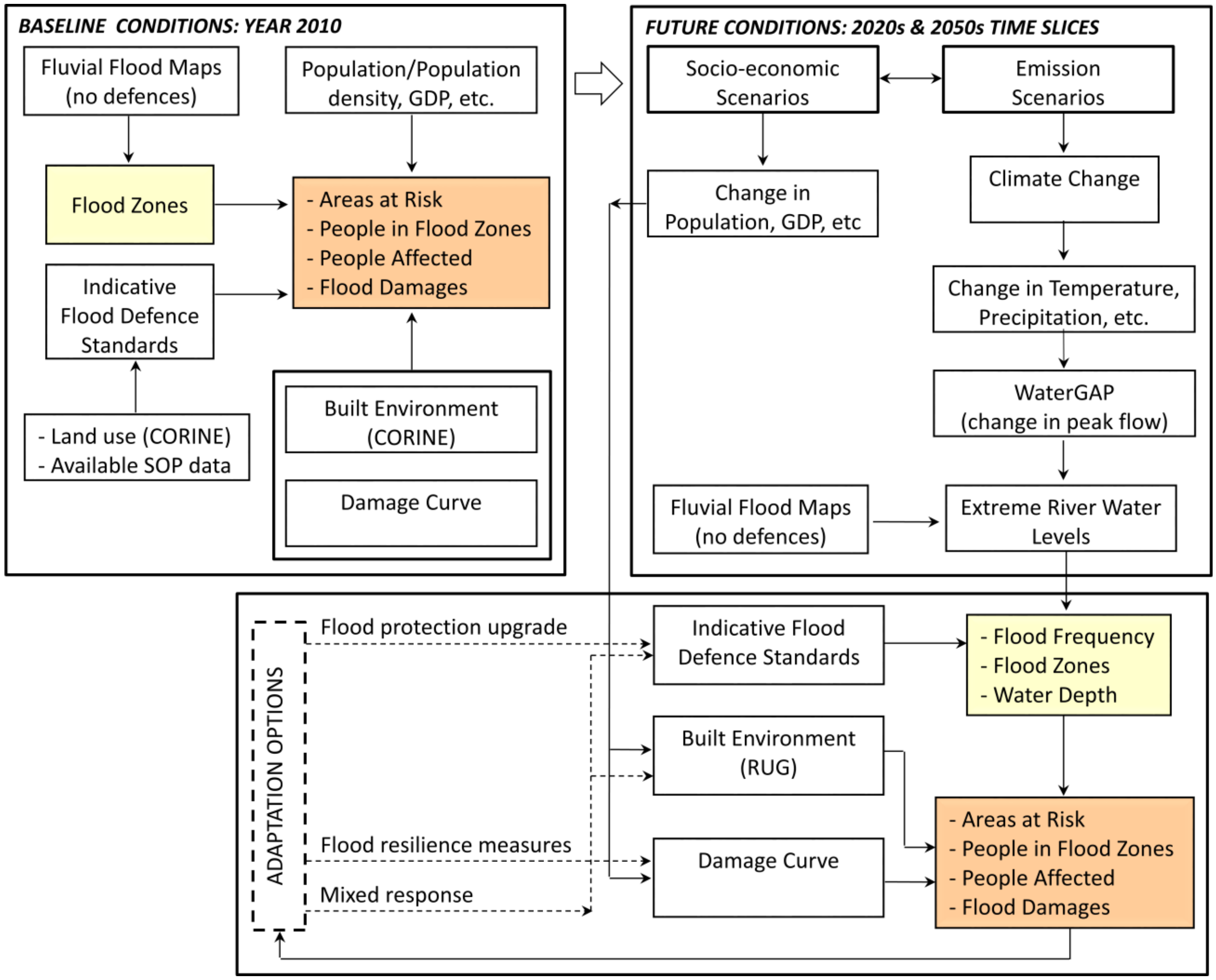

Figure 2. Overview of the fluvial flood sub-model, steps, data inputs and model outputs.

The changes in the peak river flow are derived from the WaterGAP meta-model (WGMM). WGMM emulates the performance of the WaterGAP3 model (Alcamo et al. 2003; Döll et al. 2003) on hydrology and water use (Wimmer et al. this volume). To reduce model runtime and input data requirements, the spatial resolution of WaterGAP3 (5 x 5 arc minute) has been aggregated to 92 European river basins greater than 10,000 km². Each river basin represents either a large natural river catchment or a cluster of several smaller catchments with similar hydro-geographic conditions. Climate change impacts on peak river flow are represented by changes in the median of the annual maximum river discharge (Q_{med}), where the latter are derived from catchment-specific response surfaces that relate changes in Q_{med} with changes in temperature and precipitation. Response surfaces were derived from pre-run WaterGAP3 simulations for the period 1971-2000, in which spatio-temporal patterns in the baseline climate dataset were incrementally modified with respect to temperature ([0,0.5,...,6°C]) and precipitation ([-50,-45,...,+50%]) (Mitchell and Jones 2005).

When WGMM is run with scenario input data of gridded mean annual air temperature and mean annual precipitation, it first computes the relative change in temperature and precipitation compared to the baseline in each river basin. In a second step, scenario Q_{med} is interpolated by inverse distance weighting of Q_{med} at the four neighbouring grid points in the response surface. Finally, the relative change in Q_{med} compared to the baseline value is computed and passed to CFFlood as an estimate of changes in peak river discharge (see S-Figure 1 for model performance).

2.2 Datasets

The data inputs to the CFFlood model are acquired mainly from European datasets, such as CORINE land cover, but global datasets such as the enhanced SRTM topographical dataset have also been used (Table 1). The processing required for two key datasets in the CFFlood model – topography and flood protection – is discussed in the supplementary document 2.

Table 1. Key datasets used in the development of the CFFlood model.

Data type	Description	Scale/Resolution	Processing
Fluvial flood maps	Derived from LISFLOOD simulations for 2, 5, 10, 20, 50, 100, 250 and 500 year flood events (Feyen et al. 2012)	100 m spatial resolution	Gridded at 10' spatial resolution
Land cover	CORINE 2006 dataset – version 12/2009 http://open-data.europa.eu/en/data/tag/CLC2006	100 m spatial resolution	Gridded at 10' spatial resolution, tabulated in coastal areas at 25 cm elevation bands and in fluvial flood maps.
Elevation data: The ESRI enhanced global SRTM (Shuttle Radar Topography Mission) elevation data	Void filled SRTM elevation data using the United States Geological Survey GTOPO30 (1 km) data set.	90 m spatial resolution	Tabulated at 25 cm elevation bands and gridded at 10' spatial resolution, (see supplementary document 2)
Population density, GDP	Nomenclature of Territorial Units for Statistics (NUTS) data of EUROSTAT http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction	At the NUTS 3 statistical regions (~1-10^6 km^2)	Statistically summarised at 10' and at the 25 cm elevation bands to estimate localised GDP and Population density
Extreme sea levels (astronomical tides and storm surges)	Water elevation for 1, 10, 100 and 1000 year events in 2010	DIVA database (Vafeidis et al. 2008), (average segment length of 70 km)	Gridded at 10' spatial resolution
Land uplift/subsidence	Annual rate of change		
Flood protection	Indicative dataset constructed from available flood protection data combined with indicative standards (a range specified by minimum and maximum values) based on the CORINE dataset following MAFF (1999) (see supplementary document 2)	100 m spatial resolution	Gridded at 10' spatial resolution

2.3 Structure and Content Damages

Structural and content damages are calculated for residential and non-residential properties based on the broad assessment methodology of Linham et al. (2010) (see also Hallegatte et al. 2013). The method uses the notion that the value of physical losses from a flood is no more than the value of the assets exposed to this hazard. For developed economies as in Europe, the net capital asset is approximated to be 3 times the GDP. The proportion of structural assets is considered to be 36% and 42% for residential and non-residential properties, respectively (Linham et al. 2010). Only a proportion of those assets located in a risk area are considered to be exposed to flooding, as in densely populated urban areas a significant proportion of buildings are multi-storey and, hence, a large part of the assets are above any conceivable flood level. Hence, classes of population density were used to determine the proportion of assets at risk of flooding. The Dutch Depth-Damage curve (Linham et al. 2010) is then used to estimate structural and content losses caused by flooding (see S-Figure 2 in the supplementary document for more details).

2.4 Scenarios

Climate and Sea-level rise scenarios

Climate change scenarios in CLIMSAVE were constructed following the methodology presented by Dubrovsky et al. (this volume) to capture uncertainty from different global climate models, emissions scenarios and climate sensitivity using datasets that were available from the 4th Assessment Report of the IPCC (2007). Thus, the CFFlood model can be used to explore the effects of climate pressures (changes in temperature and precipitation) under four emission scenarios (A1B, A2, B1 or B2), five climate models (MPEH5, CSMK3, HadGEM, GFCM21 and IPCM4) and three climate sensitivities (low, medium or high) on flood impacts. The sea-level rise scenarios in CLIMSAVE are produced by the SimCLIM model (Warrick 2009). The projected sea-level rise values may reach 30 cm by the 2050s under the A1B scenario with high climate sensitivity. Projections based on the four greenhouse gas emissions scenarios and three climate sensitivities in the 2020s and 2050s are shown in S-Table 1. In addition to these pre-defined scenarios, the CFFlood model allows exploration of up to 2 metres of sea-level rise by 2100 (following current guidance, Nicholls et al. 2014).

Socio-economic scenarios

Socio-economic scenarios are used to develop a series of socio-economic indicators relevant to flooding as follows:

- Change in GDP is used to reflect changes in economic conditions and how these influence flood damages.
- Change in population density is used to estimate the number of people in flood zones. The NUTS3 data set provides this variable for the baseline year.

Four socio-economic scenarios have been developed for Europe by the CLIMSAVE Project which include quantifications of population change and GDP for two time slices: 2020s and 2050s (Table 2). Both the development of the scenario storylines and the quantification of the socio-economic indicators had extensive stakeholder input. Collectively they show both population increase and decrease and GDP increase and decrease. The GDP decrease under 'Should I stay or should I go' is an unusual feature which has rarely been analysed before. Further details of the socio-economic scenarios can be found in Kok et al. (this volume).

Table 2. Future socio-economic scenarios and quantification of population and GDP for two time slices: 2020s and 2050s (Kok et al., this volume).

Name of Future	Description	% change in GDP		% change in Population	
		2020s	2050s	2020s	2050s
We are the world (WAW)	Effective government change. The focus from GDP to welfare; less inequality and global cooperation	+26	+94	+1	+5
Icarus	Short term policy planning and a stagnating economy leads to disintegration of social fabric and shortage of goods and surfaces	0	0	+5	-9
Should I stay or Should I go (SISOG)	Failure to address economic crisis leads to increase gap between rich and poor, political instability and conflicts, people live in an insecure and instable world.	0	-36	+5	+23
Riders on the storm (ROS)	Strong economic recessions but successively countered with renewable and green technologies. Europe is an important player in a turbulent world.	0	+54	+5	+16
Baseline	Default: no changes from baseline conditions.	0	0	0	0

2.5 Adaptation options within the CFFlood meta-model

A wide range of adaptation strategies were implemented within the CFFlood meta-model to focus on different approaches to reducing flood risks as follows:

a) Flood protection upgrade by 50%, 100%, 500% and 1000%: this is applied directly to the indicative protection levels explained in supplementary document and uniformly throughout Europe.
b) Resilience measures: new properties are not affected by flooding due to a resilience measure (e.g., by raising them above ground level) up to a pre-defined threshold of flood event (e.g., 100 year event), while old properties may continue to suffer from flood damage depending on the flood depth.
c) Mixed response: this provides a realistic adaptation option, where a plausible combination of flood protection improvement (i.e. 100% upgrade) and realignment of flood defences is included.

3. Results and discussion

The CFFlood model within the IAP is capable of exploring a wide range of scenario combinations by varying climate, sea-level rise, socio-economic parameters and adaptation options. For illustrative purposes, the discussion in this paper is based on a limited number of predefined and exploratory scenarios for selected flood events to identify possible trends of socio-economic flood impacts in the coming decades. Table 3 shows the scenarios that are examined herein.

Table 3. Summary of the selected scenario combinations.

Scenario group	Flooding type	Flood event	Time slice	Climate	Socio-economics
1	Coastal & Fluvial	100 year	2010 (i.e. baseline year)	Baseline conditions	Baseline conditions
2	Coastal	100 year	2010	0, 25, 50, 100, 150, 200 cm sea-level rise values	Baseline conditions
3	Fluvial	100 year	2020s and 2050s	A1B emission scenario (CSMK3 climate model)	Baseline and the four socio-economic scenarios (WRW, Icarus, SISOG, ROS)
4	Coastal and Fluvial	100 year	Not relevant (used for exploratory adaptation analysis)	100 cm sea-level rise, +25% winter and summer precipitation, +3° C in temperature	+25% population, +25% GDP

The total (i.e. coastal and fluvial) flood analysis without flood protection indicates that currently in Europe almost 28.6 million people (i.e. almost 6% of the total population) live within the 100 year flood inundation area resulting in a potential total economic damage of €236 billion. These numbers are consistent with Jongman et al. (2012), after combining both coastal and river exposures. The socio-economic flood impacts for a 100 year event under the baseline conditions, including the effect of defences, range from 0.24 to 17.4 million people flooded and €0.6 to €79 billion of economic loss, highlighting the effectiveness of the protection in reducing flood impacts (up to 99% reduction for the maximum protection estimate).

For coastal flooding alone, under baseline socio-economic conditions, 16.4 million people are estimated to live in flood zones and potential economic damages may amount to €190 billion for a 100-year event with no flood protection. The majority of people are located in Western Europe; strongly concentrated around the North Sea, especially in the Netherlands, Hamburg, and London, but other hot spots such as Venice and Ravenna in Italy can also be identified (Figure 3). The indicative flood protection levels, as described in the supplementary document, are highly effective for the baseline conditions as the minimum level of protection reduces socio-economic impacts significantly and the maximum level of protection almost eliminates these impacts (S-Figure 3). On the other hand, exploratory scenarios of sea-level rise of 0.25, 0.50, 1.00, 1.50 and 2.00m demonstrate a systematic increase in the number of people within the flood zones, reaching 22.9 million people (i.e. an almost 40% increase from baseline) and €318 billion in economic damages (i.e. a 67% increase from baseline) under 2 metres of sea-level rise (S-Figure 3). In addition, the benefits of flood protection at the minimum and maximum levels are almost the same under the investigated exploratory values of sea-level rise. For the extreme rise of 2 metres, the protection levels have almost no effect in reducing impacts as the number of people flooded is estimated at 22.7 million (S-Figure 3) and economic damages are estimated at €314 billion. Furthermore, increases in future socio-economic pressures on coastal zones are likely to exacerbate flood impacts (although not discussed herein, such scenarios can be simulated using the CLIMSAVE IAP). These results highlight the challenge presented by sea-level rise on parts of Europe's coast and the need for appropriate responses (e.g. Zanuttigh 2014). These are likely to include a significant investment in upgrading flood protection. It is noteworthy that in the UK and the Netherlands, high-end scenarios of sea-level rise are being investigated (e.g. Lowe et al. 2009; Katsman et al. 2011), and plans to prepare for these changes are being developed (e.g., Stive et al. 2011; Tarrant and Sayers 2013).

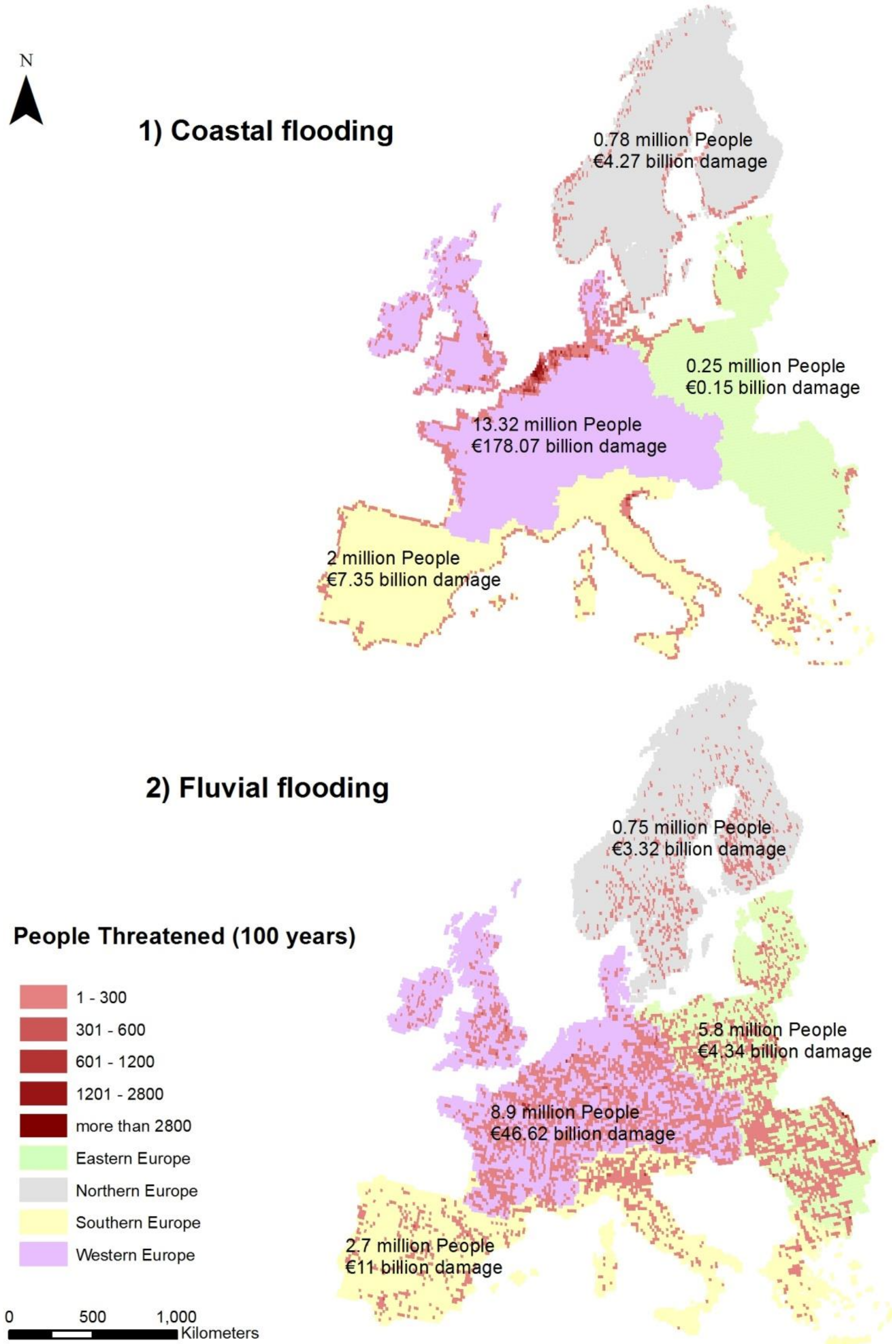

Figure 3. Potential regional exposure and economic impacts to the 100 year flood event under baseline socio-economic conditions and assuming no defences: 1) coastal flooding; 2) fluvial flooding. Western Europe shows the highest exposure and economic impact for both coastal and fluvial flooding.

For fluvial flooding, the number of people in 100 year flood zones under the baseline conditions may reach 18.17 million (Figure 3). Comparison with the combined coastal and fluvial flooding scenario shows that approximately 6 million people are located within the combined 100-year coastal and fluvial flood zones (e.g. in deltas). In the future, changes in the number of people within the 100-year flood zones at the European level is mainly influenced by changes in population, with a smaller influence being due to climatic factors (i.e. changes in river flow). This may reflect how changes in flood magnitude are estimated in the CFFlood meta-model: namely that the change in peak river flow used to adjust the flood magnitude only accounts for annual average changes in climate, and neglects potential changes in climate extremes (Kendon et al. 2014). When examining the influence of climatic factors and social factors in scenario group 3 in Table 3, fluvial flooding impacts show a general reduction in people at risk under both the WAW and ROS socio-economic scenarios by the 2050s (Table 2 and S-Figure 4). Under the 'Icarus' socio-economic scenario the number of people flooded declines over most of Europe, except in some areas of western and northern Europe. Under the SISOG scenario there is considerable spatial variation in people affected with some areas in western Europe showing a reduction in people flooded, while other areas show an increase, for example, in eastern regions of Europe. This is consistent with the increase in population (e.g. +23% by 2050s under the SISOG scenario) which leads to larger flood impacts, while a decrease in population will lead to a decrease in flood impacts. In this context, there is no significant difference in the number of people flooded in the 2020s under the low, medium and high sensitivities of the investigated A1B emission scenario, as well as across the socio-economic scenarios, as minimal climate and social variations are expected by this time slice. The economic damages follow a different pattern, as change in GDP is the primary parameter that influences changes in damages in the implemented methodology. For example, the economic damage is the largest under the 'WAW' scenario as the GDP change is the highest (+94%). While not explicitly analysed by the CFFlood meta-model, it is important to remember that while damage grows, so potentially does the ability to adapt.

The CFFlood model within the CLIMSAVE IAP can be used to explore a range of adaptation options that are uniformly applied across Europe as explained in Section 2.5. The adaptation options are influenced by the estimated flood protection standards. However, as the actual flood protection levels are not systematically available across Europe, but rather estimated based on land use/land cover types, the outcomes of the adaptation analysis should be considered as only exploratory. To explore the potential benefits of the designed adaptation options, we consider an extreme climate and socio-economic scenario of 1 metre of sea-level rise, 25% increase in winter and summer precipitation, 3° C increase in temperature, 25% increase in population and 25% increase in GDP (see scenario group 4 in Table 3), and evaluate flood consequences for the adaptation options. S-Figure 5(a) shows that this extreme scenario may lead to an increase in the people at risk of flooding from almost 28 million (at baseline) to 41 million people (i.e. 46% increase) with no defences and to 37 million (i.e. 32% increase) with the minimum level of flood protection, which by comparison can reduce the impact to almost 17 million under baseline conditions. Thus, the performance of the estimated flood protection under the investigated extreme scenario is much less effective by comparison to its performance under baseline conditions, and consequently more aggressive policies for reducing flood risk are needed under such extreme conditions. The analyses indicate that a significant increase in the level of flood protection (i.e. upgrade by 500% or more) is required in order to reduce the number of people affected to the baseline level. The implementation of resilience measures (e.g. elevated buildings) at the minimum level of flood protection may perform well, but they are not enough on their own to reduce flood impacts to the baseline level. The economic damages under this scenario demonstrate a similar pattern (S-Figure 5(b)), with the exception that even aggressive adaptation options such as upgrading defences by 500% or 1000% will not be effective in reducing economic damages to the baseline level, which can be mainly attributed to the increase in GDP. Thus, the impact of future conditions may lead to increased socio-economic damages in spite of adaptation efforts: major and costly adaptation policies will be required if we experience significant climate change. While this is not certain, it is important that European countries prepare for this challenge, following existing efforts in flood prone areas such as the Netherlands and London where planning is already underway.

4. Conclusions and future work

Socio-economic impacts from flooding across Europe under current and plausible future conditions can be investigated using the CFFlood meta-model within the CLIMSAVE IAP. This includes sub-European analysis. The flood model integrates coastal and fluvial flooding to provide indicative estimates of the impacts – it accounts for relative sea level rise and changes in the extreme fluvial flows due to change in future climates (i.e. temperature and precipitation), as well as for socio-economic changes such as population and GDP. The CFFlood model also allows the exploration of a range of adaptation options. The level of flood protection is essential to analyse actual socio-economic flood impacts, but this information is not systematically available across Europe at the present time. Hence, an indicator approach based on land use/cover type is used to estimate the level of flood protection across Europe. This is updated where protection standards are known (e.g., UK, the Netherlands). The analysis of limited set of scenarios reveals some key findings:

1. Almost 28.6 million people (i.e. 6% of European population) are at risk of flooding under the 100 year event and potential asset damage could be €236 billion. There is a notably concentration of flood risk on western Europe's coasts, with 13.3 million people in the 100 year flood plain, most especially around the southern North Sea.
2. Estimates of existing protection levels greatly reduce the socio-economic impacts, although there are important uncertainties.
3. Future sea-level rise will cause a significant increase in socio-economic impacts in coastal areas and consequently significant adaptation measures are required to maintain current risk levels. While the direction of change for coasts is certain, the magnitude of change is highly uncertain.
4. In contrast, for fluvial flooding average changes in future climate conditions may not cause a net increase in impacts at the European scale. However, the spatial distribution of flood risk may change moving from southern regions (where risk may fall) towards northern and eastern regions (where risk may rise) under the scenarios considered here (S-Figure 4).
5. Future socio-economic conditions in terms of population and GDP will have a significant influence on the level of flood damage, potentially increasing or decreasing risk depending on their future trends. The highest economic growth leads to the largest growth in risk, but such an economy also has a greater capacity to adapt.
6. Hence, high-end future climate conditions combined with an increase in human pressures will lead to significant increases in the socio-economic impacts of flooding. To manage this growing risk a major flood management effort is required, most especially in coastal areas. While vulnerable areas such as the Netherlands may already recognise the threat, all coastal areas, and many fluvial areas need to consider this challenge.

The CFFlood meta-model within the CLIMSAVE IAP offers a unique opportunity for stakeholders to quantify the socio-economic impacts of coastal and fluvial flooding across Europe. The important issue of how flood impacts interact with other sectors can also be assessed using the IAP as reported in Kebede et al. (this volume) and Harrison et al. (this volume, b).

There are a number of areas where future research could lead to improvements in projecting future flood impacts. These include: 1) improving the flood protection dataset to better represent baseline protection levels; 2) developing future adaptation options based on actual protection levels and more detailed adaptation measures which take account of spatial variation across Europe; 3) an assessment of the damage functions used to better describe failure of defences, and adaptation in general; 4) better validation which is an ongoing need with models of this type; 5) a dynamic implementation of adaptation and feedbacks; and 6) producing Average Annual Damage (AAD) as an economic impact indicator as the AAD is more relevant to the management community and decision makers. More flexibility to investigate detailed time slices (ideally 10 year time step until 2100) might also be useful. To achieve some of these aims, the model run time may need to be extended leading to two versions of the model: the current version with simpler representations that can be run over the web and one with greater complexity and functionality that would be run within an offline version of the CLIMSAVE IAP. Hence, there is much scope to develop these models further to support flood policy development.

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Supplementary Document

An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe

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1. Sea-level rise scenarios

S-Table1. Sea-level rise projections (in centimeters) at 2020s and 2050s time slices at three sensitivity levels (low, medium and high).

	Emission Scenarios											
	A1B			A2			B1			B2		
	Climate Sensitivity			Climate Sensitivity			Climate Sensitivity			Climate Sensitivity		
Year	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High
2020s	6	9	12	6	8	9	6	8	11	6	8	10
2050s	12	21	30	12	19	26	12	18	25	12	19	26

2. Data Processing

Topographic dataset

The SRTM data at 3 arc second (~90 m) spatial resolution and the GTOPO30 data at 30 arc second (~1 km at the equator) spatial resolution have been processed to produce a 200 m DEM with full European coverage. The DEM is classified into bands at 0.25 m elevation intervals along the coastline, covering the maximum possible land at flood risk due to the combined sea-level rise, land subsidence and the extreme storm surge of a 1000 year event. This data set is then gridded at the 10' spatial resolution to create a look up table that allow rapid data retrieval and processing as required by the CLIMSAVE IAP.

Indicative flood protection data for Europe

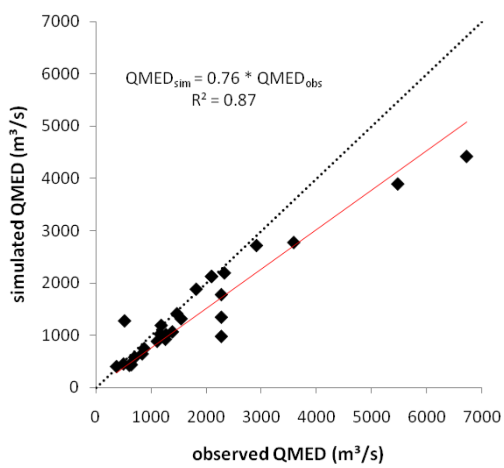
Little information is available on existing flood protection standards for coastal and river areas at the European level. A study by Feyen et al (2012) used the GDP/capita as an economic indicator to design indicative flood protection levels for fluvial flooding in Europe. More recently, Jongman et al (2014) estimated continent-wide estimates of flood protection standards for all 1,007 EU sub-basins, using a combination of literature study and modelling. In this work, an indicative flood protection dataset at the European level is constructed following UK indicative standards (MAFF, 1999), where ranges of Standard of Protection (SoP) of coastal and fluvial flood defences are determined based on land use/cover classes and the economic value of the land. S-Table 2 shows the minimum and maximum indicative standards of protection that are implemented for six land use categories in fluvial and coastal flood zones based on the CORINE land use/cover dataset. The resulting flood protection dataset has been revised using published data on flood protection in individual regions/nations including Belgium, the Netherlands, Northern Germany and London. For example, the Netherlands' extensive coastal defence system provides protection up to 10,000 year flood event and the Thames Barrier that provides London and its environs with protection against 1000 year flood event have been included. This method provides a consistent approach for establishing a European baseline dataset on flood protection for exploratory purposes.

S-Table 2. Ranges of indicative standards of protection associated with land use classes (from CORINE), (following MAFF, 1999).

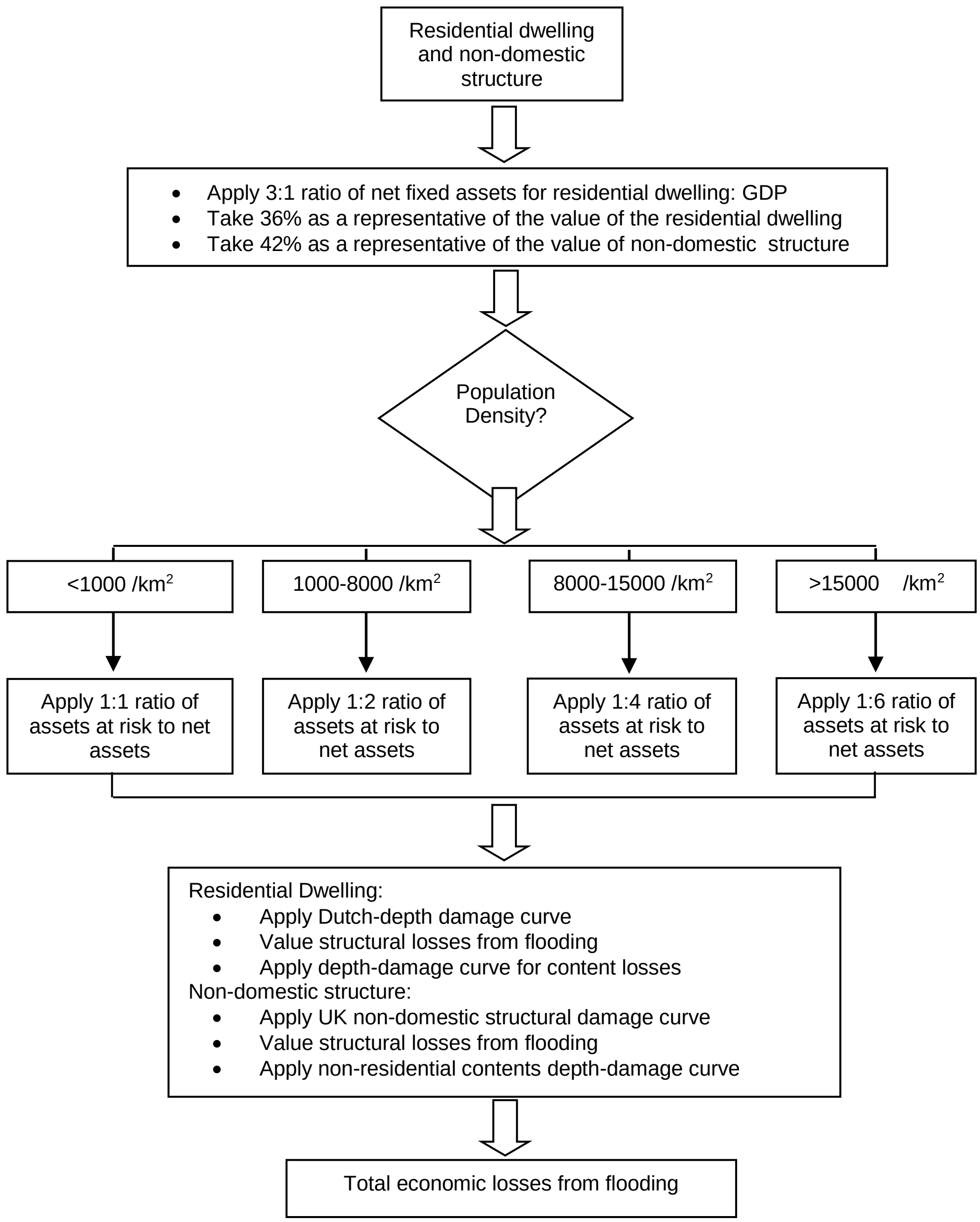
Land use band	Description	Land Use (CORINE classes – third level)	Indicative standard of protection	
			Fluvial	Coastal
			Return	Return

			period (years)	period (years)
A	Intensively developed urban areas.	111	50-200	100-300
B	Less intensive urban areas with some high grade agricultural land and/or environmental assets.	112, 121, 122, 123, 124, 131, 141, 142, 211, 212, 213, 221, 222, 223	25-100	50-200
C	Large areas of high-grade agricultural land and/or environmental assets with some properties.	132, 133	5-50	10-100
D	Mixed agricultural land with occasional properties at risk of flooding.	241, 242, 243, 244,	1.25-10	2.5-20
E	Low-grade agricultural land (often grass) or seasonally occupied properties at risk.	31, 311, 312, 313, 321, 322, 323, 324, 333	0-2.5	0-5
F		All other classes	0	0

3. Methodology

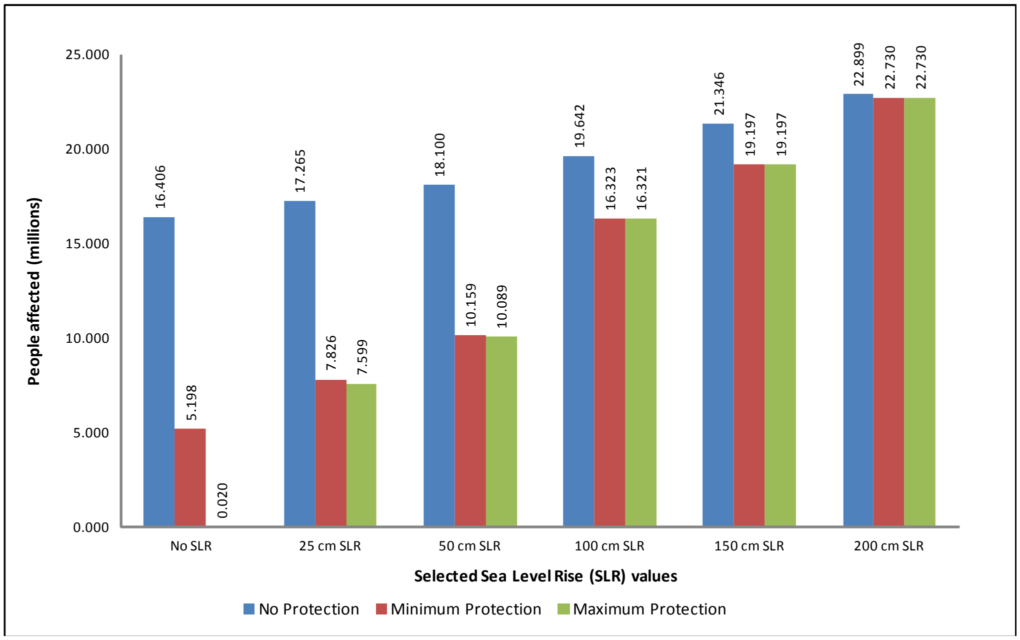


S-Figure 1. Performance of the WaterGAP meta-model - Scatter_QMED: Simulated vs. observed flood parameter Q_{med} for 25 gauging stations across Europe, dashed line = 1:1 line, red (solid) line = linear fit.

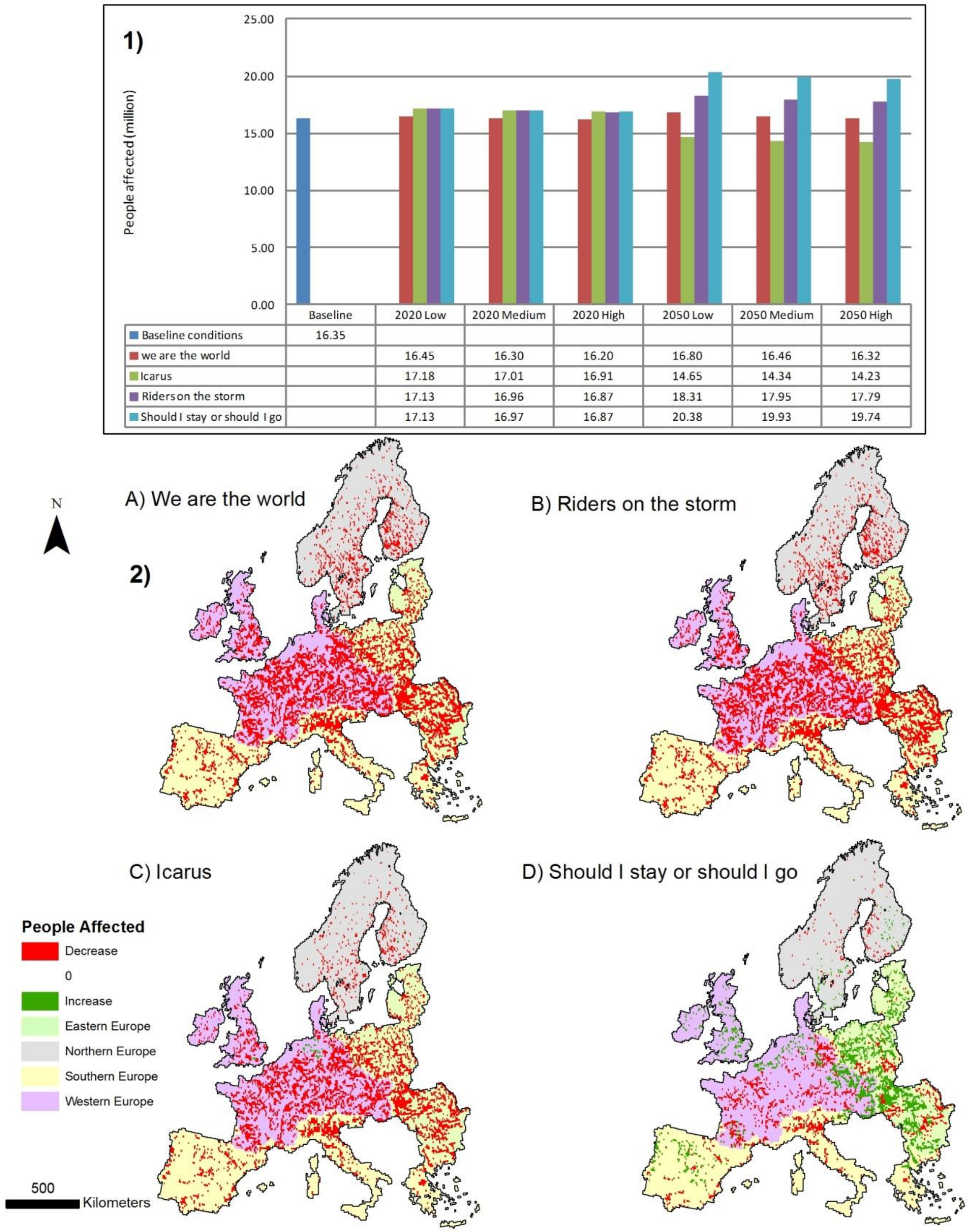


S-Figure 2. Flowchart shows the flood damage calculation (adopted from Linham et al. 2010).

4. Results

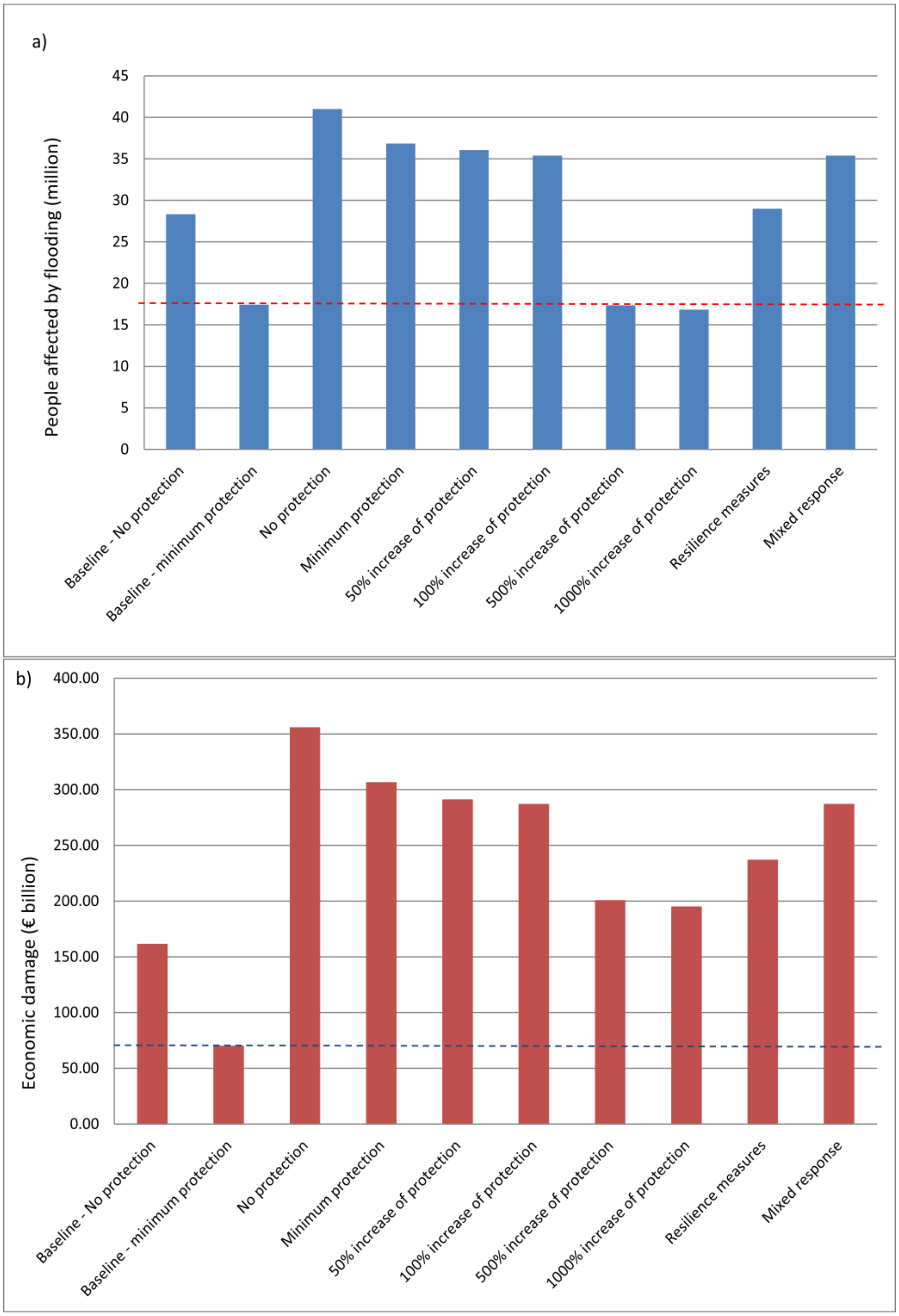


S-Figure 3. People affected by the 100 year coastal event under selected exploratory scenarios of sea-level rise (with no protection, minimum protection and maximum protection).



	Baseline	2020 Low	2020 Medium	2020 High	2050 Low	2050 Medium	2050 High
Baseline conditions	16.35						
we are the world		16.45	16.30	16.20	16.80	16.46	16.32
Icarus		17.18	17.01	16.91	14.65	14.34	14.23
Riders on the storm		17.13	16.96	16.87	18.31	17.95	17.79
Should I stay or should I go		17.13	16.97	16.87	20.38	19.93	19.74

S-Figure 4. Potential people affected by fluvial flooding under scenario group 3 in Table 3: 1) people affected by the 100 year event and the minimum level of protection at the baseline year (2010) and under future socio-economic scenarios at two time slices (2020s and 2050s); 2) regional spatial distribution of change in people affected from baseline due to change in river flows under the four socio-economic scenarios.



S-Figure 5. Socio-economic impacts by 100 year flood event under a range of adaptation options including: increasing the flood protection level by 50%, 100%, 500%, and 1000% from the minimum flood protection level, and a mixed response of increasing flood protection by 100% and realignment of defences - the investigated scenario includes 1 meter sea-level rise, 25% increase in the winter and summer precipitations, 25% population, 25% increase in GDP: a) people flooded; b) economic damage.

The red and blue dashed lines indicate the impacts under the baseline conditions and the minimum level of flood protection for people affected and economic damage respectively.