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ACCREU
Assessing Climate Change Risk in EUrope

Impacts on infrastructure and built environment

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Changes with respect to the DoA
(with justification if applicable)

1. **Dissemination and uptake**

(who will/could use this deliverable, within the project or outside the project)
Within the project, the results from D2.1 will be used by macroeconomic modelers in WP4 to assess the economy-wide effects of the impacts measured with the sectoral models presented in this report. The results also inform WP3's local and regional case studies. Outside the project, the EU commission and stakeholders on the European and national level can use the results to inform policy decisions and adaptation planning. The modeling tools and results will benefit researchers across different disciplines, including environmental economics, flood risk management, and geography.

2. **Short Summary of results (<250 words)**

This report provides a comprehensive assessment of future climate change impacts on infrastructure and the built environment in Europe, focusing on coastal and riverine flooding up to 2100. The analysis integrates three modeling frameworks - DIVA, GLOFRIS, and LISFLOOD - to evaluate expected damages and adaptation costs under various climate and socioeconomic scenarios as well as for three different levels of adaptation.

While the models show some variations in damage estimates due to different methodological approaches, they demonstrate consistent trends and spatial patterns of risk across Europe. Without adaptation, both coastal and riverine flood damages are projected to increase substantially across Europe, potentially reaching hundreds of billions of euros annually by 2100. Adaptation measures could significantly reduce these impacts. For coastal flooding, optimal protection strategies could decrease damages by up to two orders of magnitude compared to no-adaptation scenarios. For riverine flooding, retention areas and dike strengthening emerge as particularly cost-effective measures, potentially reducing Expected Annual Damages by 68-83% depending on warming levels.

These findings provide crucial input for adaptation planning at both EU and national levels, while highlighting key areas for future research, particularly in improving the representation of extreme events in long-term economic assessments and better understanding the macroeconomic implications of different adaptation strategies.

3. **Evidence of accomplishment**

(report, manuscript, web-link, other)

Table of Contents

1 Introduction

The ACCREU project sets out to provide comprehensive assessments of future climate risks under various adaptation and mitigation scenarios in order to enhance climate resilience in the EU. Work Package 2 and Task 2.1 specifically are the first step in an integrated modeling framework that connects sectoral climate impact models to macroeconomic models in order to assess climate change impacts across a broad range of socioeconomic dimensions. Special attention is given to existing knowledge gaps, specifically in the modeling of adaptation. Deliverable 2.1 (D2.1) focuses on assessing the impacts of climate change on infrastructure and the built environment, using advanced modeling tools and updated data to reflect the latest advancements in climate science. ACCREU is building on as well as extending previous assessments, such as the ones done in the COACCH project. The key focus of this deliverable is to advance our understanding of the impacts of slow onset sea level rise and extreme events (coastal and riverine flooding) on infrastructure and the built environment.

The improvements for coastal flooding (DIVA and GLOFRIS) extend to three different areas:

1. Advancing socio-economic impact assessment for slow-onset sea-level rise and extreme events (DIVA and GLOFRIS model) using updated AR6-based scenarios. This includes a higher resolution spatial assessment through improved coastal management units, enabling better adaptation planning. Coastal flood impacts for Europe can be assessed at NUTS-2 and NUTS-3 level.
2. Introducing novel adaptation options and adaptation scenarios across the different models for coastal flooding. These include coastal protection, migration, nature based solutions (wetlands), and zoning restrictions across a range of different scenarios.
3. Improved insights into distributional impacts of coastal flooding for the private sector.

The improvements for river flooding assessment (developed with the LISFLOOD and GLOFRIS models) are as follow:

1. While previous work focused on damage to transport infrastructure, we now provide a comprehensive overview of damages to all economic sectors throughout Europe, complemented with an additional piece specific to transport infrastructure based on results from recent studies, including the ongoing horizon project MIRACA.
2. Building on this overview of economic damages, using the LISFLOOD model we then disaggregated them across five macroeconomic sectors at NUTS-2 level.
3. Leveraging on LISFLOOD results we further deep dive into costs and benefits of four different adaptation options throughout Europe. These have been derived from a CBA perspective in (Dottori et al., 2023). In the last section of the deliverable we propose a methodology to translate the CBA results into macro-economic implications.
4. The direct damage assessment performed with the GLOFRIS model has been improved from a NUTS-2 to a NUTS-3 resolution.
5. GLOFRIS direct damages estimates are not only covering the residential sector but have been also extended to the private sector, disaggregated into commerce and industry.
6. GLOFRIS now includes more preset adaptation scenarios. The set of adaptation scenarios comprises of constant dike heights (the risk increases if the hazard increases), constant protection standards (the protection standards grow in tandem with the hazard), optimal protection standards (the protection standard level is optimised using a cost-benefit analysis, taking into account the risk and the costs of improving the protection standards), and zoning restrictions (limiting exposure growth in flood plains).

The results of these modelling exercises, expected annual damages and adaptation cost are delivered to macroeconomic models in Work Package 4 and will be made publicly available, along with the code used to generate the data. Furthermore the results inform local and regional case studies in Work Package 3, e.g. case studies CS1.2 and CS5.1.

2 Methods

2.1 Scenarios

2.1.1 Sea-level rise scenarios

GLOFRIS
In GLOFRIS, future Sea-Level Rise (SLR) is estimated using global mean sea-level rise projections from the RISES-AM project (Jackson & Jevrejeva, 2016; Jevrejeva et al., 2014), of which the 50th percentile serves as the baseline projection, while the 5th and 95th percentiles are used for sensitivity analysis (Tiggeloven et al., 2020). These SLR scenarios are used in combination with subsidence level estimates due to groundwater extraction from the SUB-CR model (Kooi & Erkens, 2020).

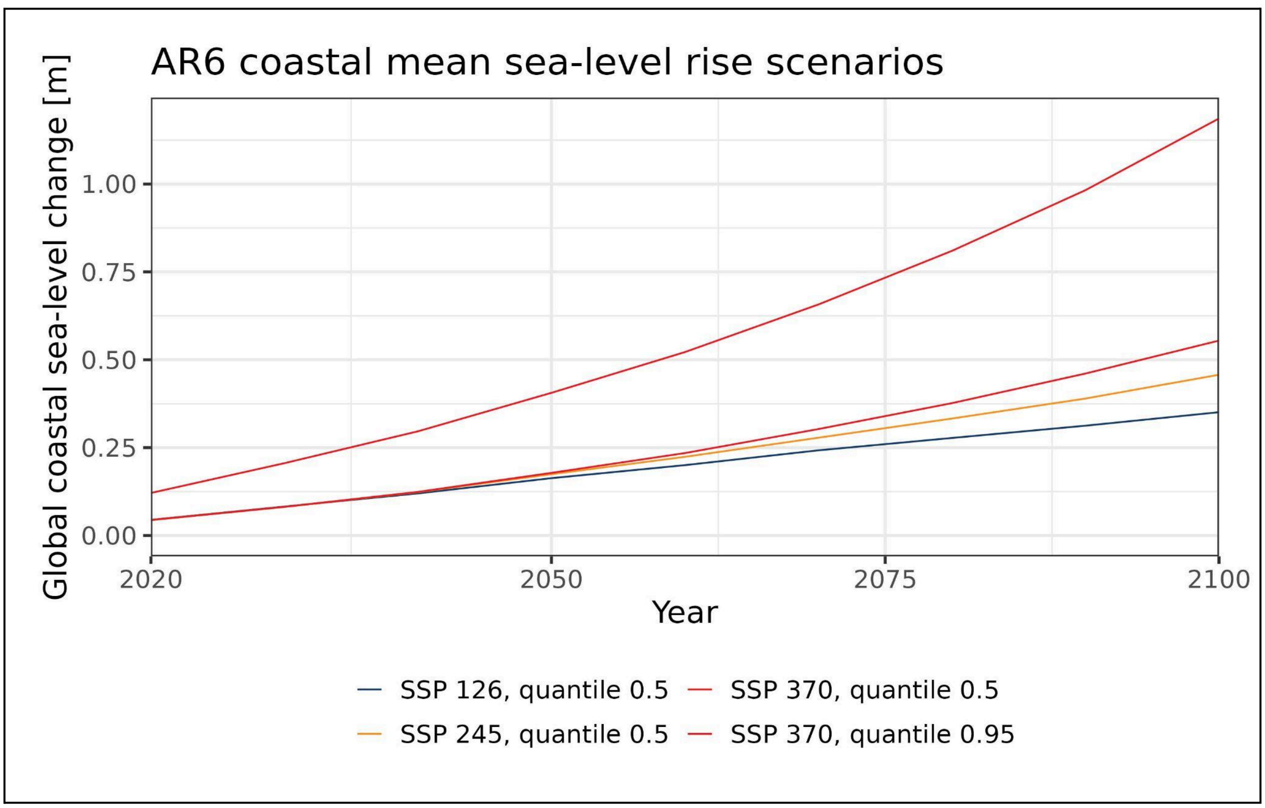

Figure 1: Global coastal mean sea-level change as provided by the AR6 scenarios.

DIVA
For the coastal impact simulations with DIVA the latest AR6 SLR scenarios were used (Fox-Kemper et al., 2021). The scenarios were generated using climate forcing from Coupled Model Intercomparison Project (CMIP6 - Eyring et al., 2016). These scenarios provide regionalised SLR projections (1x1° grid) up to 2100. While full uncertainty is provided by these scenarios (107 percentiles), in ACCREU we use only the 50th percentile of SSP126, SSP245 and SSP370, and as a high-end scenario the 95th percentile of SSP370.

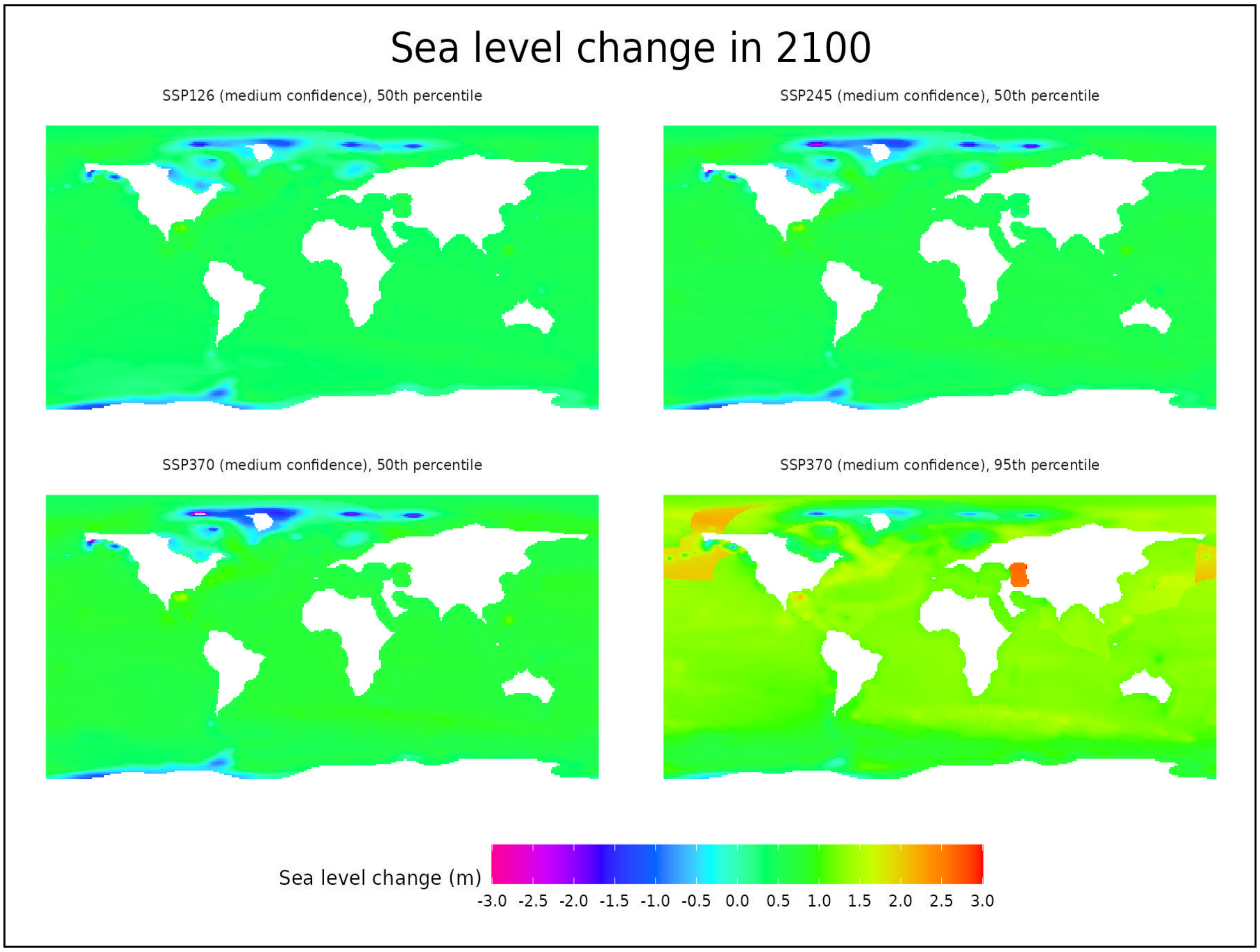

Figure 2: Regional pattern of sea-level change (in 2100) as provided by the AR6 scenarios.

2.1.2 Socioeconomic scenarios

In accordance with the scenario implementation outlined within the ACCREU project, all presented impacts are computed for the shared socioeconomic pathway SSP2. This represents a middle-of-the-road scenario of socioeconomic development with medium economic growth and medium population growth rates, that follows historical patterns and plateaus in the middle of the century. This scenario poses moderate challenges to adaptation (O'Neill et al., 2017). The socioeconomic exposure used in DIVA and GLOFRIS is driven by the economic growth and population growth rates from the "Shared Socioeconomic Pathways Scenario Database" provided by IIASA (Riahi et al., 2017)[1]. The rates of economic growth follow the OECD interpretation of the SSPs. For SSP2 in Europe, we observe a declining growth trajectory. While GDP growth for

[1] SSP scenario database: https://iiasa.ac.at/models-tools-data/ssp

the EU27+UK&Norway averages roughly 2% per year in 2010 it gradually declines to around 1% on average by the end of the century (see Figure 3).

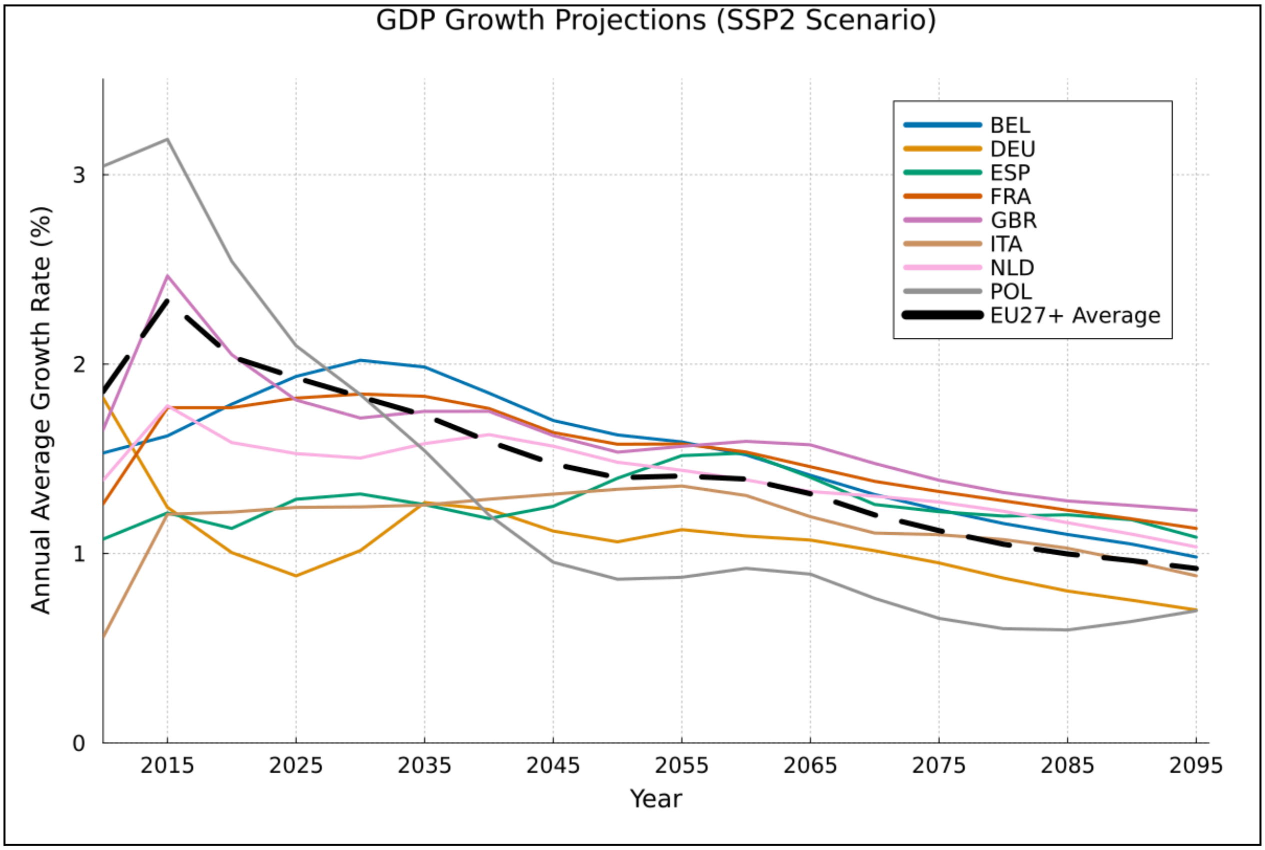

Figure 3: GDP growth rates for 7 largest countries of EU27 + UK&Norway and the average growth of EU27+UK&Norway for SSP2

2.1.3 Adaptation scenarios

In the macroeconomic models of WP4 in ACCREU, different adaptation scenarios are considered. The low adaptation scenario assumes that society's adaptive capacity is constrained. Technological progress and diffusion of technologies for example are inhibited, trade is reduced or there are institutional barriers that prevent effective adaptation. The medium adaptation scenario represents a business as usual or “middle-of-the-road” adaptive capacity, while the high adaptation scenario assumes higher adaptive capacities through increased trade and technological progress and diffusion. These scenario assumptions are translated into the sectoral models DIVA, GLOFRIS and LISFLOOD as shown in Table 1.

For the assessment of coastal flooding, DIVA and GLOFRIS employ similar adaptation scenarios.

1. Medium scenario (reference): Coastal planners pursue a business-as-usual protection strategy in which protection levels are kept constant. Dikes grow with sea-level rise in this scenario, but may not be optimal. DIVA allows for migration and it is modelled as permanent coastal retreat of people and assets as soon as they fall in the 1-in-1-year floodplain.
2. Low adaptation scenario: No additional coastal protection compared to present is built. Protection (dike) height is kept constant at the level at which the models are initialised.

The existing protection height depends on input data and assumptions that will be discussed in Section 2.3. Dikes that are overtopped permanently do not provide any protection anymore. Migration in DIVA is allowed, such that people and assets migrate from floodplains that become uninhabitable.

3. High adaptation scenario: Coastal planners in this scenario are most proactive, employing cost-benefit analysis to assess optimal protection levels. Overall coastal impacts, the sum of residual damages and adaptation cost, are minimised with respect to coastal protection. For some floodplains dike height may be higher in the reference scenario, however at suboptimal levels. Migration in DIVA is still allowed (and migration costs are included in the cost-benefit calculation).

Table 1: Accreu adaptation scenario implementation

Model	**Scenario**	**Technology & Trade**	**Adaptation options**	**Adaptive capacity**
DIVA (coastal flooding)	**No/Low adaptation**	Does not apply	Seadikes and (autonomous) migration from 1-in-1 year floodplain	No additional protection, constant dike heights. Dike might be permanently overtopped (and thus losing their protection functionality). Migration/retreat is an option.
	Medium adaption	Does not apply		business-as-usual coastal protection (keep protection level constant - dikes are raised with sea-level). Migration/retreat is an option.
	High adaptation	Does not apply		Cost-benefit optimal protection. Migration/retreat is an option..
GLOFRIS (coastal & riverine flooding)	**No/Low adaptation**	Does not apply	Dike strengthening (based on protection standards); floodplain zoning restrictions; increased foreshore vegetation (coastal only)	No additional protection, constant dike heights.
	Medium adaption	Does not apply		Business-as-usual coastal protection (keep protection level constant - dikes are raised with sea-level).
	High adaptation	Does not apply		Cost-benefit optimal protection. Investments in protection standards can be combined with floodplain zoning restrictions and/or foreshore vegetation (coastal).

LISFLOOD (riverine flooding)	**No /Low adaptation**	Does not apply	Dikes strengthening; Retention areas; Flood proofing of building; Relocation	Current protection level
	Medium adaptation	Does not apply		Implementation of private incremental adaptation, e.g. flood proofing of buildings / or 50% of the damage reduction obtained in the high adaptation scenario
	High adaptation	Does not apply		Implementation of the highest damage reduction possible, e.g. perfect decision making among the four adaptation options available

Due to the model features, the assessment of river flooding in LISFLOOD characterizes adaptation scenarios in a slightly different way. The four adaptation options considered (dike strengthening, retention areas, flood proofing of buildings and relocation) are optimised on an individual basis, forming four independent scenarios. In the context of ACCREU, to harmonise and aggregate results of multiple sectoral models, we propose to develop adaptation scenarios for different levels of implementation by combining the different adaptation options as follows. A no adaptation scenario assumes only the maintenance of current protection measures. A low adaptation scenario isdeveloped under the assumption that only private adaptation takes place by implementing flood proofing measures to buildings. As per the results presented below, flood proofing buildings delivers a low level of adaptation benefits even when optimally implemented. A medium adaptation scenario is implemented assuming adaptation can achieve 50% of the damage reduction of the high adaptation scenario. Finally, a high adaptation scenario assumes combining all the different adaptation options based on the principle of optimizing the cost-benefit performance of the mix . Throughout the entire study area this effectively corresponds to an optimal combination of dikes strengthening and retention areas.

2.2 Models and new developments

2.2.1 Model

Three different models are used for the assessment of impacts on infrastructure and the built environment. For coastal flooding, both a redesigned version of the Dynamic Interactive Vulnerability Framework (DIVA) as well as the GLOFRIS model, estimate impacts across a range of climate, socioeconomic and three distinct adaptation scenarios. River flood impacts are modeled by GLOFRIS and LISFLOOD. In section 2.3 an extensive comparison of the model design, the underlying assumptions and datasets is performed. The next subsections describe each of the models in detail.

2.2.2 GLOFRIS

GLOFRIS is a grid-based global flood risk model (Tiggeloven et al., 2020; Ward et al., 2017; Winsemius et al., 2016) that runs at a spatial resolution of 30” x 30” (roughly 1km x 1km). The model calculates flood damage estimates for several return periods (2, 5, 10, 25, 50, 100, 250, 500 and 1000 years) and can calculate flood damage estimates for riverine and coastal floods. Using GLOFRIS, flood risk is estimated as an expected annual damage (EAD), as this provides a more average statistic for flood risk management than the absolute damage that occurs for a certain exceedance probability. The EAD is calculated by taking the integral of the probabilities where protection standards (Scussolini et al., 2016) are exceeded, multiplied by the damage that a certain exceedance level causes.

GLOFRIS model improvements in the ACCREU project

New developments of GLOFRIS in ACCREU are the improved spatial resolution from a NUTS2 level to to a NUTS3 level, the estimation of coastal flood risk in addition to riverine flood risk, EAD estimates for the commercial and industrial sector alongside residential EAD, and the inclusion of more adaptation scenarios (constant dike heights, constant protection standards, optimal protection standards, exposure reduction via zoning restrictions, and the conservation of saltmarshes (coastal only)). The next sections explain how GLOFRIS calculates the EAD for riverine and coastal floods at a NUTS3 level.

Riverine flooding

The riverine flood risk setup is similar to the setup presented in COACCH (Lincke et al., 2019), with the difference that the EAD is now computed at a higher spatial resolution (NUTS3 instead of NUTS2). Baseline flood risk is estimated by modeling daily water levels per river basin using a global hydrological model, forced with historical maximum flood volumes from 1960-1999 (Ward et al., 2017). A Gumbel distribution is applied to estimate flood volumes for various return periods. Future flood hazards are projected using bias-corrected climate data from CMIP5 models, aligned with RCP scenarios. Projections are based on 40-year averages for specific future periods: 2010-2049 (2030), 2030-2069 (2050), and 2060-2099 (2080) (Ward et al., 2017). The flood hazard is combined with urban density data taken from the HYDE database (Klein Goldewijk et al., 2011). The urban density accounts for the exposure element of risk. Per gridcell that is considered as built-up area, each urban density type considered has a corresponding percentage (75% residential, 15% commercial, and 10% industrial), and a corresponding maximum damage. For each urban density type, a corresponding vulnerability curve is used to represent the percentage of maximum value lost for each inundation level (Huizinga et al., 2017). The urban density data of future periods comes from the GISMO/IMAGE model (Bouwman et al., 2006), using the method of (Jongman et al., 2012) using shared socioeconomic pathways (SSPs) (Riahi et al., 2017) taken from the IIASA SSP database.

Coastal flooding

Coastal flood risk is estimated using a similar risk framework as for riverine flooding. The hazard comes from sea level rise scenarios and hydrodynamic simulations of tide and surge (Tiggeloven et al., 2020). Exposure and vulnerability are calculated in a manner similar to the riverine risk estimation, using the HYDE database and vulnerability curves. Future coastal flood hazard is estimated using future sea levels from the RISES-AM project (Jevrejeva et al., 2014).

Coastal inundation hazards are modeled using global sea level data, combining surge simulations from atmospheric reanalysis with tidal influences from hydrodynamic models (Tiggeloven et al., 2020). Historical cyclone data is used to generate storm-driven water levels, which are integrated with sea level records to capture peak inundation risks at each location (Tiggeloven et al., 2020). The model uses the Multi-Error-Removed Improved-Terrain (MERIT) DEM .

Adaptation

GLOFRIS comes with 5 pre-set adaptation options: constant dike heights, constant protection standards, optimal protection standards, foreshore vegetation, and zoning restrictions. Constant dike heights means that the protection standards used remain constant over time. This leads to an increase in risk over time, as a dike that protects against flooding with a certain return period will get overtopped more often if the flood hazard increases. Constant protection standards mitigates this problem by letting the dikes grow in tandem with the hazard. This means that a dike that protects against a certain return period in 2010 is increased if the water-level associated with this return period increases in the future. Optimal protection standards take the costs and benefits of protection standards into account, the protection standards are chosen such that the Net Present Value (NPV) is maximised (Ward et al., 2017) over the period 2020-2080. To determine optimal protection standards, benefits are assessed up to 2080, while the investment and associated costs occur over the period 2020-2050. Over the period 2020-2050, costs and benefits accrue over 5-year timesteps. Total benefits are, then, reduced flood risk over the period 2020-2080, while total costs are investment costs made over the period 2020-2050. Costs and benefits are discounted at a rate of 5% to obtain the NPV.

Besides investments in protection standards (i.e., dykes and levees), GLOFRIS assesses costs and benefits of several other types of flood risk adaptation measures. Foreshore vegetation is an adaptation technique to reduce the risk of coastal flooding (Tiggeloven et al., 2022). This adaptation measure entails the conservation of salt marshes, which limit the impact of waves on coastal flood risk. The final pre-set adaptation option is a floodplain zoning restriction, which entails that future urban development is restricted in areas that will be inundated by a flood with a return period of 1/1000 by 2080 (Mortensen et al., 2023). The 5 adaptation measures are pre-set, meaning that for each adaptation measure there is a separate GLOFRIS run. For each adaptation measure, risk estimates for the baseline (2010), 2030, 2050, and 2080 are available, as well as aggregate cost and benefit statistics over the period 2020-2080.

2.2.3 DIVA

As part of the ACCREU project, the Dynamic Interactive Vulnerability Framework (DIVA), which has been used extensively in assessments of coastal flood impacts and coastal adaptation in predecessor projects, was completely redeveloped. This includes a much finer spatial resolution (about 143,000 local floodplains - see Fig. 4 for all European floodplains and Fig. 5 for a more detailed illustration of floodplains in the North Sea - and 744,000 coastal segments). Floodplains are determined as hydrologically connected areas below local 1-in-100 year water levels with additional 2m sea-level-rise allowance taken from COAST-RP (Dullaart et al., 2021), taking into account administrative boundaries. Underlying administrative units are NUTS2 (Europe) resp. GADM1 (Non-Europe).

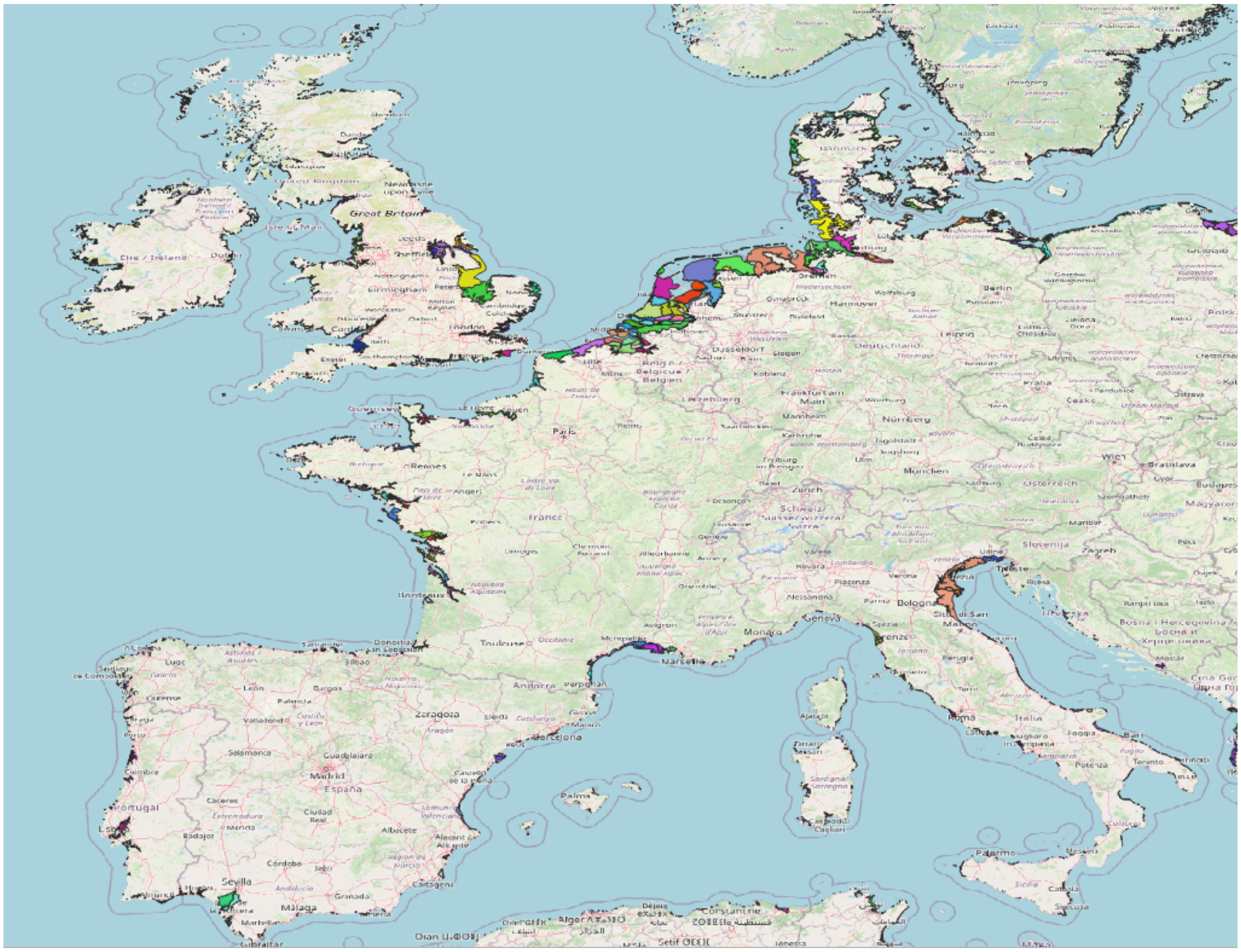

Figure 4: DIVA floodplains in Western Europe

Population exposure for each floodplain/segment is obtained by overlaying digital elevation data from meritDEM (Yamazaki et al 2017) with gridded population data from the Global Human Settlement Layer (Carioli et al., 2023). Asset exposure is calculated by scaling local population data with 2.8 times local GDP per capita which is obtained from high resolution gridded gross domestic product data (Kummu et al., 2018). Initial protection levels are estimated according to a generic rule based on GDP per capita and population density (Sadoff et al., 2015).

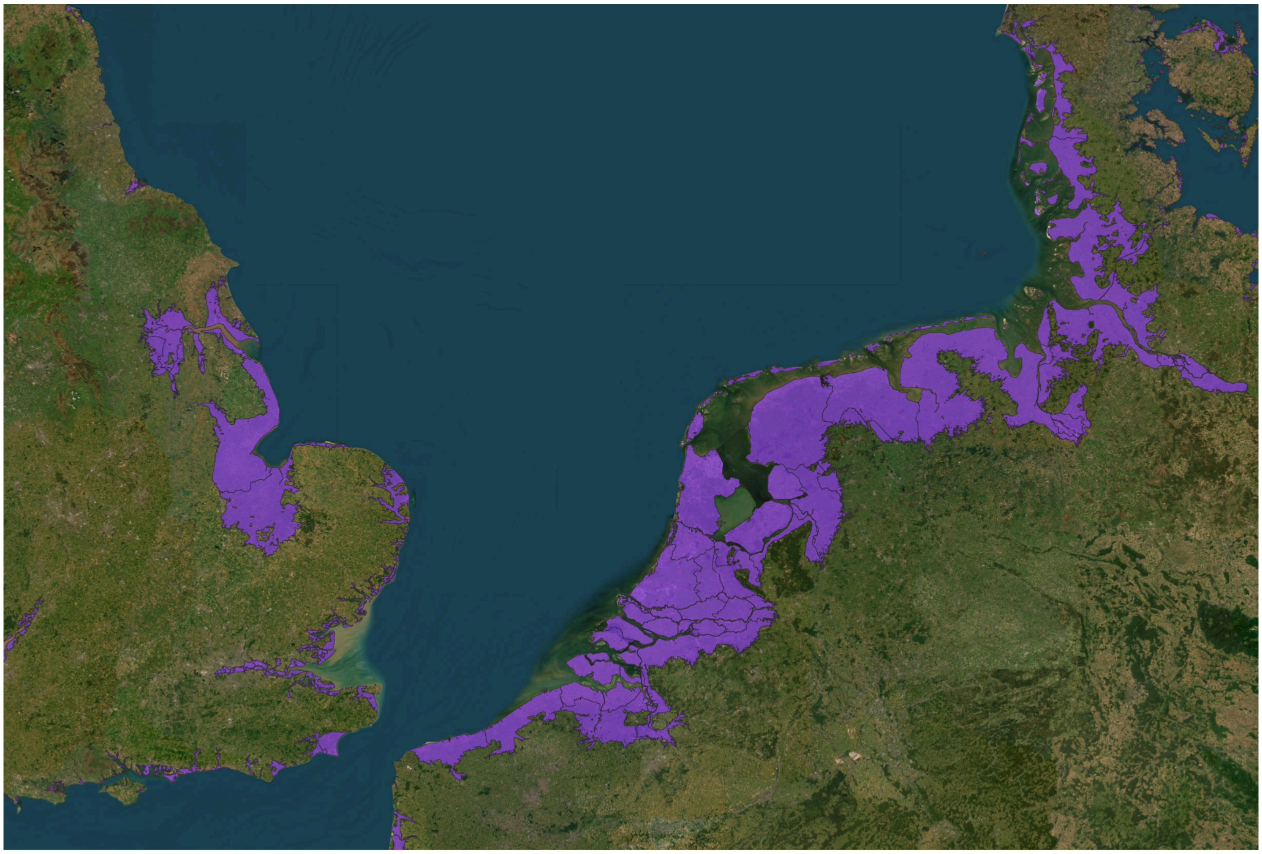

Figure 5: DIVA floodplains in the North Sea

2.2.4 LISFLOOD

LISFLOOD is a distribution, physically based hydrological model run at 5 km grid resolution (Van Der Knijff et al., 2010). In simple terms, the model first translates precipitation data into river discharge and water level data. Combining data on river discharge and terrain elevation, inundation levels are then modeled for a range of return periods from 10 to 500 years using two-dimensional hydraulic simulations with the LISFLOOD-FP model, run with a 100 m resolution. To account for climate change, the LISFLOOD model is run for an ensemble of climate scenarios. In the presence of climate change, future flood impacts are expressed in terms of shifted frequency at which a flood event happens. In each scenario, the expected annual damages are estimated by combining three sources of information, namely depth-damage functions, the current level of flood protection and the different types of land use exposed. No new LISFLOOD model runs were performed as part of the ACCREU project.

2.3 Comparison of modeling frameworks

This section provides a detailed comparison of the modeling approaches and underlying assumptions of the three models applied in this deliverable. The comparison is structured around key areas: general model differences, exposure, flood propagation, damage assessment, and adaptation strategies. The goal is to highlight critical distinctions in model assumptions, such as initial protection levels, asset valuation within floodplains, and depth-damage functions, to identify potential drivers behind the models' outcomes. Understanding these differences allows us to more accurately interpret variations in model results.

2.3.1 General model characteristics

The three models each offer unique strengths based on their intended focus and geographic scope summarised in Table 3. GLOFRIS and DIVA are both global models. GLOFRIS simulates both river and coastal flooding, DIVA specialises in coastal flooding, particularly in assessing sea-level rise impacts and coastal adaptation. For hydrology it leverages a high resolution (3arcsec x 3arcsec - corresponding to roughly 90x90m at the equator) digital elevation model. This specialization allows DIVA to provide detailed insights into coastal dynamics that are valuable for understanding long-term coastal risks. In contrast, LISFLOOD is focused on European-scale river flooding, benefiting from a high spatial resolution of 100m that allows for precise representation of river networks and floodplains within Europe. The regional focus of LISFLOOD and its high-resolution inundation maps for Europe make it best suited for detailed flood assessments in European river basins (Van Der Knijff et al., 2010; Alfieri et al., 2016).

With respect to the objectives set out in ACCREU, for DIVA we implemented the latest CMIP6 driven sea-level rise scenarios based on the IPCC's AR6. Those are linearly combined with COAST-RP extreme water levels to assess coastal flooding impacts (Dullaart et al., 2021). GLOFRIS scenarios are based on CMIP5 and LISFLOOD uses the regional model ensemble EURO-CORDEX, combining 11 global (GCMs) and regional (RGMs) climate models to produce high resolution projections for Europe. The climate models are described in (Jacob et al., 2014).

2.3.2 Exposure

Glofris and DIVA substantially differ in how exposure variables are spatially represented. While Glofris uses a grid-based approach, in DIVA the coast is divided into coastal floodplains supplemented with segments based on morphological and socioeconomic characteristics (see Section 2.2.3 for the segmentation methodology) which aggregates the gridded exposure data. Furthermore, the population and GDP data for both DIVA and LISFLOOD is spatially resolved at 100x100m, while GLOFRIS exposure is resolved at around 1x1km (30x30 arc seconds).

The three models use different methodologies in order to assess asset values in flood plains. Asset value in DIVAs coastal segments are determined by multiplying GDP per capita, population, and an empirical asset to GDP ratio of 2.8 (Hallegatte et al., 2013). To estimate asset values in GLOFRIS, the HYDE database (Klein Goldewijk et al., 2011) is used to assess the share of each spatial cell that is built up. This "urban area" is assumed to consist of 75% residential buildings, 15% commercial buildings, and 10% industrial buildings, based on BPIE (2011) and EEA (2016). The economic value of urban areas is assessed using country-level GDP per capita. Future built-up area is simulated based on SSP-data, using changes in population count and relative urbanization obtained from the GISMO/IMAGE model (Bouwman et al., 2006). The differentiation of damages between building types is derived from Huizinga et al. (2017).

These differences in the underlying datasets and the calculation of asset exposure introduce a significant source of uncertainty into the economic assessment of flood damages. The exposure within the 100-year floodplain (H100) for example exhibits large discrepancies between the DIVA and GLOFRIS models. DIVA consistently uses higher GDP values than GLOFRIS across all examined countries (Table 2). The average GDP exposed within H100 for the seven largest EU economies and the United Kingdom is more than twice as high in the DIVA model (136,557 million US$) compared to GLOFRIS (66,553 million US$). This disparity is particularly pronounced in some countries - in Spain, for instance, DIVA estimates GDP exposure at 10,852 million US$, more than three times GLOFRIS's estimate of 3,076 million US$, while in the UK, the exposed GDP in DIVA (145,226 million US$) is 2.5 times higher than in GLOFRIS (58,914 million US$). The Netherlands shows the largest absolute difference, with DIVA estimating 752,394 million US$ of exposed GDP compared to GLOFRIS's 358,651 million US$ - a difference of nearly 400 billion US$.

Interestingly, the pattern somewhat reverses for population exposure. While GDP exposure is consistently higher in DIVA, population exposure tends to be higher in GLOFRIS for most countries. GLOFRIS estimates an average of 1.63 million people exposed within H100 compared to DIVA's 1.35 million. This contrast is particularly evident in Belgium, where GLOFRIS estimates nearly twice the exposed population (618,167) compared to DIVA (343,789). The Netherlands again shows the largest absolute numbers, with GLOFRIS estimating 8.23 million exposed people compared to DIVA's 6.82 million. However the difference in population exposure is overall much less pronounced than for GDP exposure, and estimates for some countries, such as the UK, are almost identical between the two models.

Table 2: Exposure in the 100 year floodplain in DIVA and GLOFRIS for 7 largest EU economies & UK

	GDP in H100 (Mio $)		**Population in H100**	
Country	**DIVA**	**GLOFRIS**	**DIVA**	**GLOFRIS**
BEL	31,728	27,754	343,789	618,167
DEU	93,416	51,907	1,004,243	1,296,902
ESP	10,852	3,076	146,518	110,925
FRA	33,407	18,834	499,481	688,123
GBR	145,226	58,914	1,618,542	1,617,101
ITA	19,951	9,795	246,943	293,746
NLD	752,394	358,651	6,818,717	8,226,930
POL	5,479	3,498	106,738	167,703
Average	**136,557**	**66,553**	**1,348,121**	**1,627,45**

2.3.3 Flood propagation (Hazard)

Flood propagation methods also highlight key differences between the models. Both GLOFRIS and DIVA use a simplified bathtub approach to model flood propagation. This method is computationally efficient and suitable for broad-scale assessments but lacks the precision required for detailed hydrodynamic processes. LISFLOOD stands out by employing a physics-based two-dimensional hydrodynamic model (LISFLOOD-FP) for simulating flood propagation. This computationally intensive approach allows LISFLOOD to provide greater accuracy, particularly for modeling flood dynamics in complex river systems and landscapes and makes it more suitable for analyzing flood propagation in smaller scale regions with intricate topographical and hydrological features.

Additionally different assumptions about initial protection levels between the models introduces another source of uncertainty. DIVA uses a stylised protection rule (Table 2) based on GDP and population density (Sadoff et al., 2015) which is complemented with information on protection levels of 136 large coastal cities (Hallegatte et al., 2013). In this rule, urban environments are protected against higher flood return periods, which are additionally increasing with respect to the income groups (measured in GDP per capita). Regions with a population density below 30 people/km² are assumed to be unprotected. The Netherlands is treated as a special case with a protection standard of a 1 in 10,000 year return period for the entire coastline (independent of population density). In GLOFRIS, protection standards are estimated using the FLOPROS database. FLOPROS is a database that contains protection measures with associated return periods for different spatial scales. The protection standards are taken from empirical information, policy regulations or are modelled using a validated modelling approach (Scussolini et al., 2016).

Table 3: Initial protection levels in DIVA

Income Group	Urban (>1000 people/km²)	Rural (30 to 1000 people/km²)
Low income	1:10	No protection
Lower middle income	1:25	No protection
Upper middle income	1:100	1:20
High income	1:200	1:50
Special cases		
Netherlands	1:10,000	
136 coastal mega-cities	Data from Hallegatte et al. (2013)	

2.3.4 Damage Assessment

When it comes to assessing damages, GLOFRIS and LISFLOOD rely on continent-specific depth-damage functions developed by Huizinga (2017). These functions estimate economic losses based on the depth of flooding and the type of assets affected, providing a standardised approach for estimating damages at a broad scale. LISFLOOD additionally introduces flexibility by incorporating damage assessments across multiple macroeconomic sectors with higher spatial resolution. This allows LISFLOOD to deliver a nuanced understanding of economic impacts across different regions and sectors, particularly in the European context, where economic activities and vulnerabilities vary significantly between countries. For the global assessment in DIVA, a logistic depth-damage function is applied to all assets, following Messner et al. (2007). As in GLOFRIS and LISFLOOD the damage function returns the fraction of assets damaged for a given flood depth. In the specific depth-damage function in DIVA a 1-m flood depth causes damage of 50% of the asset value. This type of depth-damage function has been applied in numerous global and regional assessments (Diaz, 2016; Fang et al., 2020; Hinkel et al., 2014; Kirezci et al., 2023). DIVA assumes the same depth-damage function for different countries and asset classes, which highlights the models focus on global assessments. This makes it less suited for granular, local or regional assessments. An implementation of national and sector-specific depth-damage curves is however possible for local analysis.

2.3.5 Adaptation model

The adaptation module of the three different models used in D2.1 reflect their different focuses and capabilities. GLOFRIS and DIVA model a range of different adaptation options for coastal flooding. DIVA specialises in coastal protection and coastal retreat scenarios. Nature-based solutions for DIVA are developed in T2.4 of ACCREU. Both the protection as well as the retreat levels in DIVA can be varied flexibly. GLOFRIS also offers flexible coastal protection via dikes, NBS (salt marshes) and zoning restrictions in order to reduce exposure in flood prone areas.

A key difference in how adaptation is handled by DIVA and GLOFRIS is the timing of adaptation implementation. In GLOFRIS, adaptation is pre-set, meaning that the model is initialised with one predetermined adaptation option that is then implemented at the beginning of the model run. For adaptation measures in GLOFRIS, it is assumed that the investment is made in 2020 and that the construction is finished in 2050, using a discount rate of 5%, operation and maintenance costs of 1% and an investment lifespan until 2100 (Tiggeloven, 2020).

DIVA on the other hand assesses all adaptation options at each time step (10 year intervals). Adaptation, such as dike heights, are thus implemented incrementally with changing flooding hazards. Both models offer the possibility to estimate optimal adaptation scenarios based on cost-benefit ratios of adaptation. While GLOFRIS focuses on optimal protection levels, DIVA is able to consider either optimal protection or the optimal mix of protection and retreat simultaneously.

For river flooding, LISFLOOD additionally provides a comprehensive set of adaptation measures like dike strengthening, retention areas, flood-proofing of buildings, and relocation. The GLOFRIS river module assesses the same adaptation options as the GLOFRIS coastal module, except for the improved foreshore vegetation measure, which only applies to coastal flood risk.

Table 4: Model comparison

	GLOFRIS	DIVA	LISFLOOD
Types of impacts	coastal flooding, river flooding	coastal flooding	river flooding
Model domain	Global	Global	Europe
Climate forcing	CMIP5	AR6 SLR scenarios (driven by CMIP6) and COAST-RP extreme water levels	EUROCORDEX, combination of 11 global (GCMs) and regional models (RCMs)

Baseline time range	1960-1999	Same as the SLR scenarios	1981-2010
Resolution hydrological model	0.5° x 0.5°	Local models (floodplains) with underlying 3” x 3” elevation data (90x90m at equator)	5 km
Resolution inundation maps	30” x 30” (arc seconds). About 1x1km	Inundation maps only implicitly available - if made explicit 3” x 3” (90x90m at equator)	100 m
Exposure			
Spatial representation of exposure	Inundated cells of rivers/coast	> 100k Coastline segments/Floodplains	Inundated cells of rivers, covering EU river network for a total length of 32 000 km
Resolution exposure data	30” x 30” (arc seconds). About 1x1km	100m	100m
Digital elevation model (DEM)	Multi-Error-Removed Improved-Terrain (MERIT) DEM (Yamazaki et al., 2017) at a 3″ × 3” resolution	Multi-Error-Removed Improved-Terrain (MERIT) DEM (Yamazaki et al., 2017) at a 3″ × 3″ resolution	DEM at 100 m resolution developed for the Catchment Characterisation and Modelling database (CCM; Vogt et al., 2007)
Coastline	Same as DEM	Same as DEM	n/a
Population / assets data or method for calculating assets data	Urban density maps (HYDE-database). Value of urban share of each grid cell is based on national GDP per capita	Population is obtained from Global Human Settlement Layer (GHS-POP), assets are function of GDP per capita and population	European population density map (Batista e Silva, F. et al., 2018) and the refined version of the CORINE Land Cover (Rosina, K. et al., 2020).
Method for overlaying DEM with Population data		Resampling	

Flood propagation (Hazard)			
Initial protection levels	FLOPROS (Scussolini et al., 2016)	Stylised adaptation rules based on GDP and population density (Sadoff et al., 2015)combined with data on 136 coastal cities (Hallegatte et al., 2013)	Combined information from (Jongman et al., 2014; Scussolini et al., 2016)
Flood propagation model	Bathtub	Bathtub	Reduced physics (two-dimensional hydrodynamic model LISFLOOD-FP)
Attenuation of landscapes/wetlands	A resistance factor to simulate the reduction in flood force land-inwards	Attenuation of wetlands considered in T2.4	n/a
Damage			
Depth-damage function	Country-specific depth-damage functions (Huizinga, 2007, 2017)	Analytic (dam = d/(d+h) where d is water depth and h a parameter defining the water depth that destroys 50% of the asset value - in this study h is set to 1.0)	Country-specific depth-damage functions (Huizinga, 2007, 2017)
Adaptation model			
Discount rate	Flexible (currently 5%)	Flexible (currently 3%)	Based on (Sartori et al., 2015) 5% for EU cohesion countries[2], 3% for the other Member States
Protection	Current dike-heights Keeping protection standards constant Optimal protection standards	Flexible protection standards (constant dike height, constant protection levels, optimal protection)	Dikes strengthening Flood proofing of buildings

[2] EU cohesion countries: Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Greece, Hungary, Malta, Lithuania, Latvia, Poland, Portugal, Romania, Slovenia and Slovakia

Accommodation	-	-	Retention / detention areas
Nature based solutions	Coastal wetlands	Coastal wetlands	Retention / detention areas
Setback zone	-	-	-
Relocation	Flood zoning restrictions	Flexible retreat levels of people and assets	Relocation of buildings

3 Results

3.1 Coastal flooding

3.1.1 Expected annual damages

DIVA

Estimated expected annual damages in DIVA are generally increasing over time across the different adaptation as well as sea level rise scenarios. In the no/low adaptation case (constant dike height) however, a significant drop in EAD emerges around 2080 under the extreme SLR scenario (RCP 7.0, 95th percentile) compared to the other climate scenarios (Figure 6).

This reduction is driven by the acceleration of SLR (increased hazard) toward the end of the century, which prompts a massive migration response in the DIVA model. Large-scale migration occurs in areas with both high exposure and high hazard, leading to a substantial decrease in exposure over the following decades and, consequently, a decline in EAD from 2080 onwards.
In fact, the EAD in 2100 in the high climate scenario are around 2 trillion US$ while in the lower scenarios they are around 5.5, 5 and 4 trillion US$ for RCP 7.0 median, 4.5 and 2.6 respectively.

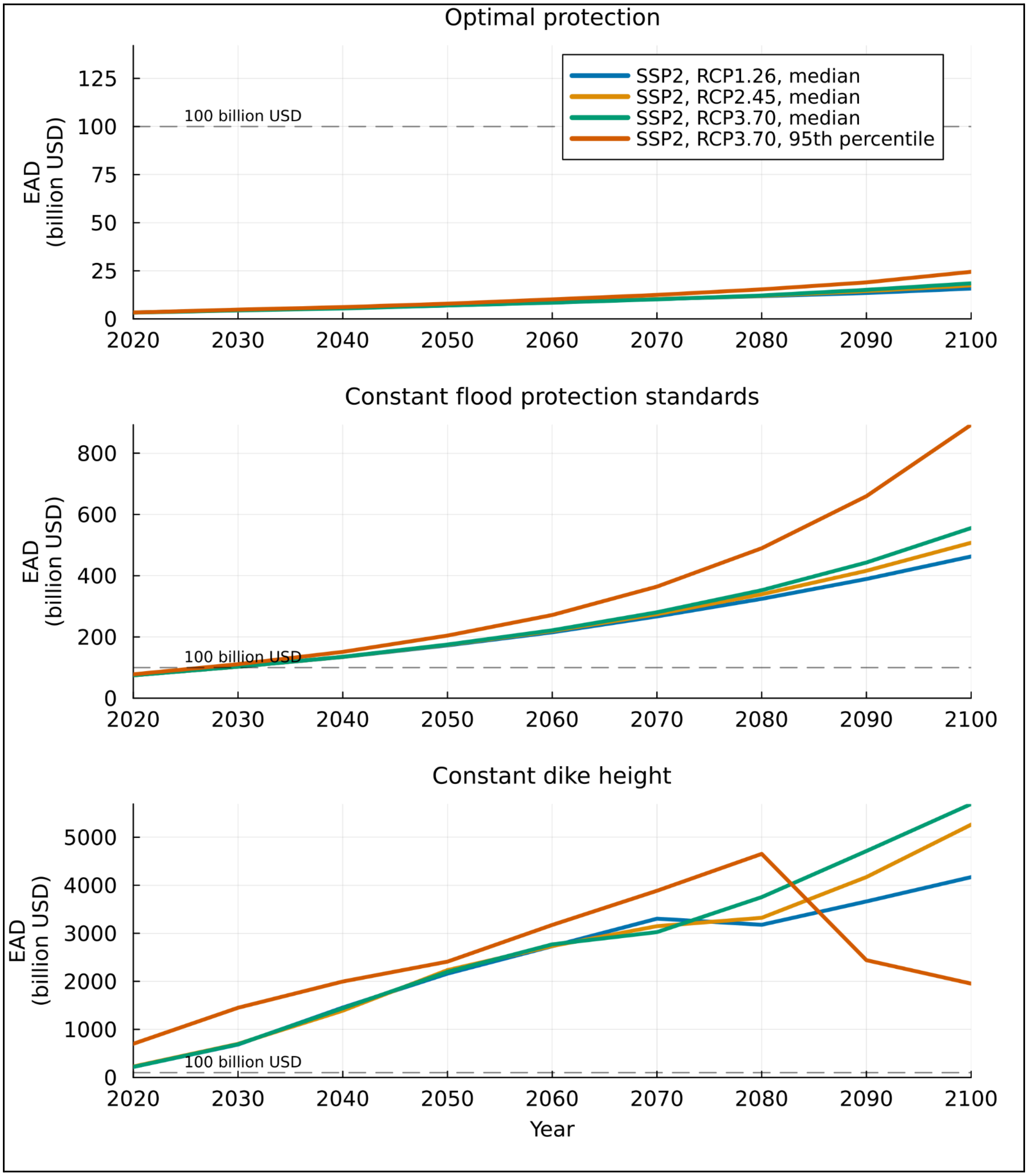

Figure 6: Global expected annual damages over time for different adaptation and SSP/RCP scenario combinations

The constant flood protection standards adaptation case shows an increase in EAD over time in all climate scenarios, reflecting the intensifying hazard as sea levels rise. The differences in damages between climate scenarios are driven by the growing impact of high-SLR conditions. Affluent, high-exposure areas adapt by upgrading dike heights to match the increasing hazard, ensuring that the same level of protection is maintained despite worsening conditions. In detail, the high SLR scenario produces around 850 billion US$ in flood damages at the end of the century while the lower scenarios produce between 600 and 400 billion US$ in damages.

The optimal protection adaptation case results in significantly lower damages compared to no adaptation and constant protection cases. In fact, in the high SLR scenario the damages by the end of the century are around 25 billion US$ (one order of magnitude lower than for constant protection levels and two orders of magnitude lower than constant dike height).
In this case, coastal planners allocate resources strategically, prioritising protection for areas with high exposure and hazard while reducing the investments in protection in regions with low exposure or low hazard.

The optimal protection adaptation strategy is significantly more effective in reducing the EAD caused by extreme SLR events compared to the constant protection strategy. Specifically, this approach reduces, on average, the EAD by one order of magnitude when compared to the application of a constant protection level adaptation strategy, which maintains the same level of protection regardless of evolving socio-economic and climatic conditions (Figure 6 and Figure 7). Moreover, the optimal strategy achieves a reduction in EAD by two orders of magnitude by the end of the century compared to the scenario where there is no adaptation, characterized by a fixed dike height that does not account for the increasing risks posed by SLR (Figure 7). The optimal protection strategy highlights the effectiveness of adaptation measures that take into account projected risks, as opposed to more dogmatic approaches that may leave infrastructure and communities more vulnerable to escalating hazards over time.

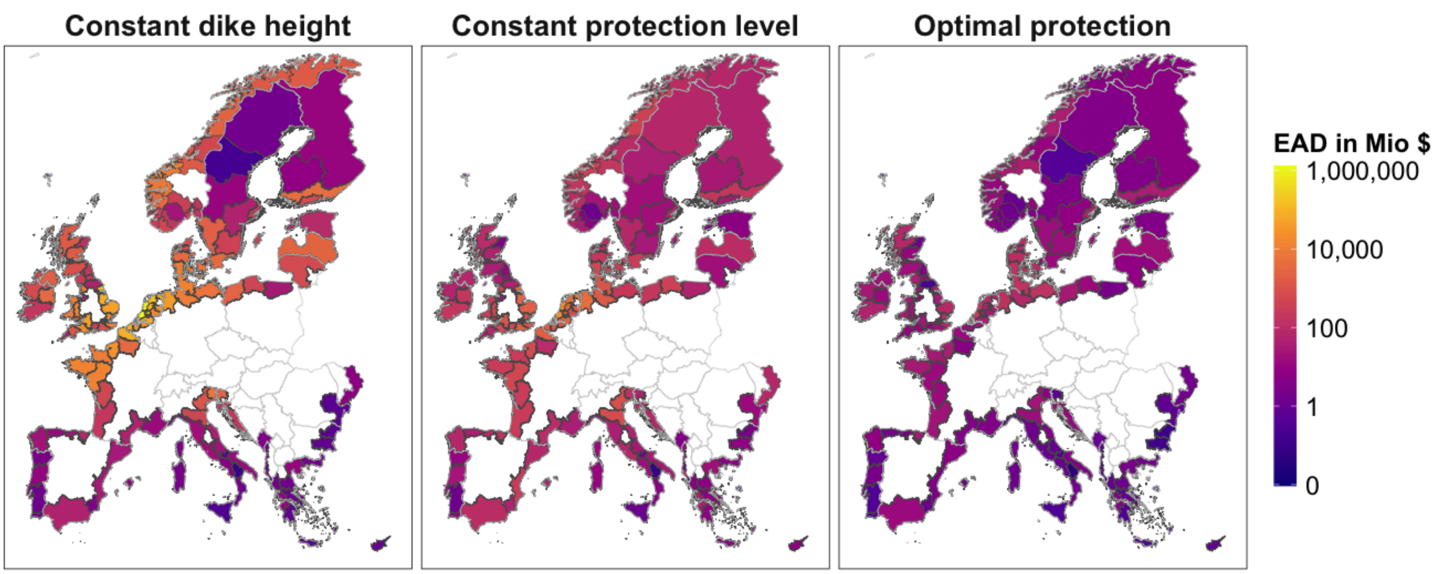

Figure 7: Expected Annual damages (EAD) in 2100 for different adaptation scenarios (SLR scenario RCP7.0, 95th quantile)

The migration effect in the no adaptation case, triggered by high SLR by the end of the century, is bigger in European countries having higher exposure, such as The Netherlands, the UK, Italy, France and Belgium (Table 5).

In several European countries, including the Netherlands, the UK, Norway, Sweden, Ireland, Greece, Lithuania, Estonia, Portugal, Cyprus, Bulgaria, and Romania, the migration effect is more pronounced under the optimal adaptation strategy compared to the constant protection case. This highlights that in the optimal protection scenario, some floodplains might not be protected which would be protected under the constant protection level strategy. For these floodplains protection is less cost-efficient (i.e., the cost of protection is higher than the flood damage plus the migration cost) than retreat through the century. This is likely because these floodplains have relatively low exposure. Consequently, in the optimal protection case, resources are prioritized towards protecting floodplains with higher exposure. This strategic relocation results in reduced protection for low-exposure floodplains, ultimately driving increased migration from these countries (Table 5).

Table 5: Expected Annual Damages in 2100 and Total Migration (2020-2100) for EU27+UK&Norway for all three adaptation scenarios (SSP2, RCP 7.0, 95th quantile)

	Constant Dike Height		**Constant Protection Level**		**Optimal Protection**	
Country	**EAD (M$)**	**Total Migration (people)**	**EAD (M$)**	**Total Migration (people)**	**EAD (M$)**	**Total Migration (people)**
NLD	789,346	7,201,033	104,215	327	942	1,322
GBR	422,322	1,764,341	23,638	18,821	772	21,640
DEU	347,079	86,672	11,295	31,196	659	13,147
DNK	2,747	182,554	2,495	30,033	624	26,272
NOR	797	220,356	2,254	7,190	292	19,969
SWE	4,311	86,710	1,032	10,867	235	11,855
FRA	2,637	809,334	5,579	60,564	195	16,860
IRL	502	72,978	662	5,881	74	7,161
FIN	3,361	40,100	531	5,490	72	3,035
ESP	269	284,480	1,351	26,101	68	24,225
BEL	9,253	508,599	6,454	0	64	0
ITA	1,254	413,070	3,062	25,290	61	10,858
POL	567	130,208	874	12,078	50	952
LVA	406	9,607	225	1,375	29	301
GRC	36	54,913	234	13,684	20	14,241
LTU	35	4,756	31	1,082	16	1,194
EST	19	1,041	19	813	15	893
PRT	46	15,840	106	3,138	15	2,627
HRV	33	34,756	116	1,136	15	5,195
ROU	4	5,987	33	1,438	4	1,483

SVN	51	9,169	79	1	1	16
BGR	3	7,559	18	793	1	347
CYP	1	5,458	15	1,049	0	2,206
MLT	0	53	0	47	0	6
Total	**1,585,080**	**11,949,574**	**164,317**	**258,393**	**4,223**	**185,805**

GLOFRIS

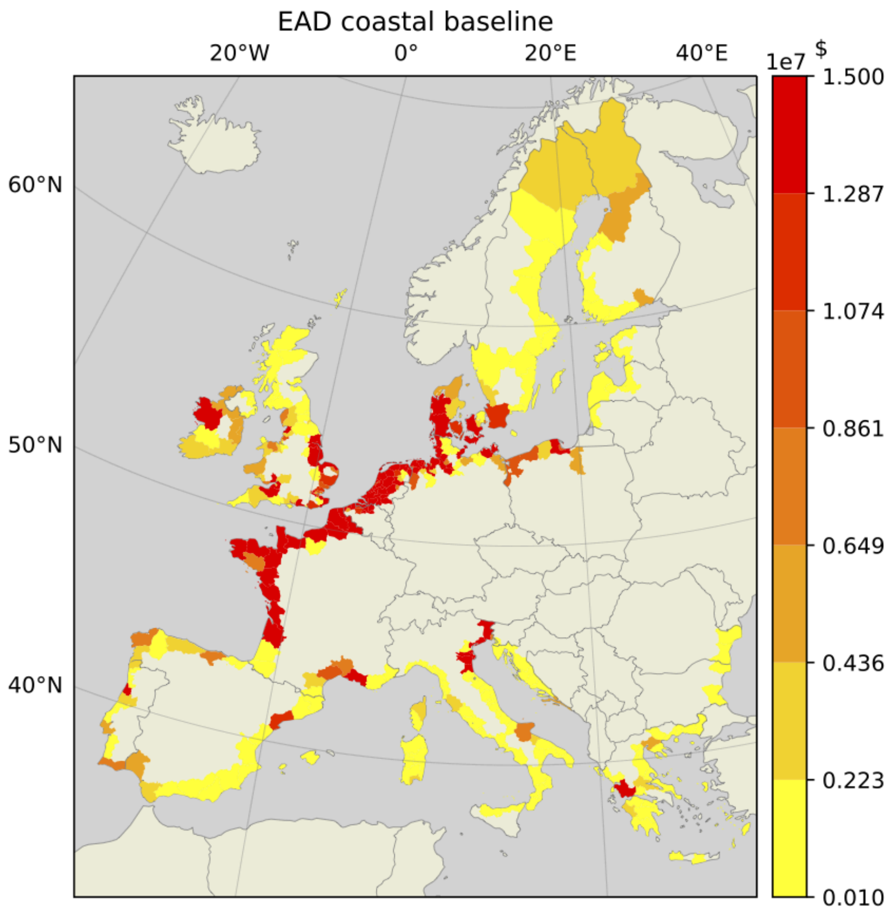

Figure 8: GLOFRIS projection of expected annual coastal flood damages in 2010, expressed in 2005 US Dollars.

Baseline coastal flood risk in GLOFRIS is projected in Figure 8 for the EU27+UK. Annual expected flood damages as a result of coastal storm surges is highest on the continental Northwestern European coast, stretching from France to Denmark. On a country-level, highest annual damages are found in the Netherlands, where EAD is approximately $1.8 billion. With its extensive coastline, the UK faces the second highest coastal EAD, which is close to $600 million. It can be seen that for the UK, this risk is largely driven by high impacts at the narrow end of the North Sea (Southeastern UK), and in the Channel of Bristol. After the Netherlands and the UK, coastal EAD is highest in France, where it is estimated at close to $500 million.

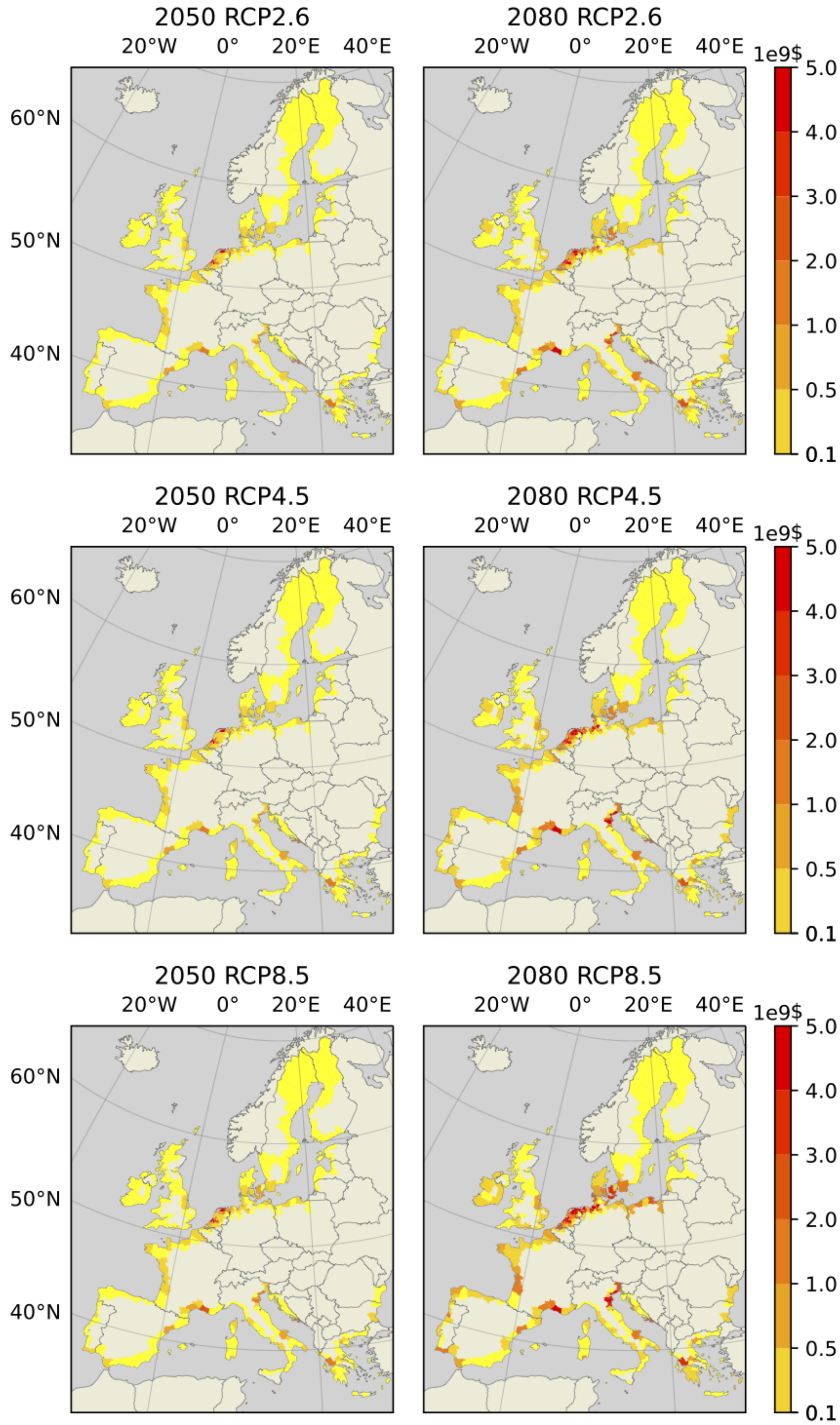

Figure 9: Expected annual coastal flood damages in 2050 (left column) and 2080 (right column) for three RCPs, considering no adaptation.

Table 6: Expected annual damage from coastal flooding for the EU27+UK considering no adaptation.

	2010	**2030**	**2050**	**2080**
RCP2.6	4.5 ($ bln)	11.5 ($ bln)	107 ($ bln)	223 ($ bln)
RCP4.5	4.5 ($ bln)	11 ($ bln)	109 ($ bln)	274 ($ bln)
RCP8.5	4.5 ($ bln)	12 ($ bln)	126 ($ bln)	395 ($ bln)

Table 6 and Figure 9 present the development of annual expected coastal flood damages over time, for varying levels of global warming, considering current socioeconomic conditions and no adaptation. It can be seen that coastal flood risk increases steadily over time and for increasing greenhouse gas concentration pathways. An interesting observation is that flood impacts increase most rapidly in low-lying coastal areas, such as the Netherlands, Northern Germany, the Northern Adriatic coast of Italy, and around the urban center of Marseille.

3.1.2 Adaptation cost

DIVA

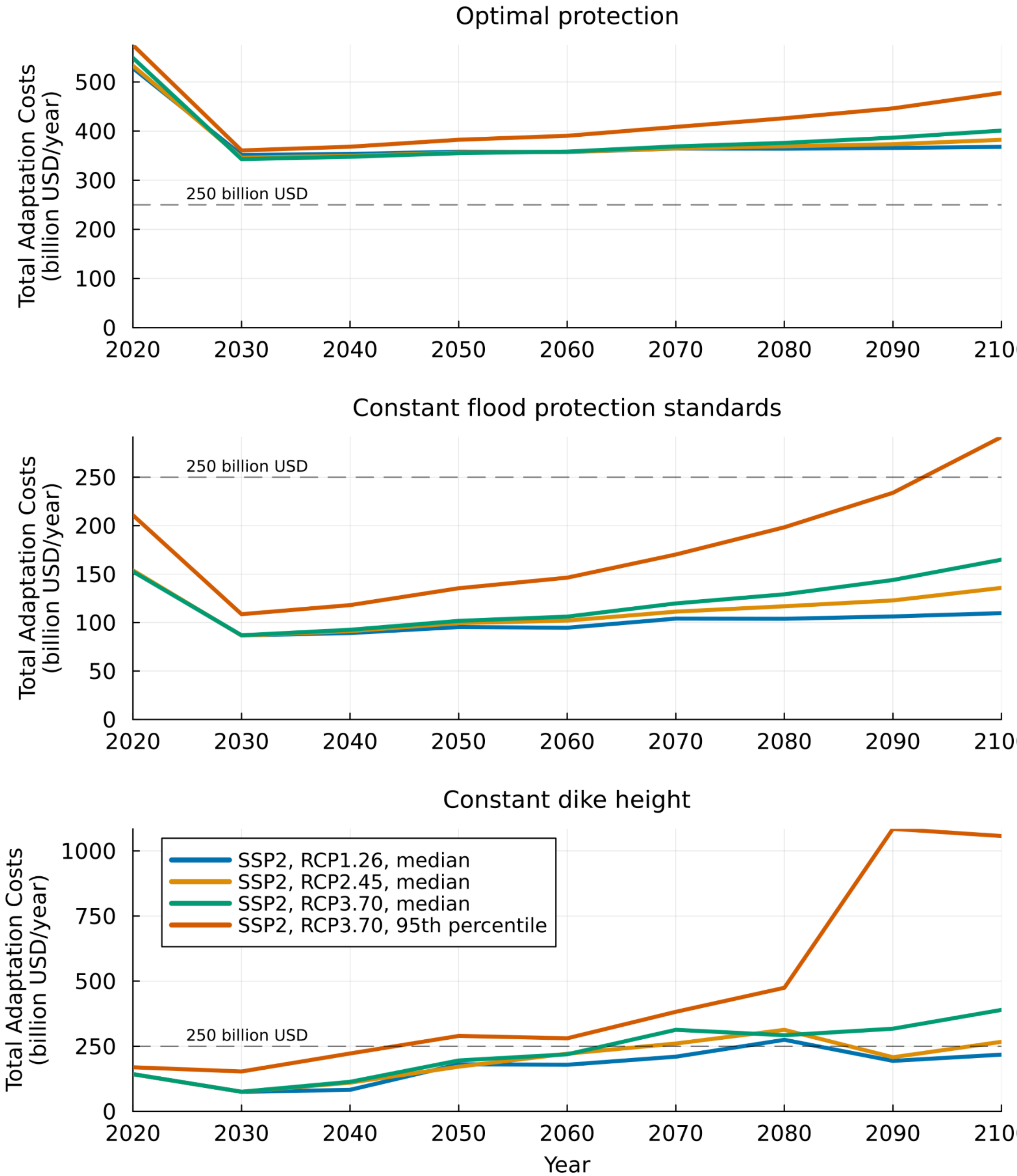

Figure 10: Global total adaptation costs over time per sea level rise and adaptation scenario. Total adaptation costs include the dike investment costs, maintenance costs and migration costs.

Adaptation costs in DIVA encompass both the costs of dikes (annualised investment and maintenance cost) and the annualised cost of migration, if migration is switched on. Costs are roughly in the same order of magnitude for all three adaptation scenarios. Optimal protection exhibits the highest cost at the beginning of the century and, after an initial drop, increases only marginally. Constant protection levels, representing medium adaptation, have the lowest total adaptation costs. Similar to optimal protection, costs first experience a drop after 2020 from roughly 200 billion US$/year to 100 billion US$/year. Subsequently the rise is gradual until the previous high point is reached again at the end of the century.

The development of the adaptation costs in the low adaptation scenario with constant dike height behaves differently from that. Costs start off at a relatively low level, but increase by almost an order of magnitude towards the end of the century, at least for high sea level rise. This increase is mainly driven by the cost of migration. At the beginning of the century adaptation cost is overall decreasing in this scenario, due to the fact that no new protection is built and permanently overtopped dikes are removed from the local impact models, no longer incurring any maintenance cost. After 2030 this effect is offset by the increase in hazard in the floodplains. Increasingly more people fall into the 1-in-1 year floodplain which triggers costly retreat. The sharp increase in adaptation cost in the high sea level rise scenario (RCP7.0, 95th quantile) from 2080 on, is explained by failing defences of larger urban areas which subsequently fall into the 1-in-1 year floodplain. This is analogous to the drop in expected annual damages in the high sea level rise scenario for constant dike height. Lower sea level rise scenarios still cause roughly a twofold increase in total adaptation costs, retreat happens more smoothly though.

The higher costs in the optimal protection scenario are compensated by the drastic reduction of expected annual damages (see Figure 6). While adaptation costs in 2100 reach up to 500 billion US$/year, EAD are an order of magnitude lower, just reaching up to 25 billion US$/year. For constant protection levels this is inverted, with EAD reaching up to 800 billion US$/year and adaptation costs only 250 billion US$/year. This suggests that the more actively managed adaptation of optimal protection, based on cost-benefit analysis, is efficiently building protection where it is most needed to minimise overall flood costs. It also suggests that the current protection levels are far from optimal, likely with some coastal areas being over- and others underprotected.

GLOFRIS

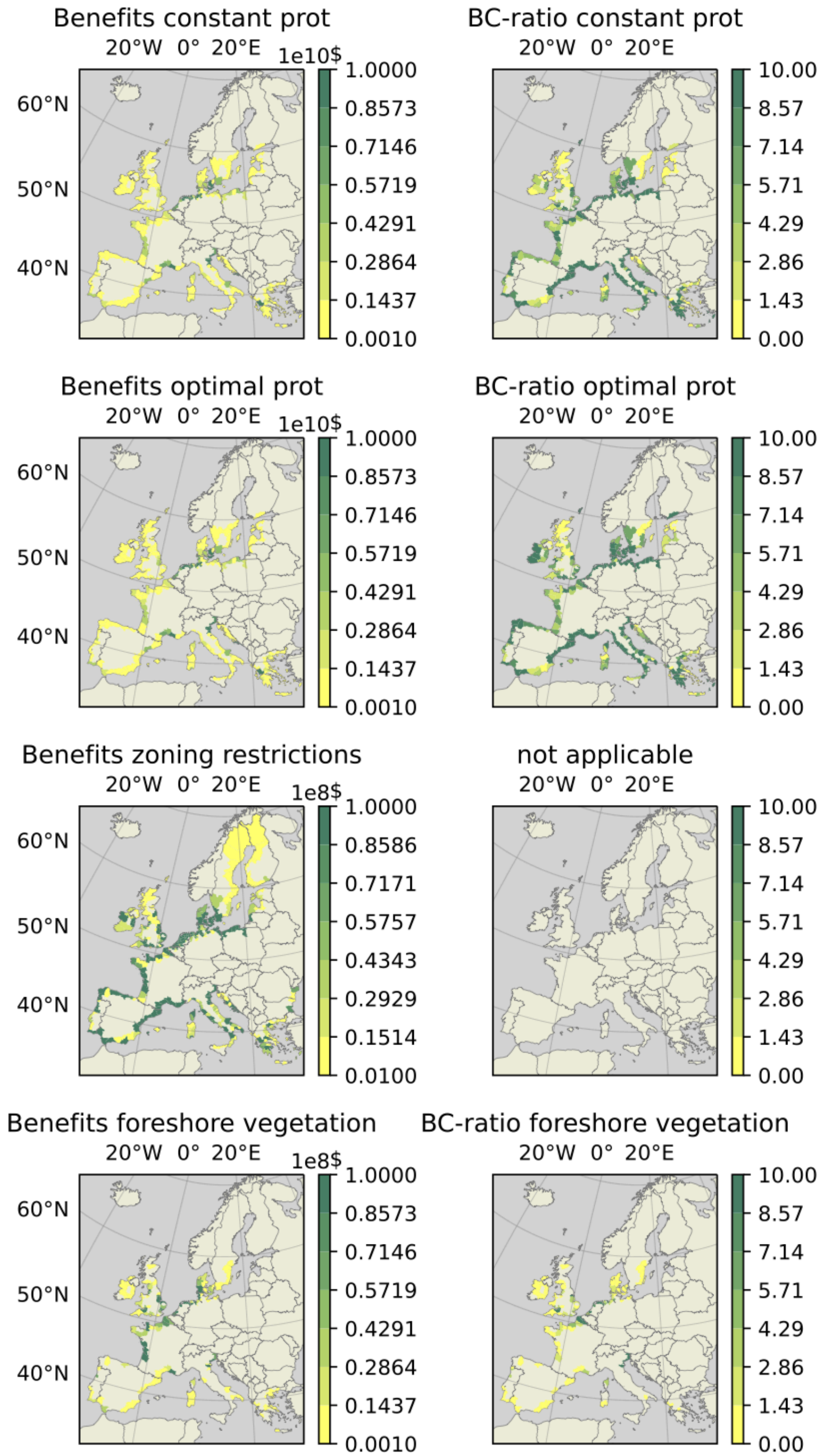

Figure 11: Left columns: The total benefits of certain adaptation measures, expressed in the reduction in EAD over the period 2020-2080. Right columns: The benefit-cost ratio associated with these measures. Results shown here apply the scenario RCP8.5-SSP2.

Table 7: Total costs and benefits of various coastal flood adaptation measures for all EU27+UK. These estimations assume that investments are made over a 30-year period starting in 2020. Benefits are accumulated over the period 2020-2080.

	Total benefits (2020-2080)	Total investment costs (2020-2050)
Flood protection constant		
● RCP2.6	647 ($ bln)	17 ($ bln)
● RCP4.5	755 ($ bln)	21 ($ bln)
● RCP8.5	1046 ($ bln)	28 ($ bln)
Flood protection optimal		
● RCP2.6	669 ($ bln)	24 ($ bln)
● RCP4.5	770 ($ bln)	25 ($ bln)
● RCP8.5	1059 ($ bln)	30 ($ bln)
Floodplain zoning restrictions		
● RCP2.6	70 ($ bln)	n/a
● RCP4.5	88 ($ bln)	n/a
● RCP8.5	183 ($ bln)	n/a
Foreshore vegetation		
● RCP2.6	9.5 ($ bln)	6.7 ($ bln)
● RCP4.5	9.7 ($ bln)	6.7 ($ bln)
● RCP8.5	10 ($ bln)	6.7 ($ bln)

Figure 11 and Table 7 present the reduction in coastal EAD as a result of several adaptation measures, as well as their costs and cost/benefit ratios. Constant protection standards refers to adaptation where protection measures (i.e., dikes/levees) are raised proportionally to increasing flood risk. For example, keeping up protection against 1/100-year flood events requires higher dikes if future 1/100-year events are associated with a higher water level. In Figure 11 and Table 6 it can be seen that this increase in protection levels generates substantial benefits compared to a future scenario without adaptation. Overall, benefits of this form of adaptation also substantially exceed their investment costs. Benefits and benefit-cost ratios increase considerably with the severity of climate change. Spatially, benefits of constant protection standards are highest in areas where the impacts of sea-level rise are most severe. That is, benefits are highest around the continental North Sea coast, the Mediterranean coast of France, and the Northern Adriatic coast of Italy. Interestingly, benefits are relatively low around the North Sea coast of the UK, where coastal flood risk in the baseline scenario is a considerable concern. This is because climate change shows to have a relatively low impact on coastal flood risk in this region, as shown in Figure 9.

Using a cost-benefit analysis framework, we can estimate the economically “optimal” level of investments in flood protection. The optimal level of flood protection in a region is the level with the highest net present value over the period 2020-2080. The aggregate costs and benefits of optimal protection standards are only slightly higher for optimal compared to constant protection standards. Also, the spatial visualization of benefits and benefit-cost ratios between the two adaptation scenarios does not differ considerably. This means that current protection standards, as reported in the FLOPROS database, to a high degree captures economically optimal standards. Climate- and socioeconomic change requires these protection standards to be maintained.

The third adaptation measure presented in Figure 11 and Table 6 is flood zoning restrictions. Under this adaptation scenario, population growth in floodplains is restricted, meaning there is lower flood exposure and, therefore, lower risk, compared to flood risk projections where floodplain populations do increase. Because this adaptation measure is mainly an administrative effort, investment costs are negligible for this adaptation measure, and therefore benefit-cost ratios are not applicable. It can be seen that floodplain zoning restrictions are beneficial all around the coast of continental Europe, as well as in the Southeast of the UK. Benefits, however, are on a substantially lower scale compared to investments in maintaining protection standards. Floodplain zoning restrictions may, therefore, not be a primary solution for coastal flood adaptation, but this may be an important measure to consider as a supplement to investments in flood protection standards. Finally, although investment costs are negligible, the true costs concerning floodplain zoning restrictions may be considered to be opportunity costs. This is because the restrictions limit economic development in floodplains.

The final coastal flood adaptation measure considered in GLOFRIS is increased foreshore vegetation. This is a Nature-based Solution (NbS), where vegetation in coastal saltmarshes reduces the impact of waves in causing flood risk. It can be seen that benefits of increased foreshore vegetation in reducing flood risk generally outweigh their costs, and are therefore economically attractive. However, foreshore vegetation is predominantly a beneficial measure around the North Sea coast, the Atlantic coast of France, and around the Northern Adriatic coast. Benefit-cost ratios show that foreshore vegetation is economically attractive mainly in Belgium and the Netherlands, as well as around the Northern Adriatic coast. It is important to note that benefits of foreshore vegetation for coastal flood protection may be much lower than those for improving flood protection standards, their societal benefits are more diverse. Besides reducing flood risk, these measures are found to improve biodiversity and have aesthetic values. Foreshore vegetation may, therefore, be considered an attractive supplementary measure to investing in flood protection standards, especially considering that the resulting reduced wave strength reduces dike-erosion and, therefore, may reduce the maintenance costs of dike infrastructure.

3.2 River flooding

3.2.1 Expected annual damages

GLOFRIS

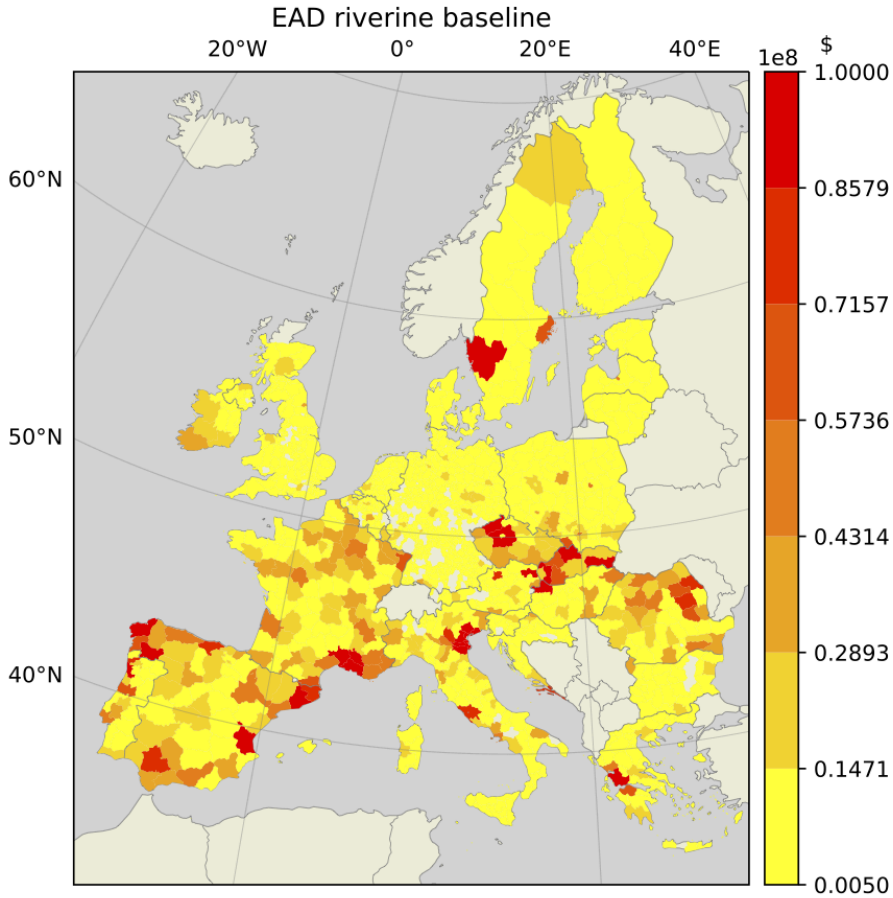

Figure 12: Expected annual riverine flood damage in 2010, expressed in 2005 US Dollars

Figure 12 presents expected annual riverine flood impacts using GLOFRIS. Riverine flood risk is particularly high in several Central European regions, overwhelmingly located in the Czech Republic and Slovakia. Moreover, the Western Mediterranean coast shows considerable flood risk, predominantly around the urban areas of Marseille, Barcelona, and Valencia. The Po river delta in Italy shows to be facing considerable risk of flooding, as well as the Northwestern coastal region of Spain. There are some regions, particularly in Germany where no data is shown concerning flood risk. In these regions there are no floodplains of major rivers (rivers of a Strahler stream order larger than 6).

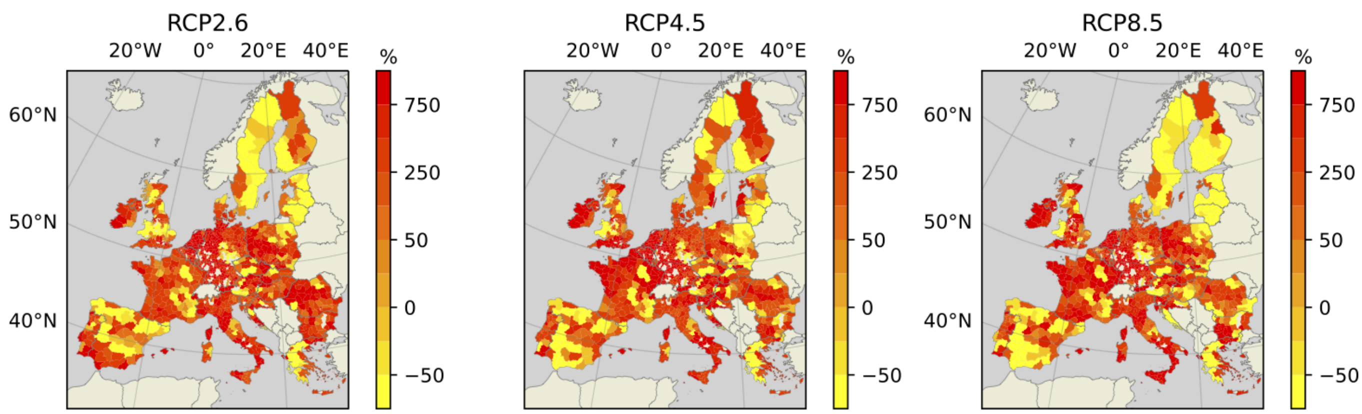

Figure 13: The percentage growth in riverine EAD in the period 2010-2080 for three RCPs, using the GCM HadGEM. All scenarios apply SSP2 and assume constant river dike heights.

Figure 13 presents the percentage change in riverine flood risk as a result of climate change. We can see that, overall, flood risk increases as a result of global warming. However, across the scenario projections, there are a considerable amount of regions where flood risk declines as a result of a drying climate. Declining riverine flood risk is most significantly observed in Spain, although under RCP2.6 flood risk is projected to increase steeply in the South of the country. Moreover, declining flood risk can be observed fairly robustly across the scenarios in the East of France, in Wales, in the West of Greece, and in Northeast Europe (Sweden, Finland, and the Baltics).

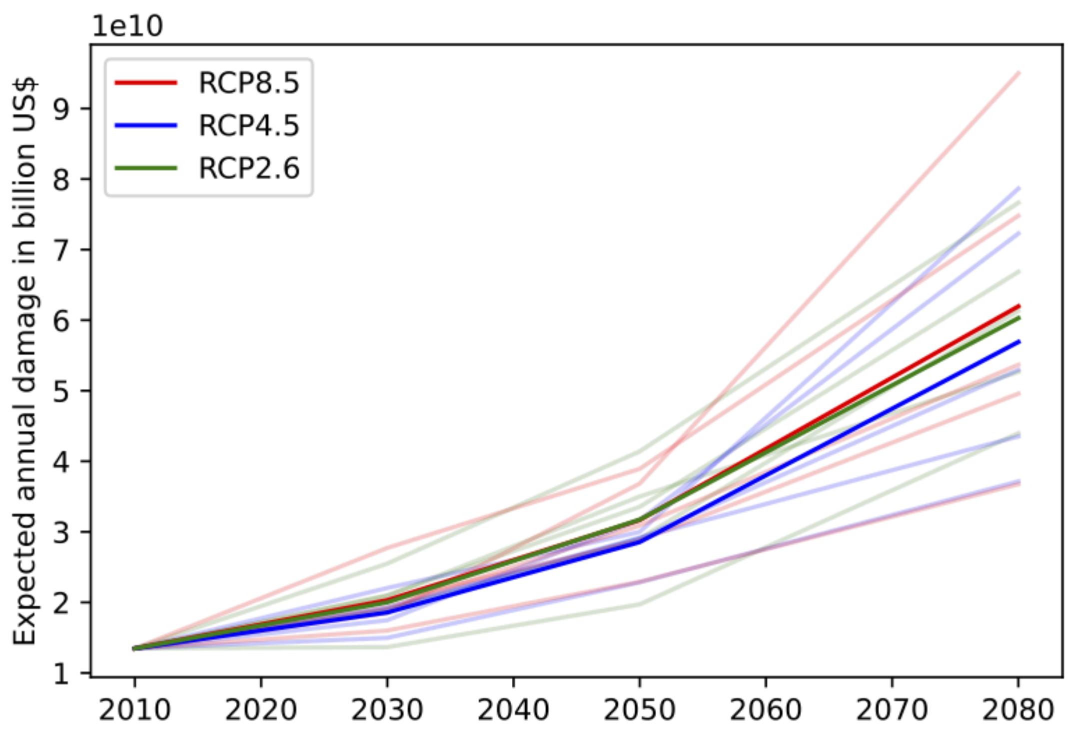

Figure 14: The development of EAD from 2010 to 2080 for the EU27+UK, under different RCPs and each of the CMIP5 GCMs. Bright colors show the ensemble mean of all GCMs for each RCP. Scenarios represent a continuation of present socioeconomic conditions and no adaptation.

Flood risk projections presented in Figure 13 show results for a specific GCM (HadGEM). In Figure 14 it can be seen that there is considerable diversity in flood risk projections across different GCMs, especially towards end of the century projections. Certain GCM-projections using RCP8.5 can be seen to cover both the upper and lower bounds of the impacts, giving an indication of the uncertainty associated with European climate projections and their impacts on riverine flood risk. The ensemble means, representing the average across the 5 GCMs under a given RCP show only slightly higher impacts of RCP8.5 in 2080 than the other two scenarios. Moreover, riverine flood risk is higher under RCP2.6 than under RCP4.5, which seems counterintuitive considering the clearly higher coastal flood risk under RCP4.5. This outcome shows that future climate projections concerning precipitation (a major driver of riverine flood hazard) are much more uncertain, resulting in a less clear causal relationship between global warming and flood risk for riverine compared to coastal flooding.

The exact values of the ensemble mean of flood risk projections per RCP are presented below, in Table 8.

Table 8: Expected annual damage from riverine flooding for the EU27+UK, considering no adaptation. Climate scenarios present the ensemble mean of the CMIP5 GCMs.

	2010	**2030**	**2050**	**2080**
RCP2.6	13.5 ($ bln)	20 ($ bln)	32 ($ bln)	60 ($ bln)
RCP4.5	13.5 ($ bln)	18.5 ($ bln)	28.5 ($ bln)	57 ($ bln)
RCP8.5	13.5 ($ bln)	20 ($ bln)	31.5 ($ bln)	62 ($ bln)

LISFLOOD

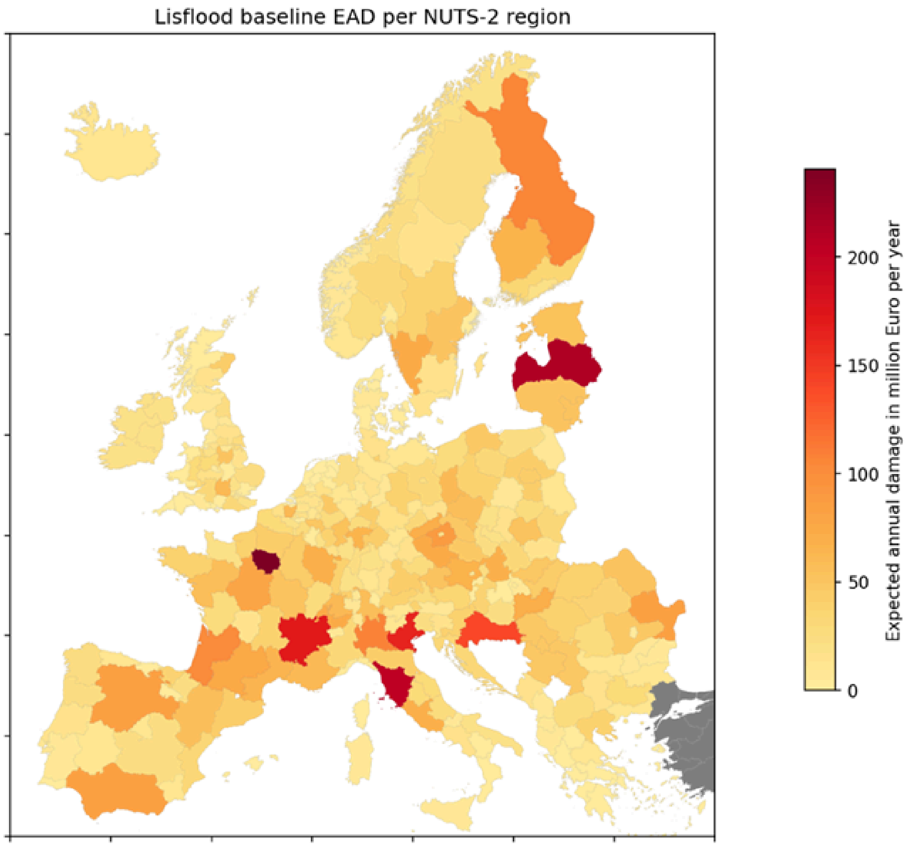

Figure 15: Expected Annual Damage (EAD) by LISFLOOD per NUTS-2 region (adapted from Dottori et al., 2023)

Figure 15 presents the baseline expected annual damage as modeled by LISFLOOD. Baseline results are computed as average of discharge data from climate simulations for the 1981 – 2010 time period, and static socio-economic conditions referred to year 2015. LISFLOOD shows widespread distribution of EAD throughout NUTS-2 regions, highlighting hotspots with an EAD above 150 million EUR per year in six regions, namely Ile-de-France (France, FR10), Tuscany (Italy, ITI1), Veneto (Italy, ITH3), Panonska Hrvatska (Croatia, HR02), Rhone-Alpes (France, FRK2) and Latvia (LV00).

Figure 16 shows the development of riverine flood risk in the EU27+UK till 2100. The left-hand panel shows that, without adaptation and for present socio-economic conditions, the flood risk is projected to increase from some 8 billion euro/year in the baseline, to some 19 billion/year in 2100 in RCP4.5, and to some 37 billion euro/year in RCP8.5. Note that the uncertainty within the ensemble is very large. In RCP4.5, the most optimistic climate model projects that 2100 damage is 'only' 10 billion euro/year, whereas the 3 most pessimistic models project an increase to more than 34 billion euro/year. In RCP8.5, the spread is even larger: the highest 3 model projections denote 185, 75 and 50 billion euro/year respectively, whereas the lowest 3 project 21, 19 and 17 billion euro/year.

The right-hand panel presents the results in terms of stabilised warming levels. This is the format in which also the results with adaptation will be presented, following (Dottori et al., 2023).

Stabilised warming levels represent scenarios where the climate forcing remains constant once a given global temperature threshold has been reached.

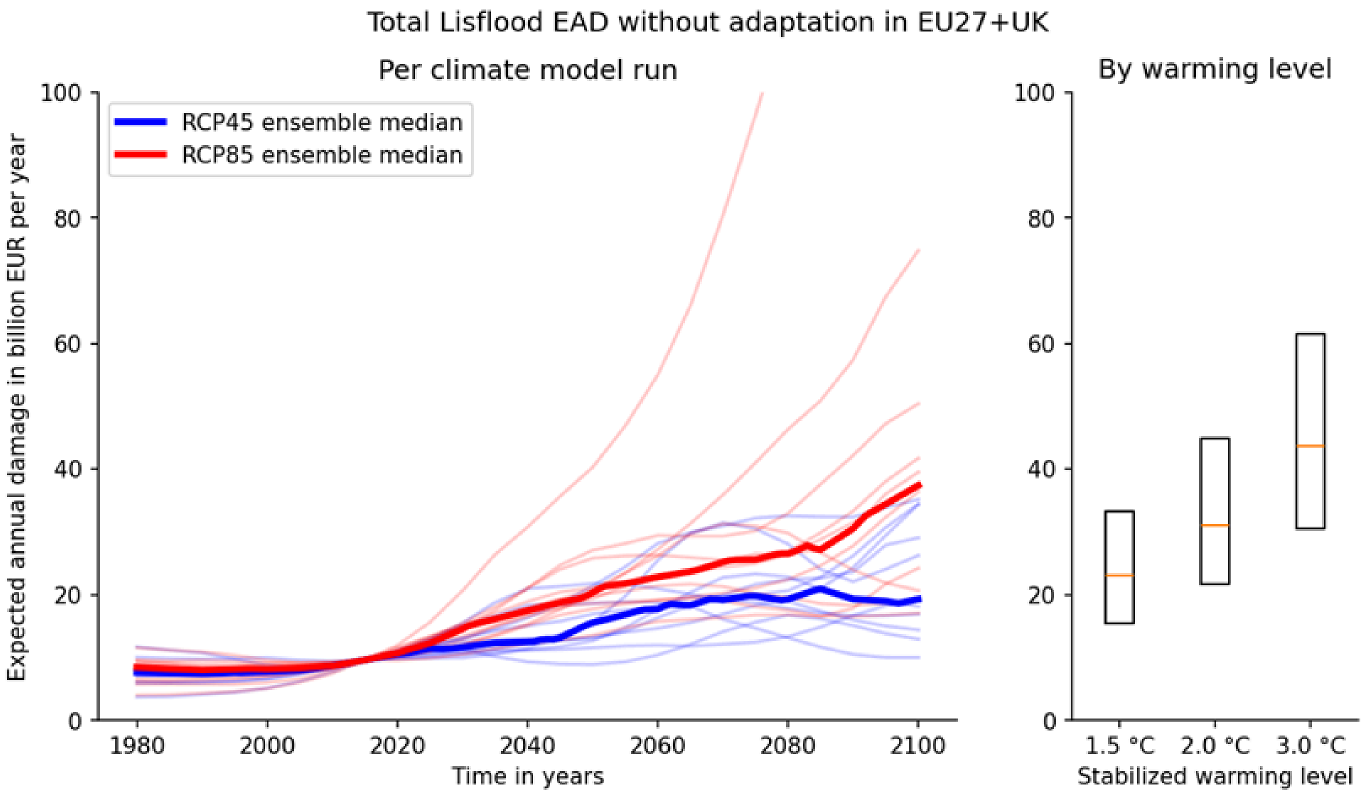

Figure 16: Expected annual damage over time (left-hand panel) and by stabilised warming levels in 2100 (right-hand panel). Both without adaptation and for present socioeconomic conditions.

Having gained insight into the increase of EU-wide damage, and the corresponding model and scenario uncertainty, we move on by looking into the spatial distribution of the increasing risk. Figure 17 shows how the EAD evolves in each region in an RCP4.5 (left) and RCP8.5 (right) scenario, in 2050 and 2100 (no socio-economic change). To reduce complexity, we show the median damage per region. That is, for a given RCP and evaluation year, we show the median of the climate model ensemble per NUTS-2 region.

In a RCP4.5 scenario, the EAD is modeled at €16.7bn in 2050, rising to €19.7bn in 2100. When aggregated at country level, France stands out with the highest EADs, incurring €3.17bn in 2050 and €2.95bn in 2100. Elsewhere, EADs are significantly lower. The second-highest EAD in 2050 is incurred by Germany (€1.87bn) and in 2100 by Italy (€2.29bn).

In 2050, a large share of EADs is concentrated in only five countries (France, Germany, Italy and the United Kingdom) incurring EAD above €1bn. The strongest regional effects are observed in France. Notably, the French regions Aquitaine (FRI1), Centre-Val de Loire (FRB0) and Pays de la Loire (FRG0) stand out, with EADs exceeding €150mil. In the Nordics, West Sweden (Västsverige, SE23) shows a remarkably high EAD, increasing by more than €200mil compared to the baseline scenario. Meanwhile, Finland's regions (apart from Helsinki-Uusimaa, FI1B) show gradual increases in EAD, which further exacerbate towards 2100. Other hotspots, already visible in the baseline scenario, persist into 2050, such as Toscana (ITI1), Panonska Hrvatska (HR02) and Latvija (LV00).

In 2100, the distribution of EAD at national level remains highly concentrated in the same countries; Poland becomes the only additional country to incur EADs above €1bn. From a regional perspective, some key hotspots incur persistently higher EADs. This is the case with Île-de-France (France, FR10), Provence-Alpes-Côte d'Azur (FRL0), Rhône-Alpes (France, FRK2) Lazio (ITI4), Toscana (Italy, ITI1), Veneto (Italy, ITH3), Panonska Hrvatska (Croatia, HR02), and Latvija (LV00), as well as Western Poland (PL43, PL51) and northern Czechia (CZ02, CZ04). However, some regions with increased EADs in 2050 experience a decrease in EAD towards 2100. This is for instance the case in France for Aquitaine (FRI1), Centre-Val de Loire (FRB0) and Pays de la Loire (FRG0).

In the RCP8.5 scenario, an aggregate EAD of €21.9bn is modelled for 2050, rising to €31.9bn in 2100. Similar to RCP4.5 France incurs the highest costs at national level, with €3.65bn in 2050 and €4.87bn in 2100. The second-highest EAD is incurred in Germany (€1.87bn) in 2050, while in 2100, the United Kingdom incurs nearly as high EAD (€4.62bn) as France.

In 2050, the countries that accumulate EADs exceeding €1bn are identical to those in the RCP4.5 scenario in 2100 (France, Germany, Italy, United Kingdom and Poland). Compared to earlier results, similar regional hotspots persist but with intensifications, especially in Northern (Finland (except FI1B), Latvija (LV00)) and Southeastern areas (Romania (RO31, RO22), Serbia). Some regions also have lower EAD in 2050 compared to the RCP4.5 scenario (Andalucia (ES61), Centre – Val de Loire (FRB0)) though such instances are rare.

The RCP8.5 scenario in 2100 generally reveals the highest EADs, as well as the strongest regional contrasts. At the national level, France, the United Kingdom and Germany incur EADs above €4bn, and a total of 10 countries incur EAD above €1bn. Despite most countries incurring higher EADs overall, stark regional differences still persist. For instance, Finland has the 7th highest EAD, with increases occurring in all regions except in Helsinki-Uusimaa (FI1B). Existing contrasts between various capital city regions (Bucuresti-Ilfov (RO32), Praha (CZ01), Berlin (DE30)) and their surroundings (respectively Sud-Muntenia (RO31), Strední Cechy (CZ02), Brandenburg (DE40)) become starker. Persistent regional differences can also be seen when comparing central Europe with its periphery, as Southern Italy, Greece, Portugal, Scotland, and Northern Norway show minimal increases in EAD throughout the different scenarios.

Finally, as with the RCP4.5 scenario, some regions (e.g. Lazio ITI4, Castilla y Leon ES41) experience higher EADs in 2050 than in 2100. This could be due to variabilities in the climate model predictions over time. For instance, a region may be predicted to face a wetter regime in 2050 and a relatively drier one in 2100. EAD due to riverine flooding could then be expected to decrease over that time period.

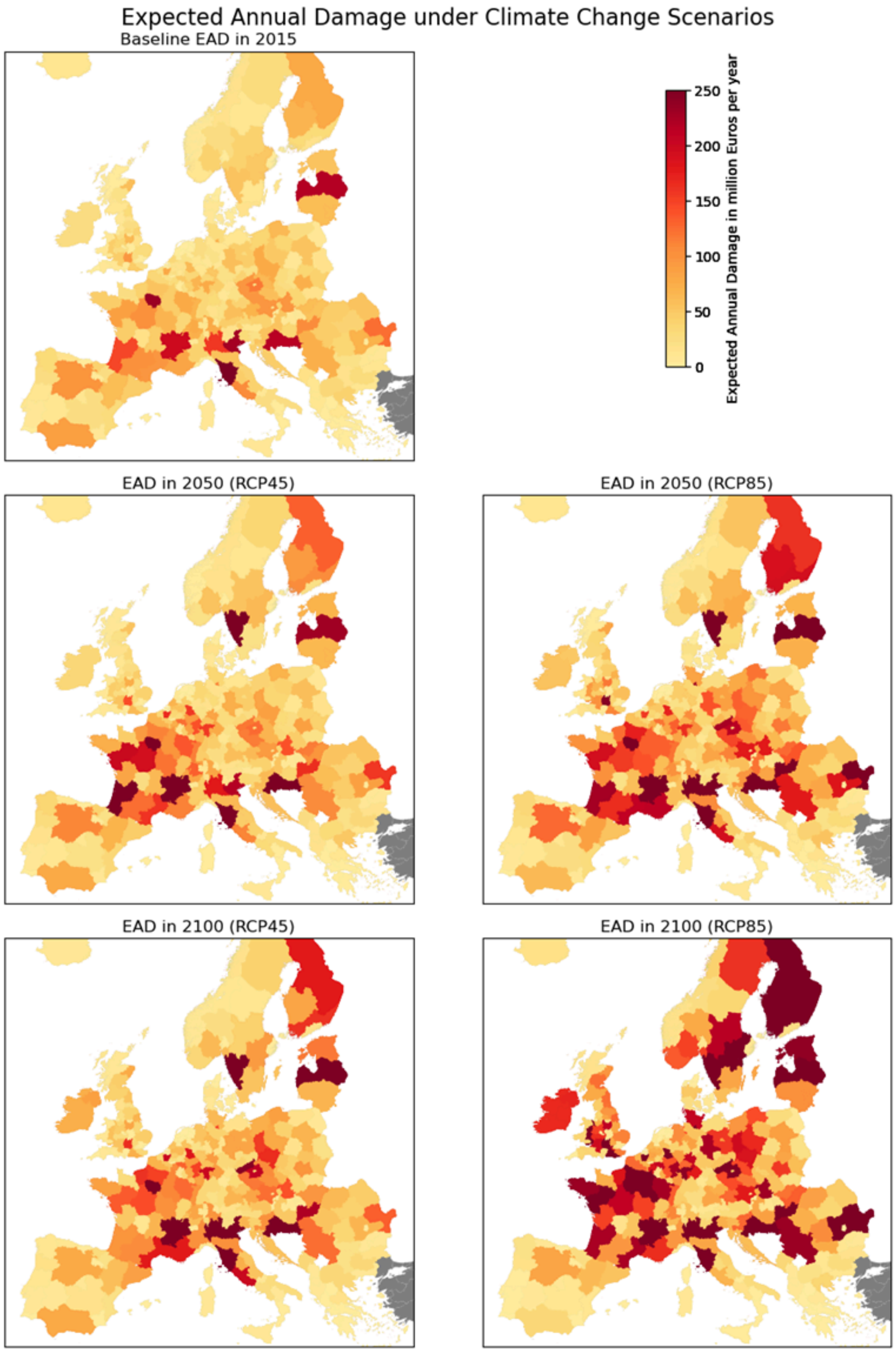

Figure 17: Expected annual damage for two climate scenarios: RCP4.5 (left) and RCP 8.5 (right) in 2050 and 2100 (no socio-economic change)

3.2.2 Distribution of damages for different types of assets

Beyond assessing which regions are most affected, evaluating how the damages are distributed throughout sectors is crucial to better understand the economic implications of river floods, as well as the effectiveness of potential adaptation strategies.

With LISFLOOD, exposure data is based on the CORINE/LUISA Land Cover map, which provides thematic classification for 44 land use classes at 100 m resolution (Rosina et al., 2020). As inundation maps are produced at the same resolution, this provides a granular overview of sectoral exposure to river flood. The land use classes are aggregated to five macroeconomic sectors, namely agriculture, industry, infrastructure, commercial and residential real estate at NUTS 2 level.

Figure 18 shows the first (left) and second (right) most affected sectors by river floods for each region throughout EU27+UK. In most regions, the first most affected sector is residential real estate. Industry typically is the second most affected sector. In a smaller number of regions, such as in central Italy, northern France, Belgium and northern Germany – as well as in the region of Budapest and Prague, industry is the most affected sector directly followed by commercial real estate. This happens to be often the case in regions around capital cities, probably due to the concentration of industries around these cities.

Infrastructure appears to be the most affected in regions which are sparsely populated, where the density of residential real estate and commercial activities is especially low, such as in the case in central Norway.

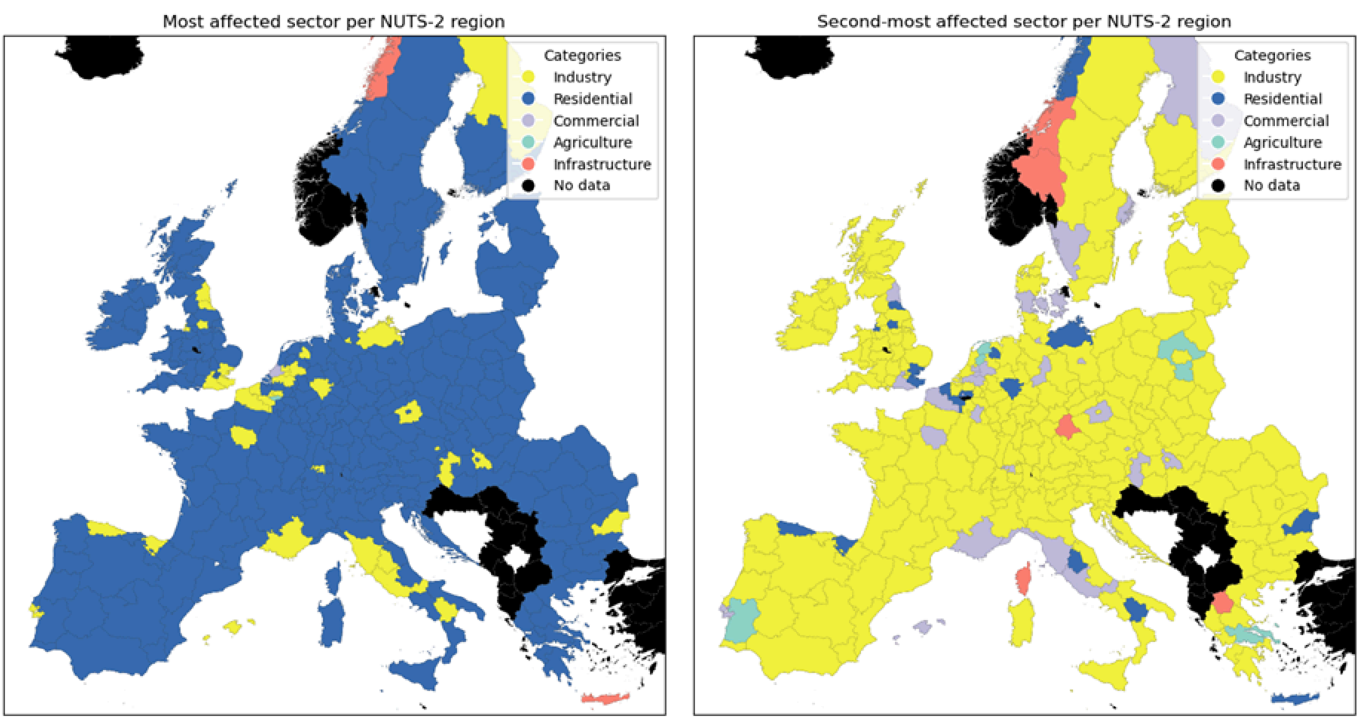

Figure 18: Most and second most affected sectors per NUTS-2 region

Damage to infrastructure

Infrastructure is one of five macroeconomic sectors for which the Lisflood model reports results. Here we put these results in context, by making a comparison with other pan-European studies, including our previous work in COACCH. By discussing this work, we seek to help the CGE and macro-economic modeling teams to make informed connections to their economic models.

In the above results, the Lisflood infrastructure category makes up 6% of the total damage, on average. It rarely is the largest damage category; Figure 4 shows that there are only 2 (out of 272) NUTS-2 regions where infrastructure is the largest category. In 5 out of 271 regions, infrastructure is the second-largest category. Infrastructure in Lisflood is a broad category, comprising road and rail networks (line infrastructure) but also freight transport hubs such as ports and terminals, airports, etc.

The Lisflood model is a grid-based damage model with a 100*100 m resolution. With respect to representing rather narrow line infrastructure such as road and railway infrastructure (order 5-30 m wide, and kilometers long), Lisflood presents some limitations. In fact, this type of infrastructure can be much more accurately represented using object-based models, which preserve the entire road geometry instead of trying to represent it on a 100*100 m grid. Therefore, the COACCH project developed a dedicated object-based flood risk model for road infrastructure, named OSdaMage[3], which is extensively described in COACCH (D2.3) and (Van Ginkel et al., 2021). A somewhat comparable approach has also been taken by the PESETA-IV project, as reported in unpublished work by (Mullholland et al., n.d.).

These studies help to interpret the damage that Lisflood attributes to the entire infrastructure category. For road infrastructure alone, Van Ginkel et al., (2021), estimate a contribution of 3.8-5.8% of total flood damage. For railway infrastructure, (Bubeck et al., 2019) find a contribution of 11-14% of total flood damage. As we explained in COACCH (D4.2), this estimate for railway infrastructure seems high, given that it is well above the damage we calculated for roads, while previous work (Doll et al., 2014) suggests that rail damage is typically smaller than road damage.

Unpublished work (Mullholland et al., in preparation) underlying the PESETA-IV reports that 20% of total river flood damage is attributable to transport infrastructure. The distribution of different transport modes is: 75% to rail, 20% to road, 5% to seaports and ports. As a percentage of the total river flood damage, this would translate into 15% to rail, 4% to road, 1% to seaport and ports. However, this study adapts the damage functions of Bubeck et al. for rail, and hence does not resolve the question as to whether this is a possible overestimation of rail damage.

The LISFLOOD data we report in this deliverable attributes 6% of total river flood damage to infrastructure. We conclude that while the order of magnitude of this number seems realistic, the number is most likely in the lower range of the actual cost. Attributing a somewhat higher percentage (e.g. 10%) of total damage to the transport sector is possibly more realistic. Pragmatically, one could equally divide the costs over the road and rail network (e.g. 5% to road and 5% to rail).

[3] The OSdaMage methodology has been further developed in the Deltares RA2CE-tool, that is used for a case study in ACCREU WP3

The Horizon Europe MIRACA project (Grant Agreement 101093854) aims to assess this aspect in more depth as it is entirely dedicated to infrastructure risk assessment for climate adaptation. Its results may also be of interest to ACCREU WP4.

3.2.4 Adaptation costs

Adapting to river flood risk requires a broad range of interventions, ranging from constructing infrastructure, nature-based solutions, to forecasting systems and risk financing instruments (Jongman, 2018). Conceptually, these options can offer protection to flood events in three ways: (1) reducing the hazard itself, either by reducing the probability that a flood event takes place or reducing the flood severity (depth, flow velocity, etc.); (2) limiting the exposure of population and assets for example by relocating them out of the hazard zone; or (3) decreasing the level of vulnerability of the population or assets exposed, i.e. making sure that the same inundation causes less damage, for example by flood-proofing buildings.

Beyond this conceptual categorization, adaptation options can be further defined based on their nature (grey/green/soft), the actors of the decision (e.g., public/private), the timing (responsive/anticipatory) or the extent to which they bring systemic changes to the existing socio-economic structures (incremental/transformational). We discuss below the different options and their key characteristics.

	Grey	**Green**	**Soft**	**Characteristics**
Hazard reduction	dikes/levees Channels Storm surge barriers	Retention areas Restoration of marshes and wetlands River re-meandering		*Public* *Incremental*
Exposure reduction	Managed retreat (relocation)			*Public* *Transformational*
Vulnerability reduction	Flood proofing of buildings		Forecasting Early warning systems Flood insurance	*Private* *Incremental*

The first group of options reduces the likelihood that the hazard materialises. This can be achieved via infrastructure (‘grey’) measures and well as nature-based (‘green’) interventions. Gray measures include the development or strengthening of dikes. In dike systems, river banks are elevated, temporarily or permanently, to enhance the maximum streamflow that can be contained without causing damage. Also in this category, channels can be developed to allow space to contain or redirect flood water thereby avoiding damage.

Green solutions to reduce hazard refer to the development of basins for water detention - if temporarily or retention - if permanently (Wohl, 2021). By converting agricultural or natural land, creating ponds or widening flood plains this option allows floodwater volumes to be accommodated without causing damage. The options in this group are planned forms of adaptation that require large structural interventions at government level and public financing.

The second group of options aims at minimizing the extent to which population and assets are exposed to flood risk. Exposure-reduction options are more transformative in nature – as they imply the relocation of people and/or assets, substantially affecting the existing social and economic structures. Examples of measures in this group are the relocation of residential or commercial buildings from areas at high flood risk (Tubridy et al., 2021). Similar to hazard-reduction measures these are ‘planned’ forms of adaptation that require large structural interventions at government level and public financing.

Finally, the third group of options reduces the vulnerability of the exposed assets or population. These measures aim at minimizing social and economic damages when a flood event materialises. For instance, buildings can be flood proofed by means of dry or wet proofing measures (Attems et al., 2020).

Alternative options in this group are the implementation of forecasting and early warning systems that enable the population to be informed of the upcoming flood event, implement emergency plans and prevent social and economic losses. Also risk financing instruments such as insurances can contribute to a reduction of vulnerability by providing financial support to the affected populations enabling an easier recovery. Differently from the two previous groups, the implementation of vulnerability reduction measures is often subject to individuals’ and firms’ evaluations of their costs and expected benefits, rather than being implemented structurally at government level.

GLOFRIS

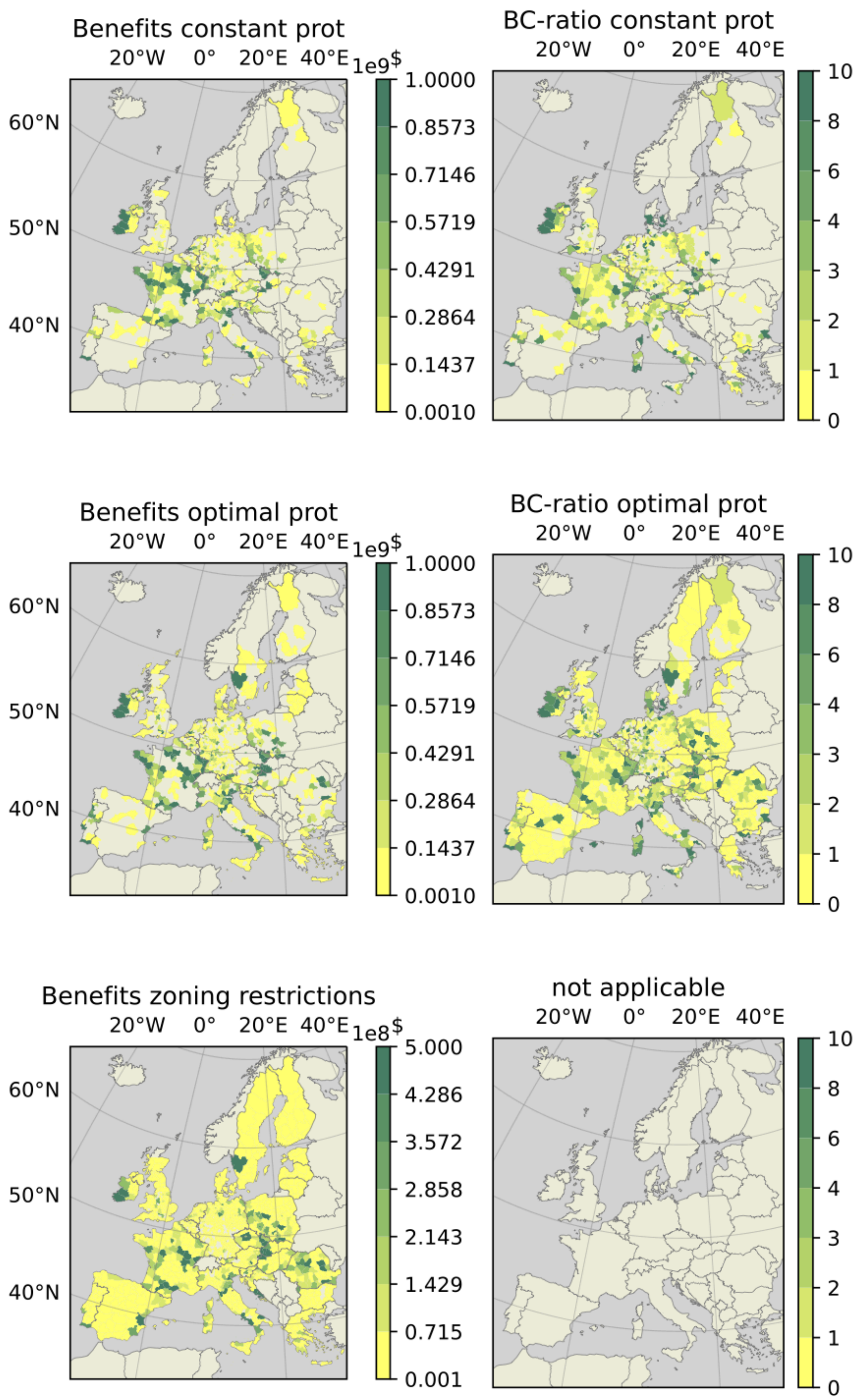

Figure 19: Left columns: The benefits of specific adaptation measures over the period 2020-2080. Right columns: The benefit-cost ratio associated with these measures over the same period. Shown data applies RCP8.5-SSP2 and the GCM HadGEM. The same plots for RCP2.6-SSP2 and RCP4.5-SSP2 can be found in Appendix A.

Table 10: Total costs and benefits of various coastal flood adaptation measures for all EU27+UK. These estimations assume that investments are made over a 30-year period starting in 2020, while benefits accrue over the period 2020-2080. Costs and benefits are discounted using a rate of 5%. Climate scenarios present the ensemble mean of the CMIP5 GCMs

	Total benefits (2020-2080)	Total investment costs (2020-2050)
Flood protection constant ● RCP2.6 ● RCP4.5 ● RCP8.5	 128 ($ bln) 115 ($ bln) 132 ($ bln)	 59 ($ bln) 61 ($ bln) 71 ($ bln)
Flood protection optimal ● RCP2.6 ● RCP4.5 ● RCP8.5	 202 ($ bln) 183 ($ bln) 204 ($ bln)	 157 ($ bln) 159 ($ bln) 170 ($ bln)
Floodplain zoning restrictions ● RCP2.6 ● RCP4.5 ● RCP8.5	 41 ($ bln) 18 ($ bln) 44 ($ bln)	 n/a n/a n/a

Figure 19 and Table 10 present the costs and benefits of riverine flood risk adaptation measures in GLOFRIS. For all regions combined, it can be seen that maintaining current protection standards delivers high benefits and considerably outweighs the costs of such investments. However, it can be seen that the benefits of maintaining current protection standards towards the future is largely driven by the effectiveness of this adaptation measure in several regions, which are overwhelmingly located in France. Moreover, it can be seen that there are many regions for which no benefits of this adaptation measure are shown. In these regions, under this particular GCM and RCP, flood hazard declines over the period 2020-2080, meaning no investment is needed to maintain current protection standards.

Under optimal flood protection standards, there are more regions (and different regions) for which data regarding benefits and benefit-cost ratios is shown in Figure 19. The main reason for more regions showing a positive impact of this measure on reducing risk is that, unlike the constant protection standard scenario, the optimal protection scenario considers the overall risk in its economic optimization procedure. For some regions, hazard may decline over the period 2020-2080, making investments in maintaining current protection standards unnecessary. However, in regions where increasing flood risk is driven by socioeconomic change, it may still be beneficial to increase protection standards considering the overall evaluation of costs and benefits of such investments. Most regions showing a benefit of optimal protection standards show a similarly positive impact of maintaining current protection standards. For all regions combined, it can be seen that benefits of optimal protection standards are considerably higher than maintaining current protection standards. However, investment costs associated with optimal protection standards are also substantially higher.

Finally, the benefits of floodplain zoning restrictions are positive in almost all regions. Regions where this measure shows particularly high benefits are mostly the same regions where the other adaptation measures are also relatively beneficial. Similar to the benefits of floodplain zoning restrictions as a coastal flood risk adaptation measure, these benefits are of a lower magnitude compared to those obtained from investments in flood protection standards. However, because also the investment costs are negligible, floodplain zoning restrictions can be considered an attractive supplementary measure to investments in flood protection.

LISFLOOD

Four adaptation options can be modeled within LISFLOOD; these are (1) the strengthening of the dike system, (2) the development of retention areas, (3) the flood proofing of buildings and (4) relocation. Their costs and benefits can be modeled as outlined below (Dottori et al., 2023).

In the case of dike strengthening, Dottori et al. model the dike elevation required to achieve a given level of protection, in the present and future climate. First, given the current level of protection, the river discharge and the depth-discharge curves, the model provides present-day dike elevation. Second, accounting for the frequency shift in flood events for future scenarios, LISFLOOD is used to compute the increase in dike elevation required to raise protection to the expected levels. Third, the dike elevation requirements are translated into cost estimates, based on estimates of unit cost for dike elevation in the different European countries.

For storage detention areas, the procedure is similar. In simple terms, LISFLOOD is used to model the volumes of water that need to be stored to achieve a given level of protection, in the present and future climate. First, LISFLOOD is used to calculate the volumes of water that can be stored at the present-day protection standard. Second, given the frequency shift in flood events for future scenarios and the new volumes of water that need to be stored, the area required is calculated. Third, the implementation costs based on construction and maintenance costs are estimated proportionally to the storage capacity of detention areas.

The approach for flood proofing and relocation is different as these do not imply any changes to the hydrological model. These adaptation measures are modeled by directly assuming that a given level of damage reduction can be achieved by reducing the surface area exposed to flood risk. The costs are then calculated based on average unit costs for the two measures, and the extent of the built-up area located within the 1-in-500 year floodplain. It is assumed that infrastructural and agricultural damages cannot be reduced with these two measures.

The average unit cost estimates of the four adaptation strategies used in Dottori et al. are reported in the table below. These are used to compute the total cost of each adaptation option throughout the EU, for an optimal level of each adaptation option until 2100. An important remark is that the achievement of a given damage reduction is linked to a total adaptation cost incurred between 2020 and 2100, which is then distributed in time as annual cost.

Table 11: Overview of average unit costs and annual cost for the four adaptation options economically optimised.

	Dike strengthening	**Detention areas**	**Relocation**	**Flood proofing**
Unit cost	6405.3 (€/m/m)	3.7 (€/m3)	1373.0 (€/m2)	375.7 (€/m2)
Annual cost EU27+UK, optimal adaptation (1.5 C)	1857 €M/year	1641 €M/year	1.7 €M/year	37.3 €M/year
Annual cost EU27+UK, optimal adaptation (2 C)	2378 €M/year	1957 €M/year	4.1 €M/year	336.7 €M/year
Annual cost EU27+UK, optimal adaptation (3 C)	3093 €M/year	2567 €M/year	11.0 €M/year	1110 €M/year

Results show that, when economically optimised, the development of retention basins and dike strengthening deliver on average higher damage reductions. Developing retention basins perform best overall, reducing EAD by 68-83%, depending on the temperature rise. dike strengthening reduces EAD by 49-70%. Meanwhile, the latter two measures only bring little damage reductions. Most notably, relocation only delivers EAD reductions of up to 0.2%. This large disparity in damage reduction likely stems from the high economic costs involved with flood-proofing buildings and relocation. Consequently, the economically optimised levels of relocation or flood-proofing are limited, leading to minimal damage reductions.

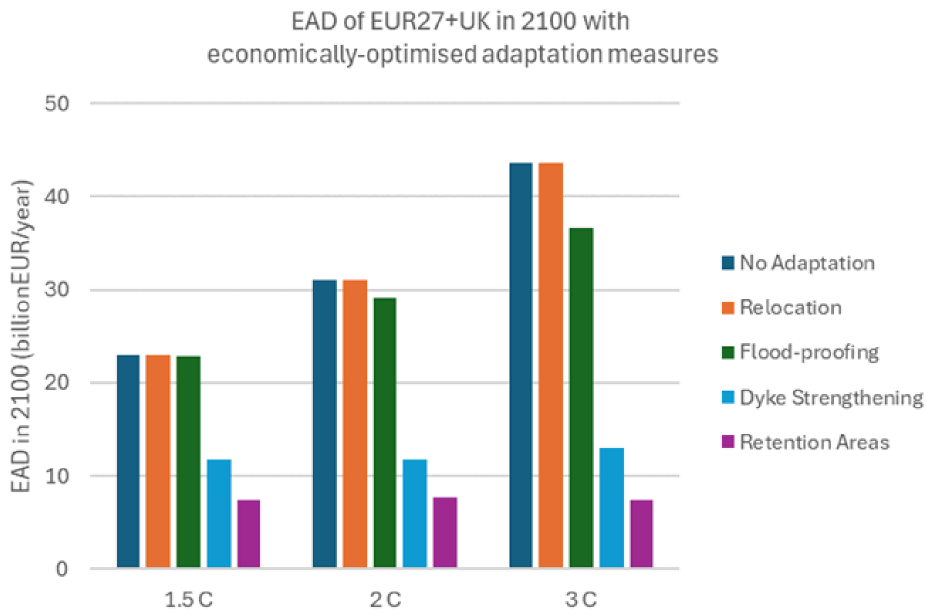

Figure 20: EAD per adaptation option (economically optimal implementation), for 1.5, 2 and 3C Global Warming Levels in 2100. Results based on median values from climate models ensemble (adapted from Dottori et al., 2023).

In Figure 21 we report the share of the total damage that is expected to be reduced via the optimal implementation of each of the four adaptation options between 2020 and 2100 in a 3 C global warming scenario. As the effectiveness of adaptation strategies is dependent on the level of protection implemented, the damage reduction figures presented are specified for the optimal level of implementation, based on the cost-benefit analysis performed in Dottori et al., 2023. The figures are computed with undiscounted damages. The purpose of the below is not representing the results of the cost-benefit analysis but instead, systematically reporting the data that can be integrated into the macro-economic modeling. While the data presented below refers to an optimised scenario, data is also available for non-optimal protection levels in the range of 2 - 2000 year return periods and for different global warming scenarios (1.5 C, 2 C).

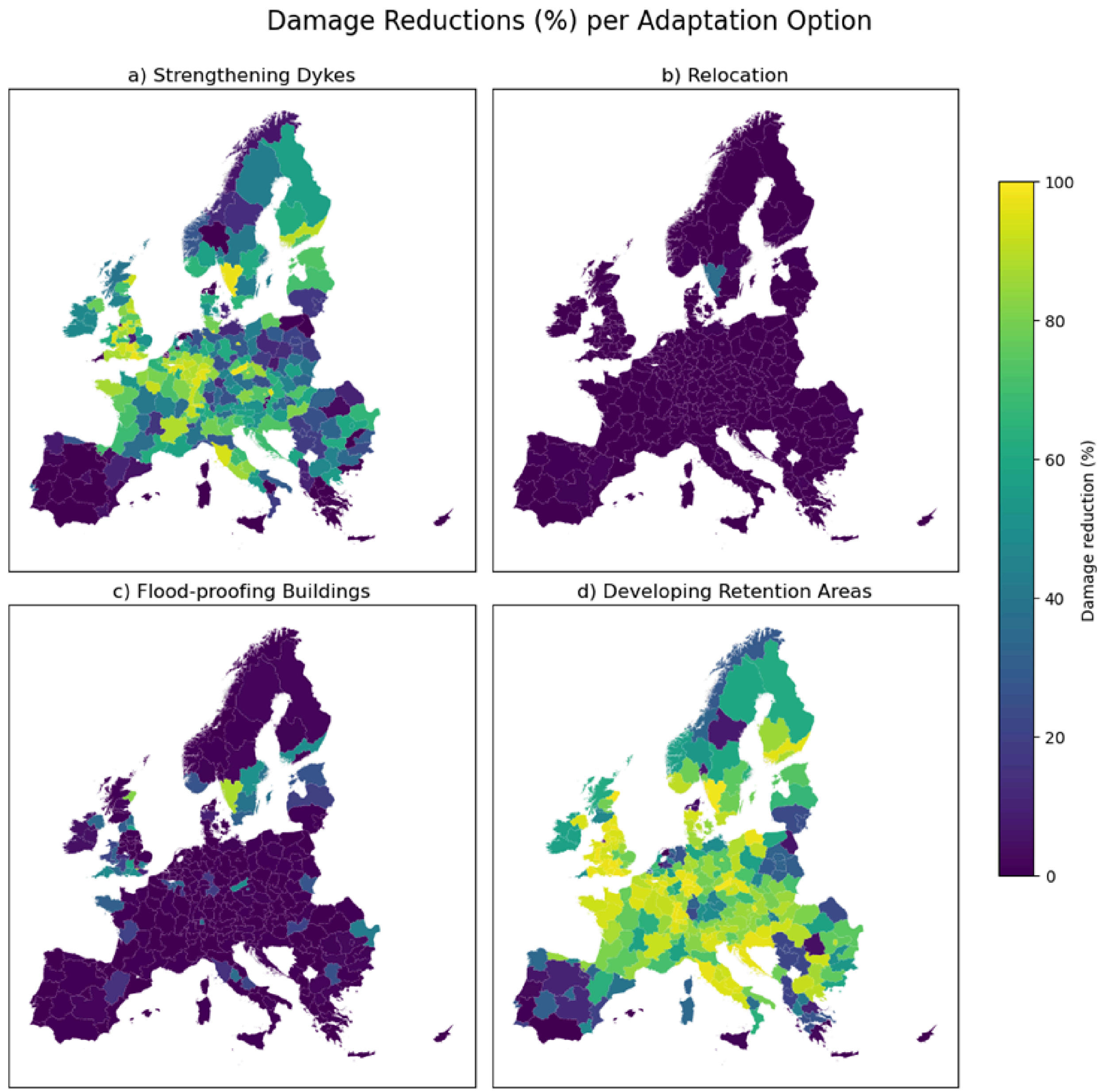

Figure 21: Share of total damage reduced per adaptation option (optimal implementation), for a 3C Global Warming Level in 2100 (adapted from Dottori et al., 2023).

4 Integrating results of sectoral models in macroeconomic models

4.1 Integration approaches

In this final section we discuss how results from sectoral models can be used to better understand the economy-wide impacts of flood adaptation strategies. While multiple studies have modelled the economy-wide impacts of floods, not many have captured the macroeconomic implications of implementing different adaptation options. A deeper understanding of these can provide complementary perspectives to the more common and rather narrow cost-benefit analysis.

To do so, in section 4.1.1 we first review literature on how the economy-wide impacts of floods are usually captured in scenarios without adaptation, to then focus in section 4.1.2 on how adaptation can be integrated in these analyses.

4.1.1 Economy-wide impacts from flood risk

What does the EAD provided by sectoral models represent in the real world?

The LISFLOOD and GLOFRIS flood models described in section 2.2 provide insights into the level of risk from river flooding throughout Europe. in terms of Expected Annual Damage (EAD). The EAD (EUR/year) captures the average annualised direct damage to property and tangible assets. It measures what it would cost to repair the assets to the original state. These assets include, for instance, productive capital stock (e.g. buildings and machinery), transport infrastructure (e.g. roads or railways) or crops and livestock.

What other effects are there that sectoral models are not capturing?

A reduction in capital stock, represented by the ensemble of these damages, means that the average annual production capacity of a region decreases due to its exposure to flood risk. In addition, as markets are interconnected systems – throughout actors, sectors and regions – the impact on one specific activity can lead to broader social and economic implications that materialise beyond the location and time of a flood event. For instance, the decrease of economic production of a sector in one region can lead to the decrease in economic activities at the level of its suppliers, or to an increase in economic activities in an adjacent region to ensure that consumers demand is met (Koks et al., 2019).

Which models can be used to capture these effects?

Capturing the broader impacts from disasters is possible through input output (IO) (see e.g., (Hallegatte, 2008)) or computable general equilibrium (CGE) models (Tirasirichai & Enke, 2007; Xie et al., 2019). Both types of models represent the interconnectedness of the economic sector, regions and economic agents and are therefore able to capture indirect effects in terms of interlinkages across producers and consumers, delivering insights into how the economy responds to a shock in terms of resource reallocation, economic gains and losses. While IO modeling is seen as useful for very short-term analysis due to the assumed rigidity of production functions, CGE models offer more flexibility in terms of economic dynamics, responses, and feedback of economic agents.

How are sectoral and macro-economic models typically connected?

To quantify the regional or national level impact associated with flood risk, a common approach is translating the output from sectoral models into shocks on production factors (endowments) of the macroeconomic models.

The factors of production impact the ability of an economic system to produce; the 'supply' side. These typically include three elements: capital, labour, and land. In simple terms these are the resources that economic sectors require – in different amounts - to produce economic outputs. For instance, the ability of the agriculture sector to produce economic output is strongly dependent on land, while industrial activities are capital intensive.

The extent to which a given sector requires a given resource for its own production determines the extent to which the sector will be affected by a shock on the productivity of that resource. Depending on the level of detail available from the sectoral models, a shock can therefore be applied to a generic factor of production, or to the economic output of specific sectors.

In addition to this 'supply side', shocks to the economic system can also impact the demand side of the economy, therefore affecting spending patterns, stimulating economic activities in specific sectors and triggering a change in resource allocation. In the context of shocks from flood events, this is especially the case when including adaptation measures, or post-event reconstruction activities – which we discuss in more detail in section 4.1.2.

The economy-wide impacts of river and coastal flooding throughout Europe have been modelled in several studies. Table 12 below provides a brief overview of recent studies that assess the economy-wide impact with a specific focus on river floods in Europe.

Table 12: Overview of studies reporting the economy-wide impacts of river flood in EU (no adaptation)

Sectoral model	Economic model	Shock	Scale	Sector	Reference
GLOFRIS	CGE (ICES)	-Shock to labour production factor based on exposed population, assuming that people affected are unable to work for 2 weeks/yr -Shock to capital stock by macro sector	EU	All	(Bosello et al., 2020)
LISFLOOD -OSDamage	CGE (ICES)	-Shock to capital production factor of the transport sector	EU	Transport	(Bosello et al., 2020)

LISFLOOD	CGE (CaGE)	-Direct damages to agriculture, shock to the productivity of the agricultural sector -Direct damages to industry, shock to the economy's capital stock -Direct damages to residential buildings: increase in households' subsistence spending	EU	Agriculture, Industry, Households	PESETA IV (European Commission. Joint Research Centre., 2020)
LISFLOOD (global domain)	IO (MRIA)	n/a	EU	All	Koks et al., 2019
CATSIM	CGE (WEGDYN-AT)	Sector specific damages for selected return periods and hypothetical larger events	Austria	All	(Bachner et al., 2024)

Table 12 shows how shocks can be applied on different elements and at different levels of specification, depending on the availability and granularity of geographical and sectoral data. For instance, in the context of a country-specific assessment, sector specific shocks are applied to the capital stock of the Austrian economy by Bachner et al., (2024). In PESETA IV , the direct damages are attributed to macro-sectors (e.g. agriculture, industry and households) based on land use data and then translated into different types of shocks. This approach allows for instance to capture – beyond the damage to productive capital – also the increased spending expected from private households.

More often, studies with broader geographical coverage (e.g., Bosello et al., 2020) do not provide an explicit sectoral specification, letting the economic model distribute the impact to sectors, based on the production factor intensities of each sector, in each regional entity.

Based on the sectoral specification of damages presented in section 3.2.2 the modelling teams in WP4 can consider applying shocks to specific sectoral economic outputs rather than on generic production factors.

Independently of the level of detail in specifying shocks per sector, this approach comes with limitations. Crucial to highlight is the use of the Expected Annual Damage (EAD) metric. As an annualised metric, the EAD suggests that every year regions incur a given damage, whereas local impacts are in reality not equally distributed over time and would be better represented on a large (e.g. 1 every 100 year) event basis, so as economic shocks instead of yearly cash flows. The smaller a country or region is, the stronger this effect will be, due to the strongly spatially autocorrelated nature of floods.

4.1.2 From flood impacts to adaptation

What is relevant to study beyond the damage and its ripple effects?

Studying the economy-wide impact of climate-related hazards is not limited to the assessment of how a given damage (or, "shock") propagates through the economy. In fact, in regions exposed to climatic hazards – economic actors (governments, households and firms) react and adapt in multiple ways.

For instance, research from the natural disaster literature, aimed at understanding the economic impact of specific events, shows that beyond the short-term economic effects – there can be positive spillover effects due to the substitution of production and the demand for reconstruction. Therefore, different recovery paths can play a significant role in the long-term economic effects (Kousky, 2014) as cited in (Botzen et al., 2019). In addition to the physical reconstruction of assets, market-driven autonomous changes also take place as a result of a flood event. This includes for example the shift in demand towards different regions, or the reallocation of labour towards different sectors.

Both cases presented above exemplify possible responses to a given event, either in terms of reconstruction or in terms of economic rebalancing effects. However, with increasing societal and political awareness of these latter effects, planned anticipatory adaptation strategies are increasingly put in place with the overall objective of avoiding social and economic losses.

What can we capture through economic models?

When it comes to applying CGE macroeconomic models to study adaptation, the default assumption is that autonomous responses are reflected via the adjustment to relative price changes (Aaheim et al., 2012; Szewczyk et al., 2021), or that some form of adaptation capital is built up that increases the adaptive capacity (Aaheim et al., 2017; De Cian et al., 2016) or by reducing climate impacts (Hoffmann & Stephan, 2018). To the best of our knowledge, the literature assessing the implications of flood adaptation strategies from a macroeconomic perspective is fairly limited Table 13. In fact, a review from (Wei & Aaheim, 2023) found that a large share of the research in this area often focuses on droughts, crop productivity and adaptation in the agriculture sector (see, e.g., (Bosello et al., 2018; Elshennawy et al., 2016).

Table 13: Overview of studies assessing the macroeconomic implications of flood adaptation strategies

Model	Risk	Scale	Sector/Focus	Adaptation option	Reference
CGE	All, incl. floods	Austria	Fiscal effects	Not specified	Bachner, 2017; Bachner et al., 2019

CGE	All, incl. floods	Austria, Spain, Netherlands	Fiscal effects	Not specified	Under review at Ecological Economics based on COACCH deliverable 4.1 (Van Der Wijst et al., 2021)
CGE (ICES-XPS)	Coastal flooding	Global	Fiscal effects	Not specified	(Parrado et al., 2020)
CGE	Flood	Switzerland	Fiscal effects	Not specified	Hoffmann & Stephan, 2018
CGE (COIN-INT)	River Flooding (GLOFRIS)	Europe	Economy-wide effects	Insurance	Knittel et al., 2023
CGE (COIN-INT)	Coastal flooding (DIVA)	Global	Economy-wide effects	Sea dikes and migration	Bachner et al., 2022

With respect to coastal and riverine flooding, there are economy-wide studies assessing the fiscal implications of financing adaptation through public budgets. These often have a narrow geographical scope in one or a limited number of countries (Hoffmann & Stephan, 2018; Preinfalk et al., n.d.). Few studies go beyond this generic account of adaptation and differentiate between different types of adaptation (structural, informational, ecosystem-based) and their economic costs and benefits (Bachner, 2017; Bachner et al., 2019; Bosello et al., 2018). Most detailed economic characterization of different adaptation strategies is provided by (Knittel et al., 2023) on river flood insurance, and by Bachner et al., (2022) on sea dikes and migration in the context of adaptation to sea level rise.

The most relevant example to this discussion is (Bachner et al., 2022), that studies the macroeconomic effects of two adaptation options to sea level rise, namely sea dikes and migration – where a sectoral model (DIVA) and a CGE model (COIN-INT) are coupled via six channels. Three of these relate to the damages from sea-level rise, namely capital costs due to sea flood damages, the labour supply losses and the land losses. The remaining three relate to the cost of adapting, namely the sea dike investment costs, sea dike maintenance costs and migration costs - captured as the cost of leaving immobile assets behind, and the costs of moving mobile capital away.

4.2 Overview of outputs for technical implementation

4.2.1 River flooding

How to model the macroeconomic effects of (river flood) adaptation strategies?

The application of macroeconomic modeling for the economy-wide assessment of flood adaptation strategies emerges as an area which has not been extensively explored yet. The relevance of this work is to provide a complementary perspective to the most traditional adaptation cost-benefit analysis, integrating a broader range of macroeconomic considerations. As per the example from Bachner et al. (2022) - there are several aspects that need to be defined. In generic terms, these can be grouped around two themes: (1) the adaptation costs and (2) their benefits.

Costs

Regarding the adaptation costs, there are multiple aspects to define. The first one refers to the overall cost for the implementation of a given measure. Beyond the necessary investment it should be specified whether this involves a one-time cost, a recurring expenditure, or both. In addition, it should further be understood which economic actor is most likely to incur these costs, among the public sector, the firms or private households. In fact, allocating the costs to different economic agents will impact the economy in different ways, and can differ by country.

It is also vital to understand the type of economic activity that is performed by the implementation of the adaptation measure. Depending on its characteristics, these measures will trigger activities in the economy (e.g., developing new dikes requires resources from the construction sector, while information provision can be allocated to the service sector).

Finally, on the investment side it should be determined how additional resources that are required for the adaptation measure to be put in place, are provided. For the private household there are essentially two options: agents can reduce savings and thereby allow higher expenditures, which comes at the cost of lower investments or shift consumption towards adaptation activities at the expense of other activities. For the public household (e.g. the government), there are several refinancing options: similar to the private households, funds can be redirected from general public consumption towards adaptation activities, which reduces non-climate related public consumption, i.e., public service provision. If the public household was to maintain its consumption level, there are two alternatives to create the necessary fiscal space, that is either by reducing transfers to the private households or by increasing the income side via tax increases (one specific or several taxes) or take on debt.

For the four river flood adaptation options analyzed above, Table 14 presents proposed specifications for representation of these latter in a CGE model. In summary, the implementation of all four adaptation options would mean that some financial resources are directed to the construction sector. Three out of the four options are likely to be public investments, with the exception of the flood proofing of buildings which typically is undertaken at the private level.

Table 14: Investment cost indicators for four river flood adaptation options

	Cost	**Who bears the cost**	**Timing of costs**	**Technical implementation in CGE**
Dikes strengthening	dike construction and strengthening, and maintenance of infrastructure	Public investment	One-off and annual maintenance	Negative investment good endowment for the public sector, reducing consumption possibilities for the public sector
Storage retention areas	Construction and maintenance based on location and storage capacity	Public investment, complemented with the occupation of portions of land (~2%) which would no longer be available for some land uses (agriculture and urbanization)	One-off and annual maintenance	Reduction of land endowment used by the agriculture sector
Flood proofing of buildings	Construction costs at building scale	Private investment	One-off and annual maintenance	Expenditure-neutral increase of consumption from the construction sector for the private household, representing individual installing wet- or dry-flood proofing measures at building site
Relocation of buildings	Demolishing, acquisition and reconstruction	Public investment	One-off (no annual maintenance)	Public investment/consumption non-welfare improving, reducing consumption possibilities for the public sector

Benefits

To capture the benefits of adaptation, the general approach is to reduce the magnitude of the shock related to the climate impact. In the simplest version of these exercises, the shock captures the annual destruction of capital assets, which is implemented in the CGE as a negative capital shock to the private household. When adaptation is implemented, this shock is reduced, by an amount that represents the effectiveness of the adaptation option analysed.

Beyond the fact that different adaptation options will provide a different magnitude of benefits, these benefits are not necessarily equally distributed throughout the various economic actors and sectors. For instance, in the case of the river flood adaptation options analysed here, dike strengthening and storage retention areas provide protection to the entire economy, reducing damage on all shocked channels. On the other hand, flood proofing of buildings and the relocation of buildings do not benefit agriculture and infrastructure assets.

Table 15: Indicators for representing benefits of four river flood adaptation options

	Who experiences the damage	**Who experiences the benefits**	**Technical implementation in CGE**
Dikes strengthening	All economic sectors in different shares, depending on geographical location	All sectors	Reduction of negative shock on capital production factor for all sectors
Storage retention areas		All sectors	Reduction of negative shock on capital production factor for all sectors
Flood proofing of buildings		Built-up area	Reduction of negative shock on capital production factor for industry, residential and commercial sectors
Relocation of buildings		Built-up area	Reduction of negative shock on capital production factor for industry, residential and commercial sectors

In summary, the following variable are available from LISFLOOD

Variable	Unit	Temporal scale	Spatial scale	Scenarios
Expected annual damages - Sectoral disaggregation: agriculture, residential real estate, commercial real estate, infrastructure, industry	EUR 2015	2020-2100 in 5 years step	NUTS2, country	1.5 C 2 C 3 C
Adaptation cost - Adaptation options: dike strengthening, retention areas, flood proofing of buildings, relocation	EUR 2015	2020-2100, total cost & annualized costs	NUTS2, country	1.5 C 2 C 3 C
Adaptation benefits - Adaptation options: dike strengthening, retention areas, flood proofing of buildings, relocation	EUR 2015	2020-2100 optimized total benefit	NUTS2, country	1.5 C 2 C 3 C

4.2.2 Coastal flooding

Table 16 : DIVA model output to be delivered to macroeconomic models

Variable	Unit	Temporal scale	Spatial scale	Scenarios
Land loss due to SLR	in km^2	2020 - 2100: in 10 year steps (more runs can be performed if necessary)	NUTS2, country, global	ACCREU scenarios
Expected annual damages	Million US$ 2015		NUTS2, country, global	ACCREU scenarios
Expected annual people flooded	number of people		NUTS2, country, global	ACCREU scenarios
Adaptation costs (dike building, maintenance and migration cost)	Million US$ 2015		NUTS2, country, global	ACCREU scenarios

Flood damage per return period	Million US$ 2015		NUTS2, country, global	ACCREU scenarios
Exposure (Assets, Area, GDP and population in 100-year floodplain)	in km², Million US$ 2015, number of people		Flexible (Exposure in 1-in-100 year floodplain is default)	ACCREU scenarios

Table 17: GLOFRIS variables available for WP4-models. These variables are available through GLOFRIS for both coastal and riverine flooding.

Variable	Unit	Temporal scale	Spatial scale	Scenarios
Expected annual damages (EAD)	US$ 2005	2010, 2030, 2050, 2080	NUTS3 for EU27+UK, country-level for rest of the world	ACCREU scenarios
Flood damage per return period	US$ 2005			
Exposed population	Number of people			
Exposed assets (GDP)	US$ 2005			
Adaptation investment costs	US$ 2005	2020-2080		
Adaptation benefits (reduced flood impacts)	US$ 2005			

The DIVA and GLOFRIS models provide complementary sets of outputs for integration into macroeconomic models. Both models deliver expected annual damages, the costs of adaptation for the different options available, as well as exposure data. DIVA additionally provides land loss and GLOFRIS provides the reduction in flood impacts due to adaptation (adaptation benefits). There are some notable differences in the temporal and spatial resolution of the data provided. DIVA offers more frequent temporal snapshots, providing data in 10-year steps from 2020 to 2100, while GLOFRIS focuses on four specific time points (2010, 2030, 2050, and 2080).

In terms of spatial coverage, GLOFRIS provides higher resolution for the EU region, offering data at NUTS3 level compared to DIVA's NUTS2 resolution. However, DIVA maintains consistent NUTS2-level resolution globally, while GLOFRIS shifts to country-level data outside the EU27+UK region. Both models provide key economic indicators in monetary terms (US$), though they use different base years (2015 for DIVA, 2005 for GLOFRIS)

4.3 Limitations and future approaches

In conclusion, the use of annual risk metrics such as EAD remains a significant limitation as it fails to capture the unequal distribution over time of flood events. As efforts are made to integrate adaptation in these modeling exercises, such limitation extends to how the costs and benefits of adaptation are integrated. Yet, to date more detailed event-based datasets, including the costs and benefits of adaptation on a European scale are not available. We suggest three ways in which the data which is currently available can be implemented in macro-economic modeling.

First, a static-comparative CGE implementation where the annual damages and annual costs are implemented once, at a given point in time. While not fully realistic, this simple implementation can yield interesting insights through the computation of macro-economic cost-benefit ratios. These differ from typical cost-benefit ratios as they capture impacts on broader welfare in each region, for the different adaptation options accounting for the different economic characterization of each (e.g. different economic agents bearing the costs). The conceptual limitation of this approach is that it assumes that a single annualised investment can deliver some degree of damage reduction.

A second approach is a dynamic implementation where the adaptation cost is implemented over multiple years, prior to the flood event at a given point in time. Such a dynamic approach could provide insights into the economic reaction to the shock and its recovery pathways over time, with and without adaptation. However, as the flood event would still be represented by a single EAD the magnitude of the shock probably remains unrealistically small.

A final and third suggestion to consider is the development of a cumulative damage approach, with the goal of representing the compound effects of 'fictitious' events (e.g. to be modeled, for instance by implementing a shock equivalent to 5 times the EAD every 5 years). Such analysis could yield interesting insights into the linearity of the response from the economic model, along with the effects of multiple subsequent shocks.

5 Conclusion and discussion of results

This deliverable provides a comprehensive assessment of climate change impacts on infrastructure and the built environment in Europe, focusing on coastal and riverine flooding. Through the integration of three different modeling frameworks - DIVA, GLOFRIS, and LISFLOOD - we provide detailed insights into expected damages and adaptation costs under various climate and socioeconomic scenarios through 2100.

Key findings demonstrate that without adaptation, both coastal and riverine flood damages are projected to increase substantially across Europe, with Expected Annual Damages potentially reaching hundreds of billions of euros by 2100. However, our analysis shows that timely adaptation can significantly reduce these impacts. For coastal flooding, optimal protection strategies could reduce damages by up to two orders of magnitude compared to no adaptation scenarios. For riverine flooding, retention areas and dike strengthening emerge as particularly cost-effective measures, potentially reducing Expected Annual Damages by 68-83% depending on warming levels.

The comparison of different modeling approaches reveals important methodological insights, particularly regarding the treatment of exposure data, protection standards, and adaptation options. While some variations in damage estimates between models can be attributed to different methodological choices, the overall trends and spatial patterns of risk are consistent across approaches.

A novel contribution of this work is the detailed framework developed for integrating sectoral flood impact models with macroeconomic models. This integration enables a more comprehensive understanding of economy-wide impacts of both damages and adaptation measures, though challenges remain in representing the temporal distribution of flood events within annual metrics.

These findings provide crucial input for adaptation planning at both EU and national levels, while also highlighting key areas for future research, particularly in improving the representation of extreme events in long-term economic assessments and better understanding the macroeconomic implications of different adaptation strategies.

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Appendix

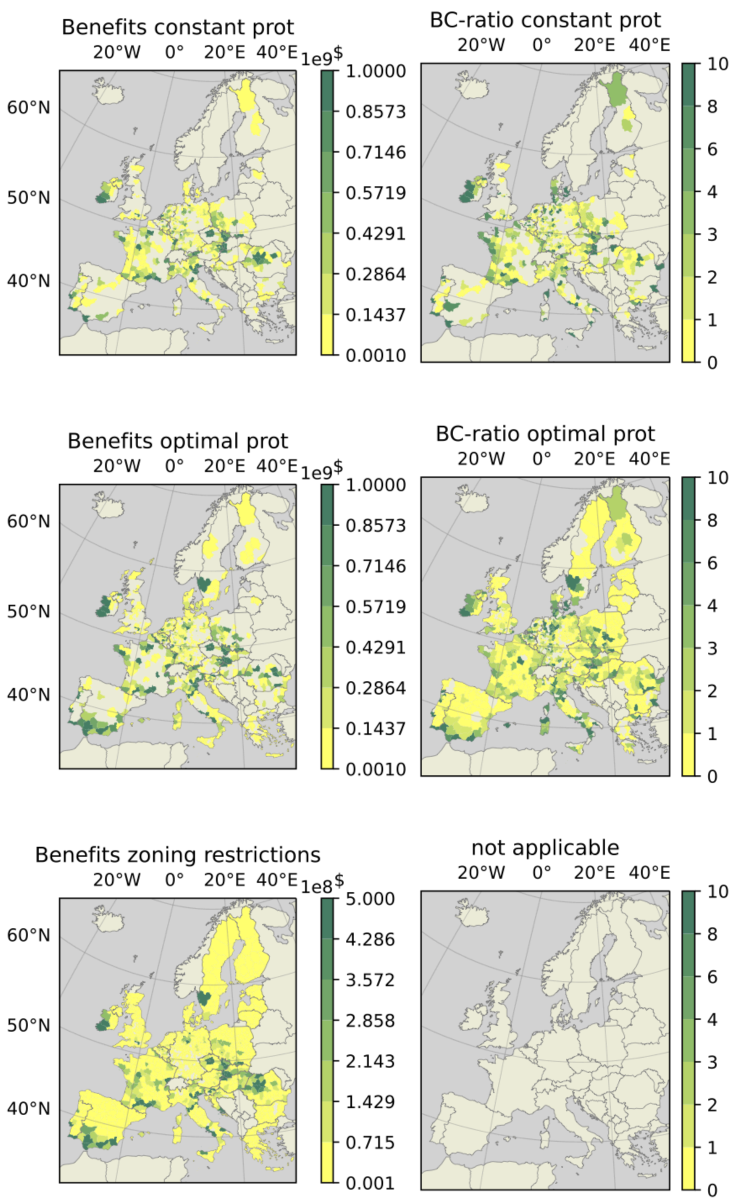

Figure A1: Left columns: The benefits of specific adaptation measures over the period 2020-2080. Right columns: The benefit-cost ratio associated with these measures over the same period. Shown data applies RCP2.6-SSP2 and the GCM HadGEM.

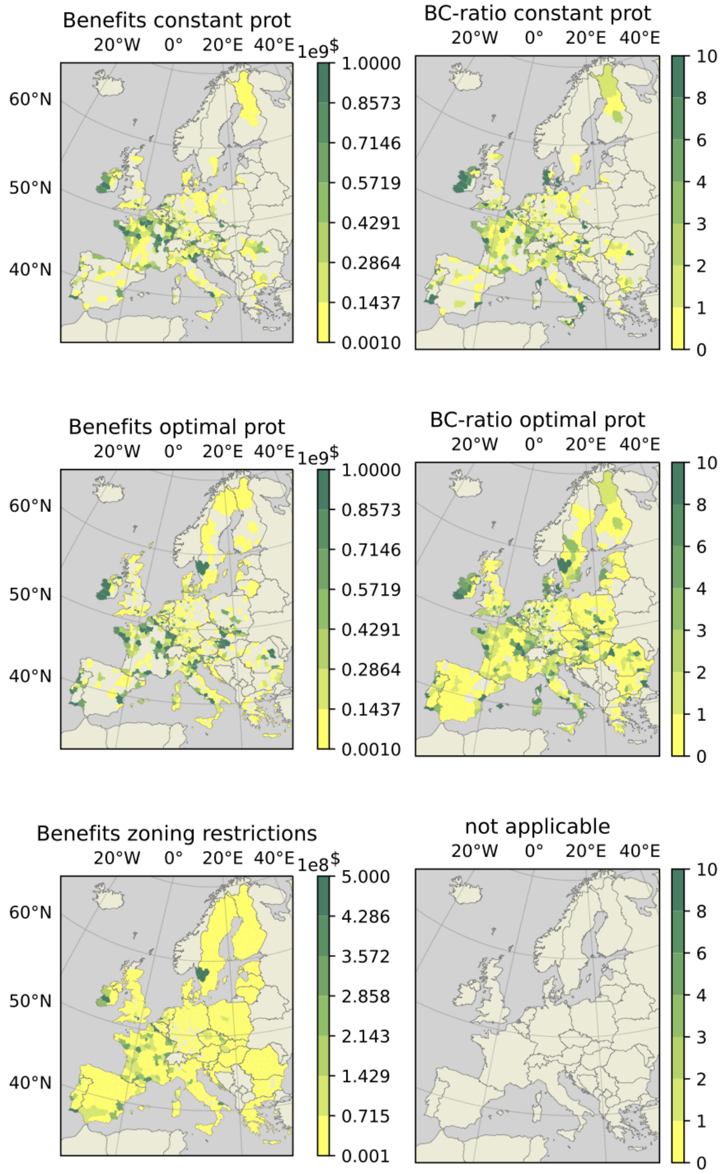

Figure A2: Left columns: The benefits of specific adaptation measures over the period 2020-2080. Right columns: The benefit-cost ratio associated with these measures over the same period. Shown data applies RCP4.5-SSP2 and the GCM HadGEM.