European Commission

JRC TECHNICAL REPORT

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

JRC PESETA IV project – Task 6

Michalis I. Vousdoukas, Lorenzo Mentaschi, Ignazio Mongelli, Juan Carlos Ciscar, Jochen Hinkel, Philip Ward, Simon Gosling, Luc Feyen

2020

Joint Research Centre

EUR 29969 EN

Contact information
Name: Michalis Vousdoukas
Address: Joint Research Centre, via E. Fermi 2749, 21027 Ispra (VA), Italy.
Email: michail.vousdoukas@ec.europa.eu
Tel.: +390332789869

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

JRC118512

EUR 29969 EN

PDF	ISBN 978-92-76-12990-5	ISSN 1831-9424	doi:10.2760/456870

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Vousdoukas M., Mentaschi L., Mongelli I., Ciscar J-C, Hinkel J.[(a)], Ward P.[(b)], Gosling S.[(c)] and Feyen L., *Adapting to rising coastal flood risk in the EU under climate change*, EUR 29969 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-12990-5, doi:10.2760/456870, JRC118512

All authors from the European Commission's Joint Research Centre, except
[(a)] Global Climate Forum, Germany
[(b)] Vrije Universiteit Amsterdam, The Netherlands
[(c)] University of Nottingham, UK

Contents

Executive summary

Around one third of the EU population lives within 50 km of the coast. Extreme sea levels in Europe could rise by as much as one meter or more by the end of this century. Without mitigation and adaptation measures, annual damages from coastal flooding in the EU and UK could increase sharply from 1.4 €billion nowadays to almost 240 €billion by 2100. Around 95% of these impacts could be avoided through moderate mitigation and by raising dykes where human settlements and economically important areas exist along the coastline. The extent to which adaptation can lessen the effects of coastal flooding and at what cost is sensitive to the investment strategy adopted.

Current effects of coastal flooding

Damages from coastal flooding in the EU and EU currently amount to 1.4 €billion annually, which is equivalent to around 0.01% of the current GDP of the EU and UK. Almost half of these damages are shared by the UK (0.4 €billion annually) and France (0.2 €billion annually). Around 100,000 people in the EU and UK are exposed to coastal flooding every year.

Impacts of coastal flooding without adaptation

Damages from coastal flooding are projected to rise sharply with global warming for all EU countries with a coastline if current levels of coastal protection are not raised. Annual damages grow to 239 €billion (0.52% of the GDP for EU+UK projected in 2100) and 111 €billion (0.24% GDP) in 2100 under a high emissions scenario and a moderate mitigation scenario respectively (Table 1), when assuming socioeconomic development according to the 2015 Ageing Report. The largest absolute damages are projected for Germany, Denmark, France, Italy, the Netherlands and UK. For some countries the damages represent a considerable proportion of future national GDP, e.g. 4.9% (Cyprus), 3.2% (Greece) and 2.5% (Denmark) by 2100 (high emissions). Although damages from, and exposure to coastal flooding, are around 50% lower with mitigation compared with high emissions, they are still significantly greater than at present. This means appropriate adaptation measures are needed to lessen the effects of future climate change along the EU coastline.

	Today	High emissions		Moderate mitigation	
		No adapt	Adapt	No adapt	Adapt
Damages (€ billion/year)	1.4	239	23	111	12
People exposed (million/year)	0.1	2.2	0.8	1.4	0.6

Figure 1. Annual damages and population exposed to coastal flooding for EU and UK at present and in 2100 under two emissions scenarios, with and without adaptation respectively. For adaptation, dykes are raised to a level of protection that maximises their economic benefit.

Adaptation options to coastal flooding

There exists a range of adaptation measures to reduce future flood risk in coastal areas. These include natural (dunes) and artificial (dykes) structures, beach nourishment, forecasting and warning systems, flood proofing of infrastructures, restricting new construction in future high-risk areas, and ultimately retreat from high-risk areas. Nature-based solutions, such as oyster beds, wetlands and salt marshes, create multiple benefits in addition to flood protection, such as increasing CO_2 storage, restoration of biodiversity, and offering recreational opportunities. They can also grow over time through the trapping of sediments and, thereby, compensate for rising sea levels. Yet, the projected rises in sea level extremes are so pronounced along Europe's coastlines that where human life may be at risk and high density, high value conurbations exist, the use of hard defence elements (dykes) will likely be unavoidable.

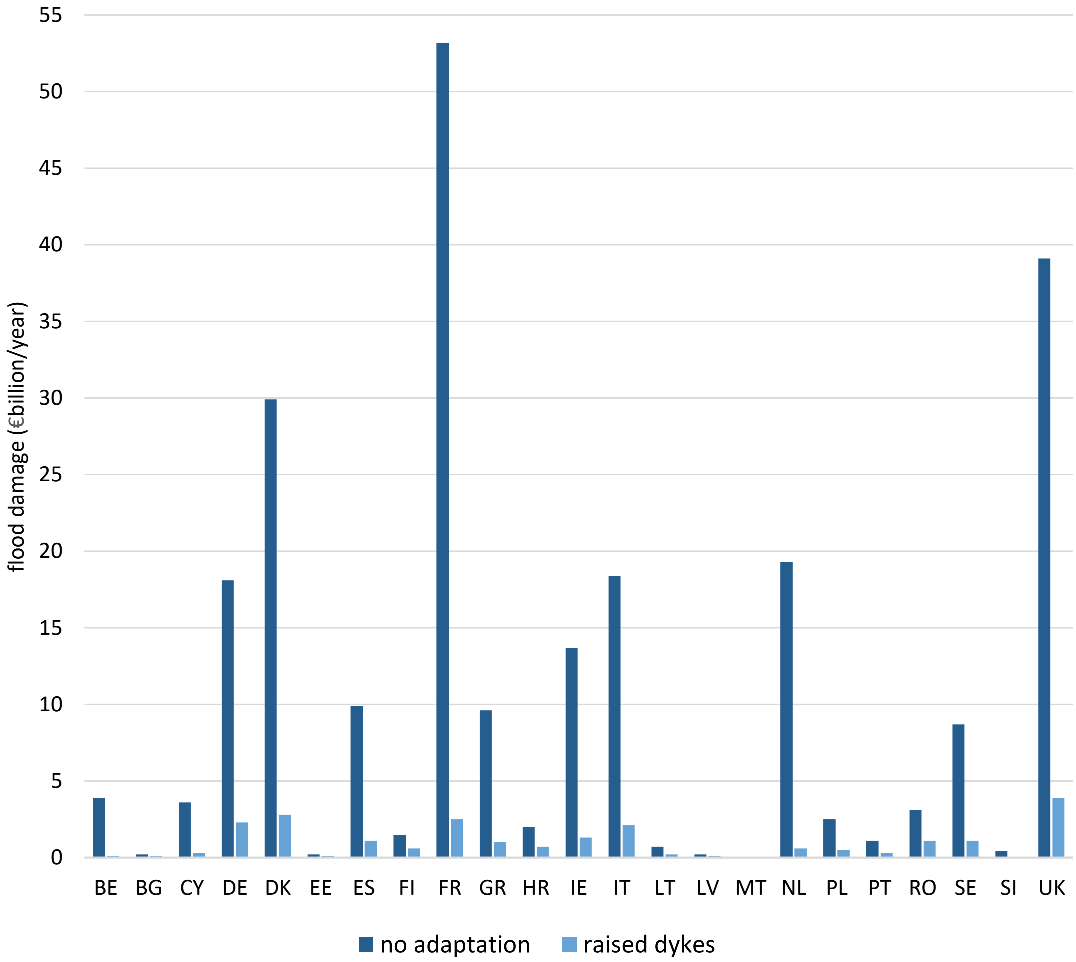

Figure 2. National annual damages without and with adaptation (for high emissions scenario in 2100).

Impacts reduction with adaptation

If dykes are raised along coastlines in the EU and UK, to a level of protection for each section that maximises their economic benefit (avoided flooding) relative to their cost, then annual flood damages could be reduced significantly relative to no adaptation (Figure 1 and Figure 2). Under the high emissions and moderate mitigation scenarios respectively in 2100, the damages are reduced by 90% (216 €billion/year) and 89% (97 €billion/year). Likewise, 63% (1.3 €million/year) and 59% (0.8 €million/year) less people would be exposed to coastal flooding respectively. The average annual cost of adaptation for the EU and UK over the period 2020-2100 is 1.9 €billion/year in the high emissions scenario and 1.3 €billion/year in the mitigation scenario. The UK, Germany and France have the highest adaptation costs because of higher construction costs and length of coastline where additional protection is required. The average annual cost of additional coastal protection is about two orders lower than the estimated reduction in annual flood losses by the end of the century. This means that investing now in coastal protection will have very large (and growing) benefits in the long term.

The costs and benefits of elevating dykes varies strongly between coastal segments in Europe. The presence of human development renders investing in dykes economically beneficial, typically when population density exceeds 500 people per km^2. In urbanized and economically important areas the benefits of raising dykes tend to be several times the costs, which is the case for 19% and 23% of the European coastline under a moderate mitigation and high emissions scenario, respectively. However, for the rest of Europe's coasts, additional protection against coastal inundation is not needed or economically beneficial. This can be either because natural barriers will sufficiently safeguard against the projected rise in sea level extremes in areas with steep morphology, or because costs of raising dykes outweigh benefits, which can happen in sparsely populated areas and along complex, winding coastlines.

The average raise in coastal defence height where further protection is needed in the EU is 100 and 84 cm under a high emissions and moderate mitigation scenario respectively. In Belgium this is even more than two meter, and also in Slovenia, Latvia, Poland, Germany, the Netherlands and the UK additional protection well above 1 meter will be required. This implies that along many densely populated and economically pivotal coastal stretches of the EU the shoreline may become disconnected from hinterland areas.

Factors that control costs and benefits of raising dykes

The results of the cost and benefit analysis are sensitive to some implementation choices. Shoreline length applies a critical control on the costs of dyke upgrades, which could be reduced substantially in areas with highly fractal coastlines by installing defences further inland. The outcomes are also very sensitive to discounting, which gives more weight to present capital costs and downgrades the benefits that will mostly come later in the century. We used discount rates in line with the EC Guide to Cost-Benefit Analysis of Investment Projects that were assumed constant in time. Using lower or time-declining social discount rates supports the view that we should act now to protect future generations. Similarly, dyke heights are optimised here considering the most likely projection of future extreme sea levels. Decision-makers could select a more conservative criterion and aim to protect against the high-end, less probable future extreme sea level scenarios. This would require higher investments but imply less risks for future generations.

Impacts of climate change on coastal zones are not limited to growing coastal flood risk. Coastlines will also be subject to increased potential of erosion, the loss of low-lying coastal ecosystems, and landward intrusion of saltwater, some of which can also be mitigated by raising dykes. In addition, the present assessment is limited to the 21^{st} century, but sea level rise and consequent flood risk is expected to continue well beyond 2100, even with accelerated rates. Including these effects would render additional protection as even more economically beneficial.

Approach

Projections of sea level rise, waves, storm surges and tides under a high emissions scenario (RCP8.5) and moderate mitigation scenario (RCP4.5) respectively, were used to estimate extreme sea levels up to the end of this century. These were used to generate flood inundation maps from which population exposure and damages were estimated using depth-damage functions. Future changes in population and economic activities are those from the ECFIN 2015 Ageing Report.

The level of adaptation (i.e. height in cm of raising dykes) was determined for each section of coastline in the EU and UK by identifying the height rise that maximises the sum over the project lifetime (up to 2100) of the costs and benefits associated with the investment, assuming discount rates of 5% (Cohesion Fund countries) and 3% (other Member States). The costs were calculated as the sum of national-level capital investment costs to raise dykes and maintenance costs. The benefits are the damages avoided by increasing the dyke height, calculated as the difference between future damages with and without raised dykes respectively. Flood losses, costs and benefits are presented undiscounted in general, but in the cost-benefit analysis of adaptation future costs and benefits are discounted. The benefit-cost ratio, which is the ratio of total benefits to total costs, is also based on discounted values and was calculated for each section of national coastline, at NUTS2, country and EU+UK level.

1 Introduction

The coastal zone is an area of high interest. At present, more than 200 million European citizens live near coastlines, stretching from the North-East Atlantic and the Baltic to the Mediterranean and Black Sea, and current trends indicate that migration toward coastal zones is continuing. Coastal areas often host important commercial activities and also support diverse ecosystems that provide important habitats and sources of food. Coastal zones are particularly vulnerable to climate change due to the combined effects of sea level rise and potential changes in the frequency and intensity of storms. Global mean sea level has increased by 13-20 cm since pre-industrial times (Kopp *et al.*, 2016). This process has accelerated since the 1990s (Watson *et al.*, 2015) and the rise after 1950 can be explained by global warming (Slangen *et al.*, 2014). This has already contributed to coastal recession (EUROSION, 2003; Mentaschi *et al.*, 2018) and made Europe's coasts more susceptible to coastal hazards. The continued rise in sea levels along Europe's coastlines in view of global warming could result in unprecedented coastal flood losses in Europe in case no additional coastal protection and risk-reduction measures are implemented.

There exists a range of possible adaptation measures to increase the resilience of future coastal societies to flooding. These include natural (dunes) and artificial (dykes) structures, beach nourishment, forecasting and warning systems, flood proofing of infrastructures, and retreat from high-risk areas. Accommodating flood hazard is another option, which involves making infrastructure less susceptible to flood damages. Nature-based solutions have recently gained attention as more environmentally sustainable ways to protect and maintain coastlines (Temmerman *et al.*, 2013). Mangroves and sea grass attenuate waves, water flow and flooding (Thomas *et al.*, 2014), reduce stormwater runoff, and help building up coasts by contributing to the processes that generate, trap, and distribute sediment across shorelines (Lentz *et al.*, 2016). In a similar manner, reefs can also reduce shoreline erosion (McAdoo *et al.*, 2011).

Despite the multiple co-benefits of nature-based solutions, estimates of their costs, benefits and long-term performance are lacking. Moreover, many of the tested approaches (e.g. reefs, mangroves) have limited applicability in Europe. Along developed coastlines, currently hard protection is the only strategy with demonstrated effectiveness against coastal extremes and sea level rise. Dyke or seawall reinforcement has been the most common practice for decades, despite the fact that hard protection can affect the landscape in a negative way, increase erosion, reduce amenity value and result in more catastrophic events in case of failure. A possible alternative strategy is relocating dwellings and infrastructure in order to reduce coastal flood risk, but relocation is often challenging due to technical issues or public opposition. Moreover, the nature of some critical assets like ports and power plants, is directly linked to their presence close to the sea, and therefore their relocation is particularly challenging.

For these reasons, we evaluated the costs and benefits of applying additional protection through dyke improvements, assuming that the densely populated and high income European coastal communities will choose to 'hold the line'. This assumption doesn't exclude the parallel implementation of 'greener' solutions, which can co-exist to further improve the resilience of the coastline against coastal hazards. There are already pilot projects in Europe towards that direction, exploring concepts like 'mega-nourishments" (Brière *et al.*, 2018), or "wide green dykes" (Van Loon-Steensma and Vellinga, 2019). Yet, there is still lack of information on long-term maintenance, performance and (cost-) effectiveness. In addition, such interventions require site-specific design, which is beyond the scope of a continental analysis. Therefore we focus only on the cost effectiveness of raising the height of flood defences using traditional approaches and assume that the cost variation of implementing alternative solutions would lie within the uncertainty intervals of the present cost estimates.

2 Methodology

We employ a probabilistic modelling framework that includes the following steps: (i) estimate present and future extreme sea levels along Europe's coastlines based on state-of-the-art projections of sea level rise, waves, storm surges and tides for a high emissions (RCP8.5) and moderate mitigation (RCP4.5) scenario; (ii) delineate the land areas inundated when extreme sea levels overtop present coastal protection and derive the corresponding flood inundation depth using 2-D hydraulic modelling and considering events of different return periods during the present century; (iii) overlay the inundation maps with exposure information on population and land use; (iv) translate this into direct flood losses using functions that relate the depth of inundation with economic damage to the assets inundated, and into the number of people exposed to inundation, taking into the socioeconomic and demographic projections of the ECFIN 2015 Ageing Report[1]; (v) repeat steps (ii), (iii) and (iv) with step-wise increases in dyke height and compare the economic benefits (= avoided flood damage during this century) with literature-based estimates of the capital expenses and maintenance costs during the century; (vi) for each coastal segment the dyke height that maximises the net present value, defined as the sum over the project lifetime of the costs (that are negative) and benefits, is considered the optimum.

Adaptation costs are the combination of the construction investment and maintenance costs. Dykes are assumed to be upgraded gradually to the desired design between 2020 and 2050, and construction costs that are obtained from literature are spread over this period, after which the dykes are maintained during the rest of the 21st century at 1% per year of capital investment costs. Benefits are the avoided losses from coastal flooding from 2020 up to the end of this century. We applied discounting to both the costs and benefits considering a rate of 5% for the EU cohesion countries and 3% for the other EU member states. The objective of the cost-benefit analysis is to find the protection standard for each coastal segment that maximises the sum over the project lifetime of the net benefit (difference between benefits and costs) and determine whether the increased protection will deliver sufficient benefits to justify the costs. We note that other potential benefits of increased protection of coastal areas against inundation, such as the avoided loss of valuable ecosystems, are not included in the analysis. Also benefits beyond 2100, which very likely will grow strongly in view of the accelerated rise in sea levels, are not considered here.

All variables computed in this study are available as probability density functions (based on 10,000 runs), but we focus our discussion on the most likely case (i.e. mean values). Results are presented and discussed at four spatial scales: along ~10,000 coastal sections of the European coastline, as well as at NUTS2, country and European level.

In PESETA IV the focus is on understanding the impacts of climate change in Europe at different levels of global warming. This is also how results are presented in the reports for the other tasks. For coastal flood risk, however, this is not possible due to the delayed effects of sea level rise in response to warming. More than 90 percent of the trapped heat in the atmosphere is being absorbed by the oceans. Water volume rises with temperature because of thermal expansion of water, yet because the convection and diffusion of heat in the ocean is a slow process, sea levels will continue to rise for centuries after climate has stabilised at a certain warming level. Hence, assuming all other factors constant, impacts at 2°C in 2050 will be smaller than impacts at 2°C in 2100, as the oceans have more time to expand. So if we would present impacts for warming levels, then the impacts at a specific warming level would be smallest for the highest emission pathway, simply because it reaches a warming level faster and there is less time for the oceans to react. We therefore present impacts in 2050 and 2100 for the two emissions trajectories, and also the adaptation analysis is done separately for the two concentration pathways.

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

3 Results

3.1 Impact estimates without climate change adaptation

The coastal hazard analysis (reported in PESETA III) projects a very likely increase of the European average 100-year extreme sea level of 34–76 cm under a moderate mitigation scenario and of 58–172 cm under a high emissions scenario. Sea level rise is the main driver of this strong increase, yet in many regions of Europe there is also a contribution of intensified coastal storms.

At present, coastal flood losses in Europe amount to 1.4 €billion/year (expressed in €2015 values), or approximately 0.01% of the EU+UK GDP in 2015, and each year about 100,000 EU citizens are exposed to coastal inundation. The UK and France are the countries with the highest current exposure to coastal flooding, both in terms of losses and people exposed. Flood risk is projected to increase strongly in Europe with global warming. In the absence of further investments in coastal adaptation, annual coastal flood losses for the EU+UK are projected to grow to 10.9 €billion (0.05% EU+UK GDP of 2050) and 14.1 €billion (0.06% GDP) by mid-century for RCP4.5 and RCP8.5, respectively (Table 1 and Table 2). In the second half of this century the rise in coastal flood risk further accelerates and by 2100 annual coastal flood losses are projected to reach 110.6 (0.24% EU+UK GDP in 2100) and 239.4 €billion (0.52% GDP), respectively. Therefore, the moderate mitigation scenario would reduce the economic damages by more than half compared to the high emission scenario. The total number of people exposed to coastal flooding in Europe is projected to rise to 471k and 581k per year by 2050 under RCP4.5, and RCP8.5, respectively (Table 3), which further climbs to 1.4 and 2.2 million people per year by the end of the century. Coastal flood risk will increase in all EU-countries that have a coastline, with France, the UK, Italy and Denmark showing the highest absolute increase in coastal flood impacts towards the end of the century. For some countries, coastal flood losses at the end of this century could amount to a considerable share of their GDP, especially under a high-emissions pathway (RCP8.5), most notable in Cyprus (4.9%), Greece (3.2%), Denmark (2.5%), Ireland (1.8%) and Croatia (1.8%) (see Table 2). It is important to note that the exposure maps do not differentiate sites of historical and cultural heritage, nor critical infrastructure, from general land use types. Hence, at locations with critical assets the socioeconomic impacts from flooding are likely higher than those estimated on land use.

At any specific point in time impacts under the high emissions scenario are always larger than under the moderate mitigation scenario, and they grow much faster with time under the high-emissions pathway. This indicates that climate change mitigation is effective in reducing future coastal flood risk. In contrast to the other PESETA IV impact analyses, coastal flood risk is not presented for global warming levels. This is because sea levels will continue to rise for decades and even centuries after climate stabilizes at a certain warming level, and consequently also the risks for coastal societies. We further note that in the PESETA III report the flood impacts reported were based on different socioeconomic scenarios (the so-called Shared Socioeconomic Pathways, more in particular we used SSP1 in combination with the moderate mitigation scenario and SSPs 3 and 5 in combination with high emissions). The estimates herein are based on socioeconomic conditions projected by the ECFIN 2015 Ageing report. Given that the socioeconomic growth is lower under the ECFIN scenario compared to SSP1, present direct flood impacts for the moderate mitigation scenario are 40% lower compared to the previous moderate mitigation – SSP1 projections (EAD around 156 €billion by the end of the century). On the other hand, projected losses under high emissions - ECFIN are more than double compared to high emissions – SSP3 (EAD around 93 €billion by the end of the century), yet much smaller than those for high emissions – SSP5 (EAD around 961 €billion by the end of the century). The present analysis is based on the ECFIN projections to ensure better consistency of the impacts with the economic and budgetary projections for EU Member States. Despite the uncertainty in future socioeconomic conditions in Europe, results for all socioeconomic scenarios, especially when expressed relative to the size of the economy, show that coastal flood risk will increase strongly along all coastlines of Europe.

Table 1. Expected Annual Damage (EAD, in €billion) from coastal flooding in 2050 and 2100 under moderate mitigation and high emissions scenarios, shown per country and for EU+UK.

		MODERATE MITIGATION		HIGH EMISSIONS	
COUNTRY	Baseline	2050	2100	2050	2100
BE	0.0	0.2	2.4	0.2	3.9
BG	0.0	0.0	0.1	0.0	0.2
CY	0.0	0.1	0.8	0.1	3.6
DE	0.1	0.8	7.1	1.1	18.1
DK	0.0	0.5	10.2	0.7	29.9
EE	0.0	0.0	0.1	0.0	0.2
ES	0.1	0.6	5.3	0.8	9.9
FI	0.0	0.0	0.2	0.1	1.5
FR	0.2	2.4	23.2	3.2	53.2
GR	0.1	0.8	4.4	0.9	9.6
HR	0.0	0.1	1.1	0.2	2.0
IE	0.1	0.6	6.7	0.8	13.7
IT	0.1	1.0	10.4	1.4	18.4
LT	0.0	0.1	0.4	0.1	0.7
LV	0.0	0.0	0.1	0.0	0.2
MA	0.0	0.0	0.0	0.0	0.0
NL	0.0	0.2	12.9	0.3	19.3
PL	0.1	0.4	1.5	0.4	2.5
PT	0.1	0.2	0.7	0.2	1.1
RO	0.0	0.0	0.1	0.0	3.1
SE	0.0	0.1	2.4	0.2	8.7
SI	0.0	0.1	0.3	0.1	0.4
UK	0.4	2.5	20.2	3.2	39.1
EU+UK	1.4	10.9	110.6	14.1	239.4

Table 2. Expected Annual Damage (EAD, expressed as percentage of the GDP) from coastal flooding in 2050 and 2100 under moderate mitigation and high emissions scenarios, shown per country and for EU+UK.

		MODERATE MITIGATION		**HIGH EMISSIONS**	
COUNTRY	Baseline	2050	2100	2050	2100
BE	0.01%	0.02%	0.14%	0.03%	0.23%
BU	0.00%	0.01%	0.04%	0.01%	0.16%
CY	0.04%	0.35%	1.13%	0.43%	4.87%
DE	0.00%	0.02%	0.10%	0.03%	0.26%
DK	0.02%	0.11%	0.85%	0.14%	2.50%
EE	0.03%	0.09%	0.23%	0.11%	0.38%
ES	0.01%	0.04%	0.18%	0.05%	0.33%
FI	0.01%	0.01%	0.03%	0.02%	0.22%
FR	0.01%	0.07%	0.27%	0.09%	0.61%
GR	0.04%	0.34%	1.50%	0.39%	3.24%
HR	0.04%	0.18%	0.96%	0.23%	1.78%
IR	0.04%	0.20%	0.87%	0.29%	1.79%
IT	0.01%	0.04%	0.23%	0.06%	0.40%
LT	0.03%	0.15%	0.38%	0.17%	0.72%
LV	0.02%	0.07%	0.20%	0.08%	0.35%
MA	0.00%	0.01%	0.06%	0.02%	0.08%
NL	0.00%	0.02%	0.64%	0.03%	0.96%
PL	0.02%	0.05%	0.11%	0.06%	0.19%
PO	0.03%	0.08%	0.20%	0.09%	0.32%
RO	0.00%	0.00%	0.02%	0.00%	0.60%
SE	0.00%	0.01%	0.10%	0.02%	0.35%
SL	0.07%	0.11%	0.23%	0.12%	0.31%
UK	0.02%	0.07%	0.23%	0.09%	0.44%
EU+UK	0.01%	0.05%	0.24%	0.06%	0.52%

Table 3. Expected Annual Population Exposed (EAPE, in thousand people) to coastal flooding in 2050 and 2100 under moderate mitigation and high emissions scenarios, shown per country and for EU+UK.

		MODERATE MITIGATION		**HIGH EMISSIONS**	
COUNTRY	Baseline	2050	2100	2050	2100
BE	0.5	2.7	15.9	3.6	25.5
BU	0.6	1.1	1.4	1.2	2.0
CY	3.0	8.9	11.6	9.3	12.7
DE	2.0	8.9	31.3	12.7	72.7
DK	1.0	7.2	71.0	9.0	158.7
EE	0.1	0.2	0.3	0.3	0.4
ES	8.1	54.0	141.2	68.8	179.4
FI	0.5	1.2	2.9	1.8	22.5
FR	3.5	30.1	139.9	42.4	254.0
GR	10.7	49.8	79.8	56.5	112.7
HR	9.2	27.4	51.1	32.1	71.1
IR	3.1	19.7	74.9	25.9	115.0
IT	12.7	81.4	202.1	102.9	270.2
LT	1.3	2.0	3.7	2.1	6.1
LV	0.2	0.3	0.6	0.4	0.9
MA	0.0	0.1	0.2	0.1	0.2
NL	0.6	3.4	4.1	4.5	7.1
PL	9.9	16.3	18.6	17.3	26.5
PO	2.6	5.1	7.9	5.9	11.4
RO	0.5	0.9	2.9	1.0	5.1
SE	0.5	2.6	31.1	3.7	74.4
SL	2.4	3.8	4.4	4.0	4.9
UK	27.7	143.7	452.1	175.7	721.9
EU+UK	100	471	1349	581	2156

3.2 Costs and Benefits of adaptation

The costs and benefits of raising dykes show high spatial variability between coastal segments. Overall, benefits exceed costs for 19% and 23% of the European coastline segments under a moderate mitigation and high emissions scenario, respectively (Table 4). Thus, present natural or hard shoreline protection is economically optimal for 81% and 77% of the European coastline, under a moderate mitigation and high emissions scenario, respectively. No economic motivation for increased protection can be related to several factors, like natural barriers with steep morphology that sufficiently protect against the projected rise in sea level extremes. In sparsely populated coastlines benefits (avoided damages) are low because of the limited exposure. Also long and complex coastlines imply higher dyke construction costs, hence lower BCR values, such as in many parts of Finland, Sweden, Estonia, and Croatia. Most of the Baltic is experiencing uplift and therefore relative sea level rise is lower compared to other parts of Europe, implying also lower future losses and potential benefits of adaptation for a significant part of Finland and Sweden. The presence of human development renders adaptation rapidly as economically beneficial, with benefits tending to outweigh costs in areas where population density is larger than 500 people per km^2. In urbanized and economically important areas the benefits tend to be several times the costs.

Table 4. Percentage of the country's coastline (i) where further protection is not economically beneficial, and (ii) where adaptation is economically beneficial. The last two columns show the country level benefit to cost ratio (BCR) with adaptation only in the coastal segments where it is economically beneficial.

	% NO ADAPTATION		**% ADAPTATION**		**COUNTRY BCR**	
COUNTRY	moderate mitigation	high emissions	moderate mitigation	high emissions	moderate mitigation	high emissions
BE	15	15	85	85	7.3	10.5
BG	96	95	4	5	2.1	1.9
CY	78	76	22	24	7.4	8.4
DE	72	53	28	47	3.6	4.7
DK	71	58	29	42	3.6	5.4
EE	99	98	1	2	3.6	3.2
ES	61	55	39	45	5.7	6.5
FI	98	91	2	9	2.1	2.4
FR	48	40	52	60	7.5	10.6
GR	93	92	7	8	11.9	11.6
HR	89	86	11	14	2.7	2.9
IE	80	75	20	25	6.1	7.9
IT	55	53	45	47	6.0	6.9
LT	73	68	27	32	3.5	3.6
LV	97	95	3	5	5.0	3.7
MT	100	87	0	13	0.0	1.5
NL	69	64	31	36	13.9	17.7
PL	76	72	24	28	3.4	4.0
PT	80	79	20	21	4.4	4.4
RO	97	87	3	13	1.5	3.0
SE	90	84	10	16	4.4	6.7
SI	50	50	50	50	3.3	3.5
UK	80	75	20	25	4.7	5.8
EU+UK	81	77	19	23	5.6	7.1

When benefits and costs are aggregated across coastal segments to NUTS2 regions, the total benefits are dominated by those in urban centres. The BCR of regions are mapped in Figure 3 and they give an indication of how much the benefits exceed the adaptation costs for the region, once the benefits and costs of the coastal segments where adaptation is economically beneficial are aggregated to the regional level. High BCR values not necessarily imply that the whole regional coastline should be protected because the cost-benefit analysis is made at the segment level. The regional (as well as the country and EU+UK) BCR value therefore is more an indication to assess the degree to which some regions (or countries/EU+UK) experience gains in terms of avoided damages much greater than the incurred adaptation costs. Adaptation comes with far stronger economic benefits in the Ionian Islands (BCR equal to 27 and 30 under a moderate mitigation and high emissions scenario, respectively), the País Vasco (25 and 27), Aquitaine (12 and 16), Hampshire and Isle of Wight (11 and 13), Calabria (10.6 and 11.3), Basse-Normandie (8 and 14), Pays de la Loire (8 and 13), Puglia (9.5 and 11), and Alentejo (11, 8).

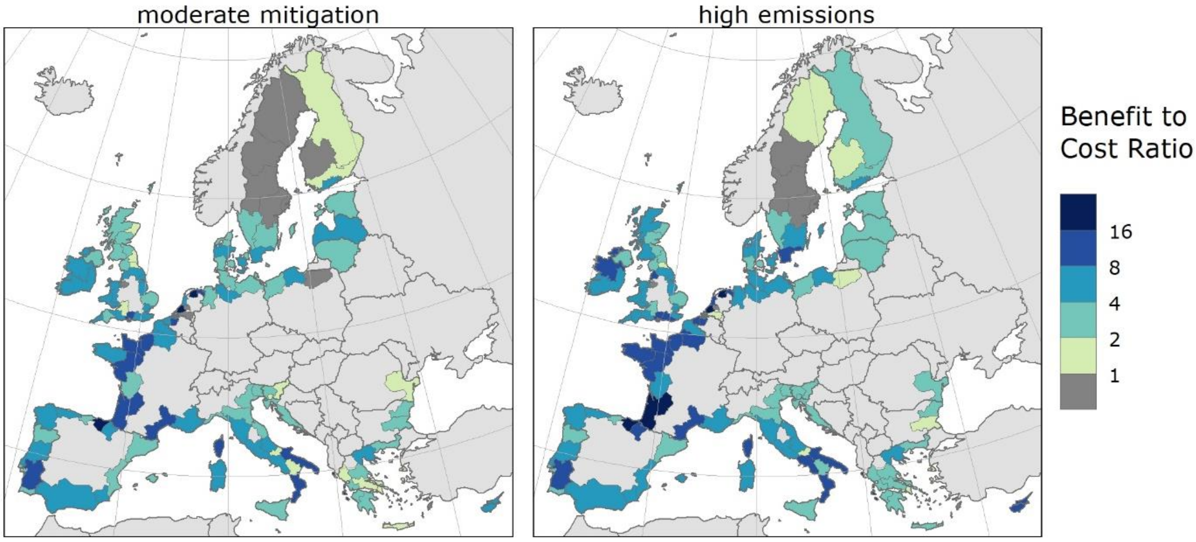

Figure 3. Benefit to cost ratios per NUTS2 region under a moderate mitigation and high emissions scenarios.

At country level, Belgium is the country with the highest percentage of coastline where benefits exceed costs (85% under both scenarios), followed by France (52% and 60% under moderate mitigation and high emissions scenario, respectively), Slovenia (50%) and Italy (45 and 47%; Table 4). When the coastal segments results are aggregated to the country level, these are also the countries with some of the highest country-level BCRs, equal to 7.3 (10.5), 7.5 (10.6), 3.3 (3.5), and 6 (6.9) under the moderate mitigation (high emissions) scenario (Table 4). Other countries with high BCR values are the Netherlands (BCR equal to 13.8 and 17.7, under moderate mitigation and high emissions scenario, respectively), Greece (11.9 and 11.6), Cyprus (7.4 and 8.4), and Ireland (6.1-7.9) (Table 4). On the lower end of cost-efficiency lies Malta for which no economic incentives to protect further against increasing sea levels were found under the moderate mitigation scenario, while under high emissions the country level BCR of 1.47 is the lowest. Other countries with low country level BCRs are Bulgaria (BCR equal to 2.1 and 1.9, under moderate mitigation and high emissions scenario, respectively), Finland (2.1 and 2.4), Romania (1.5 and 3) and Croatia (2.7 and 2.9). The BCR for the EU+UK is 5.6 and 7.1, under a moderate mitigation and high emissions scenario, respectively (Table 4).

The Netherlands is a particular case as the country is already very well protected (up to ~10,000 year return period), by an extensive network of multiple dykes and barriers. We find that with additional protection it is even less likely that the Netherlands will experience a catastrophic flood during the century. However, the country has a high income level, an extensive low-lying area and high population density, so flood events can have massive impacts when they occur, and for that reason the BCR for the Netherlands is the highest in Europe. Thus, the benefits from protecting further are high (high BCR), even though flood events are rare.

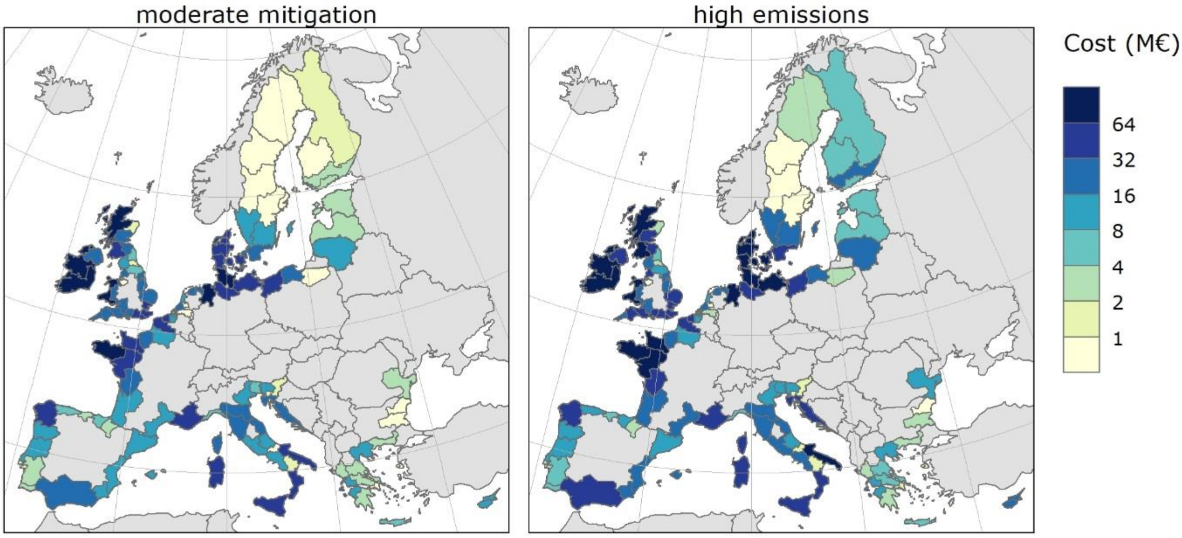

Figure 4. Average annual costs of adaptation (in €million/year; not discounted and averaged over period 2020-2100) per NUTS2 region under a moderate mitigation and high emissions scenario.

The estimated average annual investment for further dyke improvements in the EU+UK during the present century (over period 2020-2100, without discounting) is 1.3 €billion/year for the moderate mitigation and 1.9 €billion/year for the high emissions scenario, with the latter being larger due to the further protection needed against the higher extreme sea levels (Table 5 and Figure 4). Country level adaptation costs depend on the value of assets and the coastline length, with the UK (323-457 €million/year), France (217-314 €million/year), Germany (145-243 €million/year), Italy (137-189 €million/year), and Denmark (145-243 €million/year) facing the highest projected costs (Table 5). Other countries with substantial costs of dyke reinforcement are Ireland, Spain and the Netherlands (>40 €million/year), as well as Sweden, Poland, Greece and Belgium (all above €20 million/year).

Considering only the locations where further protection is economically beneficial, the additional average coastal defence height needed in Europe is 84 and 100 cm under the moderate mitigation and high emissions scenario, respectively (Table 5). Country average values vary from a minimum of 42 cm (Malta) to a maximum of 2.25 m (Belgium). Apart from Belgium, other countries that need to apply substantial additional protection are Slovenia (1.72 and 1.89 m), Latvia (1.42 and 1.98 m), Poland (1.22 and 1.49 m), Germany (1.31 and 1.38 m), the Netherlands (1.28 and 1.30 m), UK (1.2 and 1.3 m), and Estonia (1.2 and 1.35 m).

Table 5. Annual costs per country of raising the dykes where adaptation is economically beneficial (in €million/year, undiscounted, average over period 2020-2100) and corresponding country-level average increase in dyke height (m).

	COST OF PROTECTION (€MILLION/YEAR)		DYKE HEIGHT INCREASE (M)	
COUNTRY	moderate mitigation	high emissions	moderate mitigation	high emissions
BE	22.0	22.1	2.24	2.25
BG	0.6	1.6	0.57	0.76
CY	6.7	9.9	0.67	0.90
DE	144.8	242.8	1.31	1.38
DK	119.6	198.2	0.91	1.03
EE	1.3	2.6	1.20	1.35
ES	67.8	103.4	0.54	0.71
FI	3.3	21.9	0.70	0.80
FR	217.4	313.9	0.83	1.01
GR	30.1	38.6	0.63	0.73
HR	14.2	21.1	0.56	0.69
IE	73.4	114.5	0.83	0.97
IT	137.2	188.9	0.64	0.83
LT	7.5	9.8	1.08	1.18
LV	1.3	2.5	1.98	1.42
MT	0.0	0.5	-	0.42
NL	42.3	48.9	1.30	1.28
PL	28.6	40.4	1.22	1.49
PT	13.9	18.4	0.83	1.03
RO	1.4	6.5	0.90	0.98
SE	21.2	50.6	0.66	0.83
SI	7.0	7.8	1.72	1.89
UK	322.6	457.2	1.20	1.31
EU+UK	1284.3	1921.9	0.84	1.00

3.3 Avoided damages with adaptation

Applying adaptation that optimises benefits and costs everywhere along Europe will still result in losses from coastal flooding, especially towards the end of the century. By 2100, the total EAD for the EU and UK will reach 12.3 and 22.9 €billion under a moderate mitigation and high emissions scenario, respectively (Table 6), compared to 108.9 and 236.4 €billion in case of no adaptation. Hence, coastal adaptation through increased protection with dykes will reduce the 2100 EAD along the entire European coastline by 89% (96.9 €billion) and 90% (216 €billion) under a moderate mitigation and high emissions scenario, respectively, compared to a 'do nothing' scenario. In addition it will reduce the EAD down to 0.03-0.05% of the GDP, compared to 0.24-0.52% under a do-nothing scenario. The highest losses are projected for Scotland, Ireland, Denmark, Romania, Croatia, Cyprus, Andalucía, Bretagne, the south east Baltic Sea, and Provence, with NUTS2 level EAD exceeding 300 €million towards the end of the century under a high emissions scenario. The highest per country EAD reduction is projected in France (22 and 51 €billion under moderate mitigation and high emissions scenario, respectively), the UK (17, 35), Denmark (8, 25) and the Netherlands (11-19 €billion) (Table 6).

Table 6. Expected Annual Damage (EAD, €billion) and Expected Annual Population Exposed (EAPE) in 2100 after implementing additional protection, as well as their reduction (avoided impacts) compared to a 'do not adapt scenario'.

	EAD WITH ADAPTATION		**AVOIDED ANNUAL DAMAGES**		**EAPE WITH ADAPTATION**		**AVOIDED ANNUAL PEOPLE EXPOSED**	
COUNTRY	Moderate mitigation	High emissions	Moderate mitigation	High emissions	Moderate mitigation	High emissions	Moderate mitigation	High emissions
BE	0.0	0.1	2.3	3.9	13.9	7.9	2.0	17.6
BG	0.0	0.1	0.0	0.1	1.2	1.4	0.2	0.6
CY	0.1	0.3	0.7	3.3	6.8	6.6	4.8	6.1
DE	1.5	2.3	6.0	16.8	15.5	25.7	15.8	47.0
DK	1.5	2.8	8.1	25.4	25.5	48.8	45.6	109.9
EE	0.1	0.1	0.1	0.1	0.2	0.4	0.0	0.1
ES	0.6	1.1	4.7	8.8	62.0	69.5	79.2	109.9
FI	0.1	0.6	0.1	0.9	2.2	13.1	0.8	9.3
FR	1.2	2.5	22.0	50.7	40.7	58.3	99.2	195.7
GR	0.6	1.0	3.9	8.6	56.8	87.2	23.0	25.5
HR	0.4	0.7	0.7	1.3	20.8	28.5	30.3	42.6
IE	0.9	1.3	5.8	12.4	22.6	52.9	52.3	62.1
IT	1.1	2.1	9.3	16.4	61.5	78.6	140.6	191.6
LT	0.1	0.2	0.3	0.6	1.9	3.2	1.8	2.9
LV	0.1	0.1	0.1	0.1	0.5	0.8	0.0	0.1
MT	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0
NL	0.4	0.6	11.3	18.7	3.6	6.1	0.6	1.1
PL	0.3	0.5	1.2	2.0	10.4	13.9	8.2	12.6
PT	0.2	0.3	0.5	0.8	4.9	7.1	3.0	4.3
RO	0.1	1.1	0.0	2.0	2.3	2.6	0.6	2.6
SE	0.4	1.1	2.0	7.6	10.0	20.9	21.1	53.5
SI	0.0	0.0	0.2	0.3	0.6	0.8	3.8	4.1
UK	2.7	3.9	17.5	35.1	188.5	271.3	263.7	450.5
TOTAL	12.3	22.9	96.9	216.0	552.5	805.9	796.4	1349.6

Similarly, further coastal protection will still result in people exposed to coastal flooding. The EU total expected annual number of people exposed to coastal flooding (EAPE) at the end of the century reaches 552.5k and 805.9k under the moderate mitigation and high emissions scenario, respectively (Table 6). This corresponds to a reduction in people exposed to coastal flooding by 59% (796.4k people) and 63% (1349.6k) compared to a 'do nothing' scenario (Table 6). The highest per country EAPE reduction is projected in the UK (264k-450.5k), France (99k-196k) and Italy (141k-192k) (Table 6). However, if dykes are raised only along coastal segments where it is economically beneficial to do so, some coastal populations are projected to be more exposed to floods in the future. This is particularly the case in Puglia, Croatia, the Ionian Islands, Scotland, Ireland and south east UK. Designing adaptation measures to rising extreme sea levels on the basis of economic criteria alone may therefore not be the optimal strategy and also other factors should be considered.

4 Conclusions

European coastal zones will be exposed strongly to the effects of climate change. Extreme sea levels in Europe could rise by as much as one meter or more by the end of this century, and will very likely continue to rise for many more centuries. In the absence of further investments in coastal adaptation, annual coastal flood losses for the EU+UK are projected to grow from 1.4 €billion/year (0.01% EU+UK GDP) to 10.9 €billion (0.05% EU+UK GDP of 2050) and 14.1 €billion (0.06% GDP) by mid-century for a moderate mitigation and high emissions scenario, respectively. In the second half of this century the rise in coastal flood risk further accelerates and by 2100 annual coastal flood losses are projected to reach 110.6 (0.24% EU+UK GDP in 2100) and 239.4 €billion (0.52% GDP), respectively. The total number of people exposed to coastal flooding in Europe is projected to rise from 100k to 471k and 581k per year by 2050 under a moderate mitigation and high emissions scenario, respectively, which further climbs to 1.4 and 2.2 million people per year by the end of the century.

The above economic loss estimates obtained in PESETA IV for the ECFIN 2015 scenario are within the range of the estimates previously reported in PESETA III for the Shared Socioeconomic Pathways (SSPs), where expected annual losses by the end the century varied between 93 and 961 €billion, depending on the socioeconomic scenario. This confirms that global warming will result in an unprecedented rise in coastal flood impacts in case no further adaptation measures are taken to protect European coastal societies. The use of different socioeconomic scenarios further shows that the absolute magnitude of these impacts is further amplified by the projected rise in economic activity in coastal areas. At the same time, findings of PESETA III and IV clearly show that climate change mitigation is effective in reducing future coastal flood risk in the EU, as projected impacts by 2100 under a moderate mitigation scenario are less than halve of those without mitigation.

The rise in coastal flood losses is so pronounced that where human life may be at risk and high density, high value conurbations exist, the use of hard defence elements may be unavoidable. The PESETA IV analysis shows that applying further dyke improvements in the most economically optimal way along Europe's coastlines will reduce the 2100 EU total annual damages to 12.3 and 22.9 €billion under a moderate mitigation and high emissions scenario, respectively, or by 89% (96.9 €billion) and 90% (216 €billion). The EU total annual people exposed to coastal flooding will be reduced to 552.5k and 805.9k under a moderate mitigation and high emissions scenario, respectively, corresponding to a 59% (796.4k people) and 63% (1349.6k) decrease.

The cost-effectiveness of increased protection varies strongly across Europe. When looking at individual coastal segments we see that costs often outweigh benefits, especially in less developed areas. Existing natural barriers or structural protection was found to be optimal in about 80% of coastal segments, while the benefits of additional protection exceed the costs in 20% of the European coastline. The European average additional coastal defence height required in these areas is 84 and 100 cm under a moderate mitigation and high emissions scenario, respectively. In Belgium this even amounts to 2.25 m, while also Slovenia (1.72 and 1.89 m), Latvia (1.42 and 1.98 m), Poland (1.22 and 1.49 m), Germany (1.31 and 1.38 m), the Netherlands (1.28 and 1.30 m), UK (1.2 and 1.3 m), and Estonia (1.2 and 1.35 m) will require protection well above 1 m to protect their coastal communities.

The estimated annual investment (undiscounted average costs over 2020-2100) on further dyke improvements during the present century is €1.3 million for the moderate mitigation scenario and 1.9 €billion for the high emissions scenario. At country level, the highest annual adaptation costs are estimated for the UK (323-457 €million), France (217-314 €million), Germany (145-243 €million), Italy (137-189 €million), and Denmark (145-243 €million). Shoreline length applies a critical control on the costs of dyke improvements. Therefore, in areas with highly fractal coastlines, like Finland, and Sweden, costs could be substantially reduced by installing defences further inland, without following the shoreline shape to all its detail. Moreover, the present results are very sensitive to the discount rates considered. High discount rates tend to put more weight on short term capital investment costs and downgrade future benefits of adaptation, hence may discourage taking action now. The same analysis without discounting would allow for an average additional dyke increase of 5-10 cm along the European coastline. The benefits of such additional interventions would be that an additional 7.7% to 9.6% of Europe's coastline would be protected to rising seas, and the EAD and EAPE by the end of the century would be reduced by 5.6-13.2 €billion and 119 to 255 thousand people, respectively.

The probabilistic framework that we applied allows decision makers to interpret the results according to the amount of risk they consider as acceptable. Our projections of future coastal hazard and risk, as well as dyke costs, come with uncertainty, and in this report we evaluated the adaptation option that optimises the benefits vs costs considering the most likely case. However, stakeholders could select a more conservative criterion and optimise adaptation investments in view of high-end, less probable future scenarios, under which flood impacts will be higher. Such a choice would result in higher adaptation costs, but would also imply less risks for future generations, as the analysis would prioritise protection against the rarer and more catastrophic events.

The present analysis has shortcomings that are inherent to the scale of application. The socioeconomic projections do not take into account the relocation away from the coast spurred by the increasing costs of living along the coast. Also, near river deltas and estuaries coastal and river flooding could coincide. Such compound events could reinforce each other and give rise to impacts that are larger than the sum of the impacts of the single events. With rising extreme sea levels along Europe's coastlines and increasing river flood hazard in many parts of Europe (see PESETA IV task on river floods), compound flood hazard will likely increase in Europe (Bevacqua *et al.*, 2019). A proper assessment of this hazard and the consequent risk is yet lacking at continental scale and in PESETA IV both hazards were considered as independent. It should be noted, however, that to date compound flood risk represents only a marginal fraction of the total flood risk in Europe (Paprotny *et al.*, 2018).

Sea levels are projected to increase long after 2100 and very likely this will happen at an accelerating rate (Kopp *et al.*, 2014; Rasmussen *et al.*, 2018). Hence, even though that our impact and cost-benefit analysis is limited until 2100, adaptive measures taken now will also lower flood risk during the 22nd century and beyond. Considering longer time spans, the benefits of rising dyke heights are therefore likely much higher than estimated herein.

This study focusses only on the costs and benefits of further dyke improvements. Nature-based solutions have shown capacity to mitigate erosion and flood risk under current sea levels, yet there is no solid evidence about their effectiveness to protect European coastal communities against the expected rise in sea level extremes, that could be up to one meter and more. However, this doesn't exclude the parallel implementation of more sustainable environmental practices to enforce the physical and ecological resilience of coastal zones.

Annex

Coastal flood risk and adaptation modelling framework

The coastal flood risk analysis is based on the model LISCOAST (Large-scale Integrated Sea-level and COastal ASsessment Tool). The modular framework has been developed to assess weather-related impacts in coastal areas in present and future climates. It combines state-of-the-art large-scale modelling tools and datasets to quantify hazard, exposure and vulnerability and compute consequent risks (Vousdoukas, Mentaschi, Voukouvalas, Bianchi, *et al.*, 2018). The modelling framework was further extended to evaluate costs and benefits of heightening dyke heights and find the optimal adaptation design based on maximizing the net present value. More details on the different steps of the analysis are provide below.

Hazard assessment

Coastal flood impacts are driven by nearshore Extreme Sea Levels (ESLs). In this study ESLs are modelled along the European coastline using segments of variable length with a maximum of 25 km for the most straight coastline stretches. Our projections go to the end of the 21st century and we consider Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5, for which an ensemble of 6 climate models have been used to account for uncertainty in climate projections. RCP4.5 can be considered as a moderate emissions-mitigation-policy scenario and RCP8.5 as a high-end, business-as-usual emissions scenario. ESLs are calculated by adding linearly the contributions of different components:

$$\mathrm{ESL} = \mathrm{SLR} + \eta_{\mathrm{CE}} + \eta_{\mathrm{tide}} \quad (1)$$

where

SLR is the Sea Level Rise, obtained from a GCM ensemble combined with contributions from ice-sheets and ice-caps (Vousdoukas *et al.*, 2017).

η_{CE} is the contribution from extreme wind and atmospheric pressure, driving waves and storm surge, that is obtained dynamic ocean simulations (Mentaschi *et al.*, 2017; Vousdoukas *et al.*, 2017).

η_{tide} the maximum tidal level sampled probabilistically to express the spring-neap variation of the high tide water level.

We then apply in each coastal segment non-stationary extreme value analysis (Mentaschi et al. 2016) to the ESL projections. From the fitted extreme value distributions we obtain ESLs for a range of return periods (inverse of probability) between 2 and 20000 years. Hence, ESLs are expressed as a function of time and return period (Vousdoukas, Mentaschi, Voukouvalas, Verlaan, *et al.*, 2018)

$$\mathrm{ESL} = f(\mathrm{year,RP}) \quad (2)$$

The ESLs in equation (2) are subsequently used as forcing for coastal flood inundation calculations at 100 m resolution using the hydrological model Lisflood-FP (Vousdoukas *et al.*, 2016), taking into account present coastal protection standards obtained from the FLOPROS dataset (Scussolini et al. 2015) and other available sources (Vousdoukas et al. 2018). Land surface elevation data are provided from the Shuttle Radar Topography Mission (SRTM) DEM (Reuter, Nelson and Jarvis, 2007). This results in time-varying coastal flood inundation maps for each of the considered return periods and for each coastal segment.

Exposure and vulnerability

The resulting flood inundation maps are combined with exposure and vulnerability information at the corresponding point in time in order to estimate direct flood damages (Vousdoukas, Mentaschi, Voukouvalas, Bianchi, *et al.*, 2018). Baseline exposure (reference year 2012) is available from the refined CORINE land use/land cover dataset (CLC) at 100 m resolution, featuring 44 different land use classes (Batista e Silva, Lavalle and Koomen, 2012). Baseline population maps (reference year 2011) are available from Batista e Silva et al (Batista e Silva, Lavalle and Koomen, 2012). For future GDP and population exposure we used the projections of the EU Reference scenario (based on the ECFIN 2015 Ageing Report). Asset values for future time slices were adjusted by scaling per NUTS3 region the depth damage functions according to changes in the future NUTS3 GDP per capita compared to the baseline.

The ECFIN 2015 Ageing Report scenario acts as a benchmark of current policy and market trends in the EU. High-resolution land use and population projections based on the EU Reference Scenario were derived with the LUISA modelling platform (Jacobs-Crisioni *et al.*, 2017). As the Ageing report deals with projections only to the year 2060, the projections have been extended to the year 2100. Regarding the GDP projections, the Ageing Report assumes that two out of the three determinants of economic growth, technical progress and capital accumulation, would reach a steady state (with constant growth rates) by the year 2060. That has been assumed as well for the following decades. The third contributor to growth (the labour input) has been assumed to evolve in a proportional way with respect to population (i.e. same growth rate). That means ignoring possible changes in the labour markets conditions, such as changes in the participation rates or the employment rate. The population projections for 2061-2100 are taken from the latest United Nations demographic report (medium variant), and they are explicitly considered in the computation of the economic growth figures (more details can be found in Ciscar et al. (2017).

The vulnerability to coastal flooding of coastal infrastructure, societies and ecosystems is expressed through depth-damage functions (DDFs) (Alfieri *et al.*, 2015; Rojas, Feyen and Watkiss, 2013). DDFs define for each of the 44 land use classes of the refined CORINE Land Cover the relation between flood inundation depth and direct damage. The country-specific DDFs were further rescaled at NUTS3 level based on GDP per capita to account for differences in the spatial distribution of wealth within countries.

Estimation of people exposed and direct losses

For each coastal segment, people exposed and direct flood losses in time for the different return periods are calculated at 100 m resolution by combining the corresponding flood inundation maps with the exposed people and assets and the vulnerability functions. Areas that are inundated on a regular basis (which could happen in the future with sea level rise), here defined as the areas that lie below the high tide water level, are considered as fully damaged and the maximum loss according to the DDFs is applied. For areas inundated only during extreme events, the damage is estimated by applying the DDFs combined with the simulated inundation depth for the respective return period events. For each coastal segment this results in annual estimates up to 2100 of coastal flood damage D (and people exposed) for the range of return periods considered

$$\mathrm{D} = f(\text{year,RP}) \tag{3}$$

Probabilistic projections of flood impacts

Projections of future flood impacts are estimated in a probabilistic framework. For a correct statistical description of the hazard, it is necessary to consider spatial dependency in the occurrence of extreme events along the European coastline. If a severe storm hits a point along the coast, nearby locations will likely also be exposed to extreme conditions, and neglecting such dependency would lead to an underestimation of the aggregate risk. To that end, the spatial dependencies of ESLs were estimated through copulas. Considering the spatial dependencies among coastal segments, we produce 10,000 realizations of sequences of ESLs during the present century though Monte Carlo simulations. This produces annual time series of return periods (corresponding to the respective ESLs) for each coastal segment. The time series cover 80 years from 2020 until 2100, resulting in a 80 x 10,000 matrix of extreme event return periods (RP_{matrix}) for each segment, with dimensions corresponding to the number of years and Monte Carlo realizations, respectively. The matrices of return periods are transformed into matrices of direct losses (D_{matrix}) for each segment according to equation (3). The number of realizations was chosen after several preliminary tests during which it was shown that 10,000 ensured convergence both in terms of mean and standard deviation values (fluctuations below 0.001%).

Estimation of adaptation costs

In order to estimate the optimal dyke design for a coastal segment we consider dyke heights (Z_{prot}) that vary from the current level ($Z_{prot,pres}$) to a maximum elevation. The latter exceeds by 1 m the 99th ESL quantile estimated for that coastal segment during the present century (ESL_{max}). We discretize the range between $Z_{prot,pres}$ and ESL_{max} in 40 increments. Hereby we assume that $Z_{prot,pres}$ is upgraded gradually to the desired design between 2020 and 2050, and remains constant until the end of the century.

Costs of dyke heightening are calculated by aggregating investment and maintenance costs during the entire study period. Country estimates of investment costs of dykes are available from two sources: (i) the dataset used in the analysis of global investment costs for coastal defences of Nicholls *et al.* (2019); and (ii) the dataset used in the global flood analysis of Ward et al. (2017). In both datasets costs are expressed as investment costs in US$ per meter heightening considering differences in construction costs across countries, which were converted to €2015 values using GDP deflators and market exchange rates obtained from Eurostat. Maintenance costs are assumed to be 1% per year of capital investment costs (Jonkman et al., 2013). The km length of dykes is equivalent to the coastline length of each segment that was derived from OpenStreetMaps. Dyke heights are assumed to be uniform over the entire segment. Both datasets on dyke unit costs come with confidence intervals, on the basis of which cost probability density functions were fitted. In the probabilistic framework costs are randomly sampled from these distributions assuming that each dataset has equal probability of occurrence.

Estimation of adaptation benefits

Benefits are represented here as the avoided damages by increasing the dyke height in a coastal segment. For each of the 40 increments, benefits are calculated for the 10,000 projections of ELS up to 2100 (equation 2) as the difference between future losses with and without additional coastal protection, aggregated over the entire study period. We assume that if the ESL of the event (equation 2) does not exceed the dyke height then the damage of that event will be zero. If the ESL overtops the dyke, then it breaches and the damage is obtained from equation (3). For each coastal segment. This results in a matrix of 40 increments vs 10,000 estimates of benefits.

Cost-benefit analysis

The objective of the cost-benefit analysis is to find the protection standard for each coastal segment that maximises the Net Present Value (NPV). The latter is the sum over the project lifetime of the costs and benefits associated with a specific investment and determines whether a project will deliver sufficient benefits to justify the costs. We therefore sample 10,000 realizations of unit cost from the cost distributions, which are used to generate 10,000 estimates of the (capital and maintenance) costs for each of the 40 increments in a coastal segment. These are combined with the 10,000 realizations of benefits for each increment, and the NPV is calculated. This results in 10,000 NPV values for each dyke increment. This allows to derive the probability that a certain dyke design is cost-effective, and central estimates for each increment can be used to choose an optimal dyke height. Here we use the mean NPV of the 10,000 NPV to choose the optimal design. For the dyke elevation that maximises mean NPV in a coastal segment, we also calculate the Benefit-Cost Ratio (BCR), which is the ratio of its total benefits to its total costs. Results at larger scales (e.g., NUTS2, country, or EU-level) are obtained by summing NPV estimates over the coastal segments in the area of interest.

The benefits delivered by dykes often occur long after they have been constructed. Discounting is used to reflect that the costs and benefits incurred in the future are of less value than those delivered in the near term. In order to determine the present value of future costs and benefits, they are discounted and aggregated according to

$$X_{present} = \sum_{t=1}^{T} \frac{X_t}{(1+r_{sw})^t} \quad (4)$$

where T represents the duration of the project's lifetime in years, X_t is the cost or benefit incurred over a year by the project and r_{sw} is the social welfare discount rate. The choice of the latter can largely influence the cost-benefit analysis of the adaptation measure. Larger values of r_{sw} tend to discourage the implementation of the policy, as discounted future benefits of the measure become smaller compared to its costs that are incurred earlier in time. We note that we limit T by putting 2100 as the end of the project lifetime, yet in reality the lifetime of the dykes is likely longer.

We calculate the social discount rate using the Ramsey equation (Ramsey, 1928), which combines information about the growth of the economy with two main parameters: the rate of pure time preference of society and the elasticity of the marginal utility of consumption. The formula is:

$$r_{sw} = \rho + \eta . g \tag{5}$$

where:

ρ is the rate of pure time preference;

g is the growth rate of per capita consumption;

η is the elasticity of the marginal utility of consumption.

The Ramsey equation reflects the two main reasons why the society or a hypothetical social planner would discount future benefits. A value of ρ larger than zero reflects impatience and a preference for consumption in the current period rather than consumption in the future. On the contrary if ρ is equal to zero, the society has no preference for a unit of consumption today or in the future. It is often referred to as the inter-generational equity parameter, as it reflects preferences between the present and future generations. The other reason why future costs and benefits are discounted is for the decreasing marginal utility of consumption (η) and the growth rate of per capita income (g). A high value of η reflects a fast declining utility as consumption increases. The interpretation is that the wealthier the society, the lower the utility derived from an equal increase of the consumption level; therefore with a positive g, future benefits will have a lower value in the present.

Here the Ramsey equation is calibrated using average growth rates for consumption per capita. As suggested in the EC Guide to Cost-Benefit Analysis of Investment Projects (EC, 2015), we distinguish between the so-called cohesion countries, which benefit from the Cohesion Fund, and the rest of the EU Member States (Sartori *et al.*, 2014). For the 2014-2020 period, the Cohesion Fund concerns Bulgaria, Croatia, Cyprus, the Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Romania, Slovakia and Slovenia. From our macroeconomic projections the average growth rate of consumption per capita for cohesion countries is equal to 2%, while for the rest of the countries is 1% per year.

We further assume a value of 1 for ρ, which is chosen as a central value between 0, i.e. no preference for current or future generations, and 2, which is the value attributed by Weitzman in is review of the Stern Review (Weitzman, 2007). Values of η in literature typically range between 1 and 4, with a central estimate of 2 (Gollier and Hammitt, 2014), which is the value that we assume here.

With these values for g, ρ and η, the resulting discount rates are 5% the cohesion countries (poorer countries in Europe) and 3% for the other Member States. The resulting discount rates appear to be in line with those suggested by the European Commission for the cost-benefit analysis of major investment projects (Gollier and Hammitt, 2014; Weitzman, 2007).

References

Alfieri, L., Burek, P., Feyen, L., and Forzieri, G. 2015. Global warming increases the frequency of river floods in Europe. Hydrology and Earth System Sciences 19:2247-2260.

Batista e Silva, F., Lavalle, C., and Koomen, E. 2012. A procedure to obtain a refined European land use/cover map. Journal of Land Use Science 8 (3):255-283.

Bevacqua, E., Maraun, D., Vousdoukas, M.I., Voukouvalas, E., Vrac, M., Mentaschi, L., and Widmann, M. 2019. Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change. Science Advances 5 (9):eaaw5531.

Brière, C., Janssen, S.K.H., Oost, A.P., Taal, M., and Tonnon, P.K. 2018. Usability of the climate-resilient nature-based sand motor pilot, The Netherlands. Journal of Coastal Conservation 22 (3):491-502.

Ciscar, J.C., Mongelli, I., and Szewczyk, W. 2017. PESETA III: Task 2 - Socioeconomic scenarios dataset: European Commission.

EC. 2015. Guide to Cost-Benefit Analysis of Investment Projects - Economic appraisal tool for Cohesion Policy 2014-2020.

EUROSION. 2003. Trends in Coastal Erosion in Europe. Final Report of the Project 'Coastal erosion - Evaluation of the need for action'. Leiden, The Netherlands: Directorate General Environment, European Commission.

Gollier, C., and Hammitt, J.K. 2014. The Long-Run Discount Rate Controversy. Annual Review of Resource Economics 6 (1):273-295.

Jacobs-Crisioni, C., Diogo, V., Perpiña Castillo, C., Baranzelli, C., Batista e Silva, F., Rosina, K., and Kavalov, B.L., C. . 2017. The LUISA Territorial Reference Scenario 2017: A technical description. Luxemburg: Publications Office of the European Union.

Kopp, R.E., Horton, R.M., Little, C.M., Mitrovica, J.X., Oppenheimer, M., Rasmussen, D.J., Strauss, B.H., and Tebaldi, C. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future 2 (8):383-406.

Kopp, R.E., Kemp, A.C., Bittermann, K., Horton, B.P., Donnelly, J.P., Gehrels, W.R., Hay, C.C., Mitrovica, J.X., Morrow, E.D., and Rahmstorf, S. 2016. Temperature-driven global sea-level variability in the Common Era. Proceedings of the National Academy of Sciences 113 (11):E1434.

Lentz, E.E., Thieler, E.R., Plant, N.G., Stippa, S.R., Horton, R.M., and Gesch, D.B. 2016. Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood. Nature Clim. Change 6:696–700.

McAdoo, B.G., Ah-Leong, J.S., Bell, L., Ifopo, P., Ward, J., Lovell, E., and Skelton, P. 2011. Coral reefs as buffers during the 2009 South Pacific tsunami, Upolu Island, Samoa. Earth-Science Reviews 107 (1-2):147-155.

Mentaschi, L., Vousdoukas, M.I., Pekel, J.-F., Voukouvalas, E., and Feyen, L. 2018. Global long-term observations of coastal erosion and accretion. Scientific Reports 8 (1):12876.

Mentaschi, L., Vousdoukas, M.I., Voukouvalas, E., Dosio, A., and Feyen, L. 2017. Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. Geophysical Research Letters 44 (5):2416-2426.

Nicholls, R.J., Hinkel, J., Lincke, D., and van der Pol, T. 2019. Global Investment Costs for Coastal Defense through the 21st Century: The World Bank.

Paprotny, D., Sebastian, A., Morales-Nápoles, O., and Jonkman, S.N. 2018. Trends in flood losses in Europe over the past 150 years. Nature Communications 9 (1):1985.

Ramsey, F.P. 1928. A Mathematical Theory of Saving. The Economic Journal 38 (152):543-559.

Rasmussen, D.J., Klaus, B., Maya, K.B., Scott, K., Benjamin, H.S., Robert, K., and Michael, O. 2018. Extreme sea level implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd century. Environmental Research Letters in press.

Reuter, H.I., Nelson, A., and Jarvis, A. 2007. An evaluation of void - filling interpolation methods for SRTM data. International Journal of Geographical Information Science 21 (9):983-1008.

Rojas, R., Feyen, L., and Watkiss, P. 2013. Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. Global Environmental Change 23 (6):1737-1751.

Sartori, D., Catalano, G., Genco, M., Pancotti, C., Sirtori, E., Vignetti, S., and Bo, C.D. 2014. Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for Cohesion Policy 2014-2020: European Commission.

Slangen, A.B.A., Carson, M., Katsman, C.A., van de Wal, R.S.W., Köhl, A., Vermeersen, L.L.A., and Stammer, D. 2014. Projecting twenty-first century regional sea-level changes. Climatic Change 124 (1):317-332.

Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., and De Vriend, H.J. 2013. Ecosystem-based coastal defence in the face of global change. Nature 504:79.

Thomas, R.E., Johnson, M.F., Frostick, L.E., Parsons, D.R., Bouma, T.J., Dijkstra, J.T., Eiff, O., Gobert, S., Henry, P.-Y., Kemp, P., McLelland, S.J., Moulin, F.Y., Myrhaug, D., Neyts, A., Paul, M., Penning, W.E., Puijalon, S., Rice, S.P., Stanica, A., Tagliapietra, D., Tal, M., Tørum, A., and Vousdoukas, M.I. 2014. Physical modelling of water, fauna and flora: knowledge gaps, avenues for future research and infrastructural needs. Journal of Hydraulic Research 52 (3):311-325.

Van Loon-Steensma, J.M., and Vellinga, P. 2019. How “wide green dikes” were reintroduced in The Netherlands: a case study of the uptake of an innovative measure in long-term strategic delta planning. Journal of Environmental Planning and Management 62 (9):1525-1544.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F., and Feyen, L. 2018. Climatic and socioeconomic controls of future coastal flood risk in Europe. Nature Climate Change.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., and Feyen, L. 2017. Extreme sea levels on the rise along Europe's coasts. Earth's Future:n/a-n/a.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L.P., and Feyen, L. 2018. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nature Communications 9 (1):2360.

Vousdoukas, M.I., Voukouvalas, E., Mentaschi, L., Dottori, F., Giardino, A., Bouziotas, D., Bianchi, A., Salamon, P., and Feyen, L. 2016. Developments in large-scale coastal flood hazard mapping. Natural Hazards and Earth System Science 16:1841-1853.

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

Watson, C.S., White, N.J., Church, J.A., King, M.A., Burgette, R.J., and Legresy, B. 2015. Unabated global mean sea-level rise over the satellite altimeter era. Nature Clim. Change 5 (6):565-568.

Weitzman, M.L. 2007. A Review of the Stern Review on the Economics of Climate Change. Journal of Economic Literature 45 (3):703-724.

List of abbreviations and definitions

EAD	Expected Annual Damage
EAPE	Expected Annual People Exposed
IPCC AR5	Intergovernmental Panel on Climate Change Assessment Report 5
RCP	Representative Concentration Pathway
GWL	Global Warming Level
ESL	Extreme Sea Level
SLR	Sea Level Rise
BCR	Benefit to cost ratio
NPV	Net present value

List of figures

List of tables

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

KJ-NA-29969-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

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

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office of the European Union

doi:10.2760/456870

ISBN 978-92-76-12990-5