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Assessment of risk and uncertainties

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Summary

This deliverable is part of the Task 6.5 'Production of geospatial data layers on flood risk assessment and residual uncertainties' of the CoCliCo project. It first presents the assumptions, methods and data that have been used and developed to deliver new authoritative and beyond the state-of-the-art pan-European coastal flood risk assessments following Integrated Scenarios. In brief, this task combines flood hazard geospatial layers and exposure layers and vulnerability functions developed during the CoCliCo project. Then, the results and main findings of the risk analysis are provided, together with a detailed analysis of various uncertainty sources. The main findings of this risk analysis provide additional evidence that coastal adaptation needs to start today, especially in those countries such as France and Spain where impacts will emerge most rapidly. This means action in terms of decisions on upgrade of defences or their abandonment - this will probably be challenging for national and local governments. Furthermore, the results presented in this deliverable allow establishing that:

- CoCliCo provides an authoritative and beyond-the-state-of-the-art coastal risk database and framework that (i) are validated against historical records, (ii) allow future risk projection at the pan-European scale, and (iii) provides a foundation for future developments in coastal climate services;
- In protected areas, maintaining and upgrading defences is needed to keep the level of risk as low as possible but this will require massive investment;
- On the European scale, infrastructure exposure increases proportionally with sea-level rise (SLR), but the magnitude of additional impact will be very different depending on the country; in other words, even the lowest SLR scenario would have large impact in many European countries;
- Socioeconomic development throughout the 21st century will have a major impact on the evolution of coastal risk, including the decisions to be made over the coming three decades;
- People and infrastructures at risk increase more quickly in coastal urban than rural areas.

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Executive summary

This deliverable is part of the Task 6.5 “Production of geospatial data layers on flood risk assessment and residual uncertainties” of the CoCliCo project. It first presents the assumptions, methods and data that have been used and developed to deliver new authoritative and beyond the state-of-the-art pan-European coastal flood risk assessments following *Integrated Scenarios*. In brief, this task combines flood hazard geospatial layers and exposure layers and vulnerability functions developed during the CoCliCo project. Then, the results and main findings of the risk analysis are provided, together with a detailed analysis of various uncertainty sources.

The main findings of this risk analysis provide additional evidence that coastal adaptation needs to start today, especially in those countries such as France and Spain where impacts will emerge most rapidly. This means action in terms of decisions on upgrade of defences or their abandonment – this will probably be challenging for national and local governments.

Furthermore, the results presented in this deliverable allow establishing that:

- CoCliCo provides an authoritative and beyond-the-state-of-the-art coastal risk database and framework that (i) are validated against historical records, (ii) allow future risk projection at the pan-European scale, and (iii) provides a foundation for future developments in coastal climate services;
- In protected areas, maintaining and upgrading defences is needed to keep the level of risk as low as possible but this will require massive investment;
- On the European scale, infrastructure exposure increases proportionally with sea-level rise (SLR), but the magnitude of additional impact will be very different depending on the country; in other words, even the lowest SLR scenario would have large impact in many European countries;
- Socioeconomic development throughout the 21st century will have a major impact on the evolution of coastal risk, including the decisions to be made over the coming three decades;
- People and infrastructures at risk increase more quickly in coastal urban than rural areas.



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Table of Contents

1. Introduction.....	6
2. Data & Methods.....	6
2.1 Data.....	6
2.1.1 Flood maps library.....	6
2.1.2 Population projection.....	7
2.1.3 Infrastructures & vulnerability curves	7
2.2 Methods	8
2.2.1 Population at risk.....	8
2.2.2 Infrastructure exposed and costs.....	9
2.2.3 Considering flood defences.....	10
2.3 Uncertainty analysis.....	11
3. Comparison with historical events	12
3.1 Flood extent	14
3.2 Damaged buildings and associated costs.....	14
4. Future projections	16
4.1 Assessment of pan-European exposure changes	16
4.1.1 Contemporary status.....	16
4.1.2 Projections	18
4.2 Implications for adaptation	22
4.2.1 How many more buildings will be protected in the future?	22
4.2.2 Impact of SLR on population displacement	25
4.2.3 Impact of current defences.....	26
5. Analysis of uncertainty	27
5.1 Comparison of integrated scenarios and sources of uncertainty.....	28
5.1.1 Uncertainty related to the hazard level	28
5.1.2 Uncertainty related to the exposure changes	29
5.1.3 Uncertainty related to integrated scenario in 2100 and beyond	29
5.2 Sensitivity analysis.....	30
6. Conclusion	34
7. References	34
8. Appendix	37



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1. Introduction

Sea-level rise is a pronounced effect of climate change, with implications for regions worldwide, including Europe (Oppenheimer et al., 2019; Cooley et al., 2022). Continued sea-level rise and increased frequency and magnitude of extreme sea level events will increasingly encroach coastal human settlements, damage coastal infrastructure, commit low-lying coastal ecosystems to submergence and loss, and expand land salinization (IPCC, 2023). Anticipating these changes is necessary to adapt, but their projection remains very challenging, especially at large scales, such as Europe.

Current widely used climate services for coastal flood risk assessment, e.g. Climate Central Coastal Risk Screening Tool (Kulp and Strauss, 2019), provide broad-scale flood maps that raise awareness about climate change impacts. This broad-scale approach, however, lacks detailed on local context and consideration of adaptation efforts, and often leads to significant overestimation of flood risks (Oppenheimer, 2019; Sanders et al., 2024). On the other hand, localized tools tailored to specific regions (e.g., CoSMoS for San Francisco Bay; Barnard et al., 2014) better engage practitioners but have resulted in a fragmented array of climate services that are not well connected to authoritative data sources (Le Cozannet et al., 2017). This fragmentation prevents transparent comparison and benchmarking across regions, which is crucial for gaining public trust and effective risk management policies.

One of the objectives of the CoCliCo project was to construct and deliver a consistent pan-European coastal risk assessment to meet the multi-faceted challenges posed by sea-level rise over the coming decades and centuries. In this deliverable, we first describe the methods and datasets used for assessing coastal risk (Sect. 2), we then compare the assessment with historical events (Sect. 3), then present the main results and their implications for coastal planning and decision-making (Sect. 4). Finally, we discuss the impact of the main uncertainties (Sect. 5).

2. Data & Methods

2.1 Data

Details on data and scenarios used for the risk assessment are provided below.

[2.1.1 Flood maps library](#)

Flood hazard scenarios rely on the pan-European flood maps library developed by UC-IHCantabria (CoCliCo's deliverable D4.3). The flood modelling was mostly based on the Copernicus Digital Elevation Model (DEM) of 25 m resolution, except in some regions, where higher resolution (e.g. Spain, 5 m) or lower resolution (e.g. Ukraine, 30 m) DEMs were used. The RFSM-EDA 2-D flood model was used (Jamieson et al., 2012) and the boundary conditions (e.g. relative sea-level projections, nearshore wave conditions, total water level) were delivered by WP3. More details are provided in D4.3.



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In total, 8 combinations of Shared-Socioeconomical Pathways (SSPs) and time horizons (or time slices) have been modelled (see **Table 1**) and 1 hindcast (i.e. with no SLR) not shown in **Table 1**. Note that 2100 is the time horizon that was selected to simulate the largest panel of SSPs. This includes also a high-end projection, which relies on the 83rd percentile of the low-confidence SSP5-8.5 SLR projections of the AR6 (see D3.2 for details). All remaining SSPs (i.e. SSP1-2.6, SSP2-4.5 and SSP5-8.5, hereinafter referred to as SSP1, SSP2 and SSP5, respectively) were based on the projected median SLR estimate.

For each SSP-Time slice combination, 4 coastal flood scenarios were performed: 1 permanent inundation scenario (i.e. mean spring tide conditions) and 3 episodic flooding associated with the 1-year, 100-year and 1000-year events of total water level (TWL). Note that return periods on TWL are retrieved over the hindcast period and are assumed to remain static in the future. Finally, for each SSP-Time slice combination and flood episode scenario, 3 flood maps were computed: 1 undefended (without defences) and 2 defended (with defences) (see also §3.2.3). This leads to 108 flood hazard maps to consider.

The flood maps are delivered with 25 m horizontal resolution and are projected in the ETRS89 LAEA coordinates reference system.

Table 1. Combinations of SSPs and time slices available from the flood map library. Boxes filled in grey indicate the combinations that are available.

Timeslice Scenario	2030	2050	2100	2150
SSP1-2.6				
SSP2-4.5				
SSP5-8.5				
High-End				

2.1.2 Population projection

We used the CoCliCo population projections that provide rasterized spatial projections of population at a ~1km resolution until the year 2100 for the EU countries and under several SSPs. The spatial projections are produced by downscaling the national population projections (Release 3.1) (Kc et al., 2023), which are provided by the International Institute for Applied Systems Analysis (IIASA). The basis of the downscaling model is a gravity model, which is extended by additional proxies that account for the attraction of people to specific locations. Following the integrated scenarios (D2.2), the projections for SSP1, SSP2 and SSP5 and for the years 2010, 2030, 2050 and 2100 were used (see D5.6 for details). Population projections for the two remaining SSP3 and SSP4 and in-between timesteps will be accessible through the publication by Bonatz et al., 2025 (in preparation).

2.1.3 Infrastructures & vulnerability curves



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For infrastructures mapping, we used the Coastal European Exposure Database (CEED) (Koks, E., & De Plaen; 2023). CEED relies on the EUBUCCO database (Milojevic-Dupont et al., 2023) and OpenStreetMap (OSM) data, enriched by various auxiliary data, ensuring both comprehensive coverage and data accuracy. The dataset is an extensive repository encompassing critical infrastructure (CI) assets and buildings along the EU and UK coast. It is structured around seven major CI systems (transportation, energy, telecommunication, waste, water, education, and health) as identified by Nirandjan et al. (2022). The defined area considered in CEED aligns with the coastal zone as developed by Lincke (2022) to define the exposure of CI to coastal flooding. The area encapsulated by the coastal zone falls within 1 km of the coastline or below 20 meters of elevation from the coastline. Note that CEED is a vector database where CI assets and buildings can be defined as polygons (e.g. buildings), lines (e.g. networks) or points (e.g. transmission tower). Moreover, the CEED database has been used as basis for Local Administrative Unit (LAU)-level statistics used on the CoCliCo platform. More details are provided in the deliverable D5.6.

To assess flood damage to infrastructure, we used the global flood depth-damage functions database from Huizinga et al. (2017). We also tested the vulnerability curves of André et al. (2013).

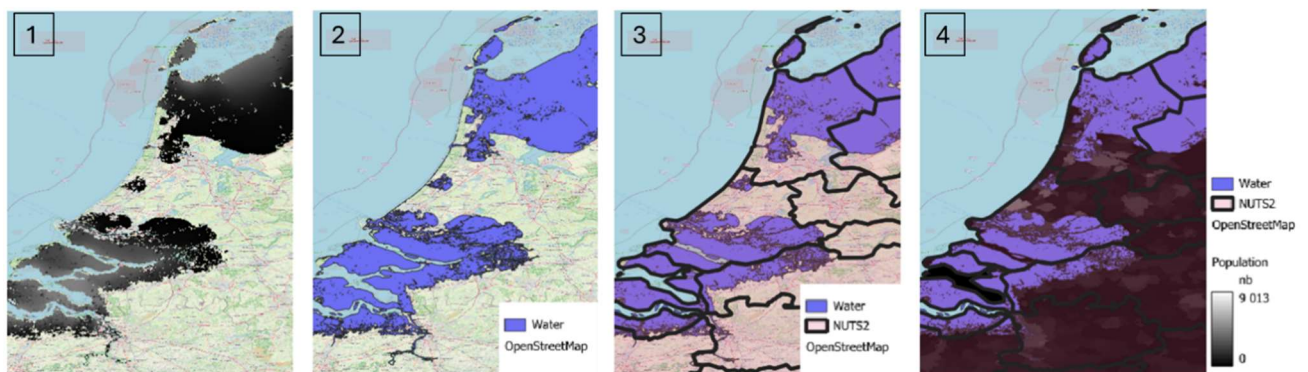


Figure 1. Illustration of the workflow designed to calculate population exposure to coastal flooding from CoCliCo risk datasets.

2.2 Methods

The coastal risk is assessed by combining the hazard, exposure and vulnerability. Below, we detail the metrics, the choices made, and the geographic information system-based (GIS) methods used to compute the risks.

2.2.1 Population at risk

The population exposed to flood is assessed by intersecting the flood maps with population projections. Note that the resolution of the flood maps (~25 m) and the population projections (~1 km) differs by nearly two orders of magnitude. In this regard, diving into the detailed information that flood maps provide (e.g. flood depth at pixel scale) to refine statistics on population exposed is pointless and may create a misleading precision fallacy. Therefore,



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we simply relied on the flood extent, considering all pixels where flood depth is greater than 1 mm.

The workflow developed to process the population exposed to flooding is shown on **Figure 1**. First, the raster of flood hazard is vectorized (step 1 to 2) to isolate coastal flooded areas. Then the flood map geometry is clipped per administrative unit at which the analysis is performed (step 2 to 3); here NUTS2 level is shown but for CoCliCo, analysis down to LAUs level has been performed. Finally, the flooded area per administrative unit is intersected with the population raster by summing all the population within the flood area (step 3 to 4). For this later stage, we assume the population to be uniformly distributed within the 1 km-side pixel and consider that the exposed population in a pixel is proportional to the ratio of the flood extent within the pixel.

2.2.2 Infrastructure exposed and costs

The infrastructures dataset is a vector database, where each asset is represented by its geometry. Therefore, exposure and damage costs are calculated for each infrastructure individually and then aggregated at the LAU scale. The method to calculate exposure and damage costs for e.g. a building is illustrated on **Figure 2**. For the exposure, we consider that a building is affected if its geometry – even partially – is overlapping with a flood pixel. To assess the damage costs, we calculate the averaged water depth (\bar{H}_S) of all pixels n overlapping the building spatial footprint in order to retrieve a percentage of damages D_S . Then, we multiply the damaged building area per the percent of damages and per the building’s costs of repair. Note the costs of repair depends on the country and is further refined by applying a weight considering the GDP per capita at NUTS3 scale.

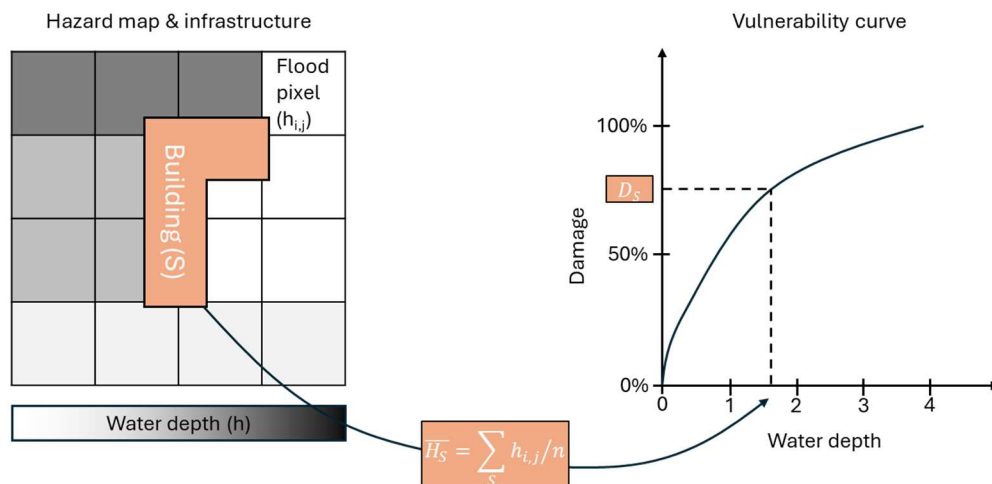


Figure 2. Illustration of the workflow designed to calculate infrastructure exposure to coastal flooding from CoCliCo risk datasets.

The method described above applies for geometries represented by polygons, for which the spatial footprint is limited (i.e. typically much smaller than the spatial extent of a LAU). For



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lines geometry (e.g. rails), the approach used must be able to handle very long networks that can cross over several administrative units. Therefore, lines objects are clipped first within each LAU and then chunked into segments of an equal chosen length (typically 50 m). The exposed networks are computed as the number of segments that are affected by flooding multiplied by their length and then added up at the LAU scale.

2.2.3 Considering flood defences

As already mentioned in the §3.1.1, 3 flood scenarios are considered: 1 undefended (without defences) and 2 defended (with defences). The dataset of protection standards used to build defended scenarios collects the minimum and maximum policy-based return periods at the province level (NUTS2). The low-defended, high-defended, map is based on the minimum, maximum, level of protection in each province applied to the whole province, respectively (see D4.2 for details).

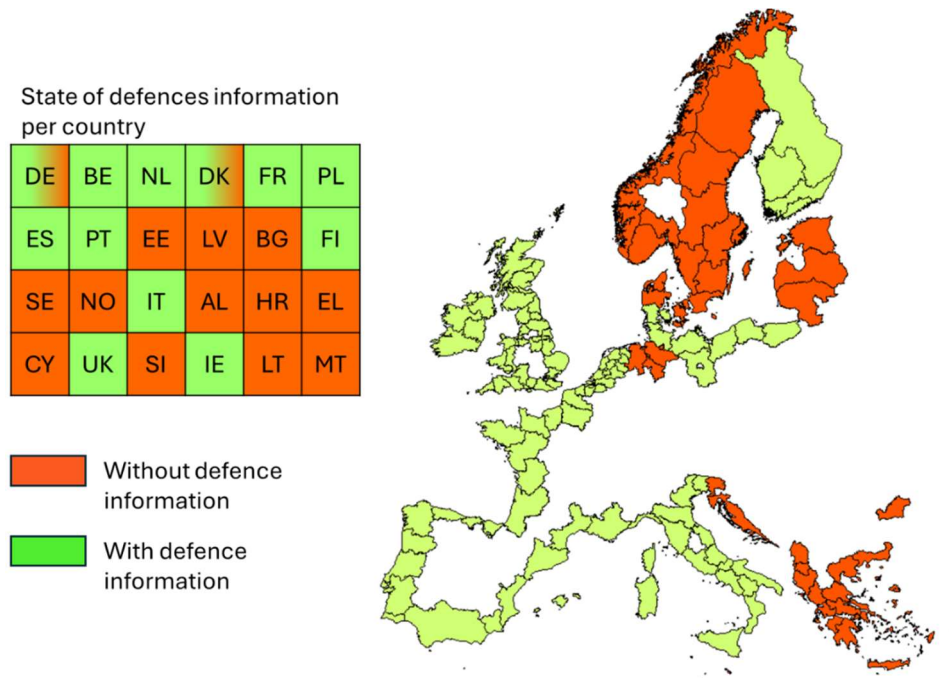


Figure 3. Policy-based spatial dataset used to account for coastal defences against marine flooding in Europe. This dataset is provided on NUTS2 scale. Orange areas depict NUTS2 regions where information on coastal defences could not be used in flood modeling.

The information on policy-based coastal defences is not available for the whole Europe at NUTS2 scale as shown on **Figure 3**. For instance, policy-based information on coastal defences could not be obtained for European countries from the East Mediterranean Sea States (e.g. Greece), nor for the Baltic States (e.g. Estonia). For Germany and Denmark, the dataset on policy-based defences could be used only for some provinces. The latter case therefore requires great caution when producing and interpreting the results at country scale.



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Overall, low- and high-defended scenarios could be provided for nearly 70% of the coastal NUTS2 regions in Europe, while undefended scenarios have been provided for all regions. It is important to recall that no information on the policy-based defences does not mean that there are no effective defences on the ground. For instance, the North-Sea flank of Germany is well protected by dikes in the reality. But the information on policy-based standards could not be obtained and therefore not be included in the unified CoCliCo flood modelling chain.

For the risk assessment presented hereinafter, we ensure, when performing pan-European or country scale analysis including defences, to integrate only NUTS2 regions where policy-based information on defences was available and modelled.

2.3 Uncertainty analysis

The risk assessment is processed through several successive steps that each embed a myriad of modelling choices and/or sources of uncertainty of various kind; i.e. aleatory or epistemic (e.g., Apel et al., 2008). This applies to the risk assessment method itself as described above, but also to assumptions and choices that were done, and data that were used, to produce the sea level (WP3), hazards (WP4) and exposure/vulnerability (WP5) datasets needed for the final risk assessment products (WP6). For instance, regional sea-level projections for a given SSP need to account for climate variability, climate model uncertainty but can also consider highly uncertain physical processes that may trigger ice-sheet rapid collapse. The flood hydrodynamical modelling is for instance sensitive to the resolution of the DEM, the land cover, the model formulation and its calibration or the boundary forcing. For obvious computational and data storage reasons, scanning the full space of parameter uncertainty and modelling choices is not achievable, in particular at pan-European scale, which is the CoCliCo's target. Nonetheless, the construction of various scenarios, depending on SSPs, sea-level assumptions or protection levels, and the possibility to play around with some of the risk calculation assumptions and parameters offer some flexibility to explore the relative importance uncertainty sources in the final risk calculation. This is done through a global sensitivity analysis (Iooss and Saltelli, 2017).

The objective of the global sensitivity analysis is to quantify the contribution of each uncertain factor to the uncertainty in the risk metric of interest. In this study, we focus on the damage costs. In practice this is done by running a series of computer experiments by estimating the risk metric of interest for varying values of the uncertain factors. In this study we consider the following uncertain factors:

- The SSP scenario (High End (HE) scenario, SSP126, SSP245, SSP585);
- The level of defence (High level of defence HD, low level LD, undefended UD);
- The choice in the fragility curve (JRC database described by Huizinga et al. (2017), or those based on insurance data by André et al., 2013);
- The asset's repair price (a single value per asset or a single value per country per asset);
- Estimate of the flood-induced water depth at the asset (maximum, mean, minimum, median value, see Sect. 3.2.2);
- Asset's area hit by the flood (whole building or pixels only).



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For each LAU across different countries in Europe, we conducted a total of 368 computer experiments and for each of them the corresponding risk metric was calculated. This dataset (uncertain factors vs risk metrics) was processed to derive a sensitivity index for each uncertain factor, which measures the contribution of the corresponding factor to the uncertainty of the risk metric. To do so, we rely on a popular method in the machine learning community, namely, the dependence measure based on the Hilbert-Schmidt Independence Criterion HSIC (da Veiga (2015)). Contrary to the popular ANOVA method, this generic measure has the advantages of being applicable to a broad range of situations, i.e., any type of dependence between the uncertain factor and the risk metric (linear, monotonic, nonlinear), and any type of uncertain factor's representation (e.g., continuous scalar, scenarios). Besides, it allows to analyse the full probability distribution of the variable of interest, and not only some statistical moments like the variance (Borgonovo, 2007).

In addition, the combination of HSIC with a hypothesis testing procedure (El Amri and Marrel, 2022) provides a rigorous setting for quantifying the significance of the considered covariate through the computation of p values. When the p value is below a given significance threshold (typically of 5%), it indicates that the considered uncertain factor has a significant influence on the risk metric of interest.

3. Comparison with historical events

In this section, we analyse historical events and compare CoCliCo's results with observations and recent modelling results published in the literature. A comparison with historical coastal flood events in Europe is performed to validate CoCliCo risk calculation methods and the related datasets. Three historical storms are studied:

- Xynthia (2010) caused damages over coasts of Western Europe countries: particularly Portugal, Spain and France. Xynthia reached its maximum intensity when passing through the Bay Biscay between the 27th and 28th of February 2010. The perfect concomitance with high tides led to extremely high total water levels and the flooding of large polders along the French Atlantic coast in Vendée and Charente-Maritime. The cities surrounding the "Baie de l'Aiguillon" in South Vendée were particularly affected and deplored 47 fatalities.
- Johanna (2008) affected the French Brittany and the South of United Kingdom on the 10th and 11th of March 2008. The city of Gâvre (France) was one of the most affected and is selected for comparison.
- Emma (2018) hit the Southwest coast of the Iberian Peninsula in early March 2018.



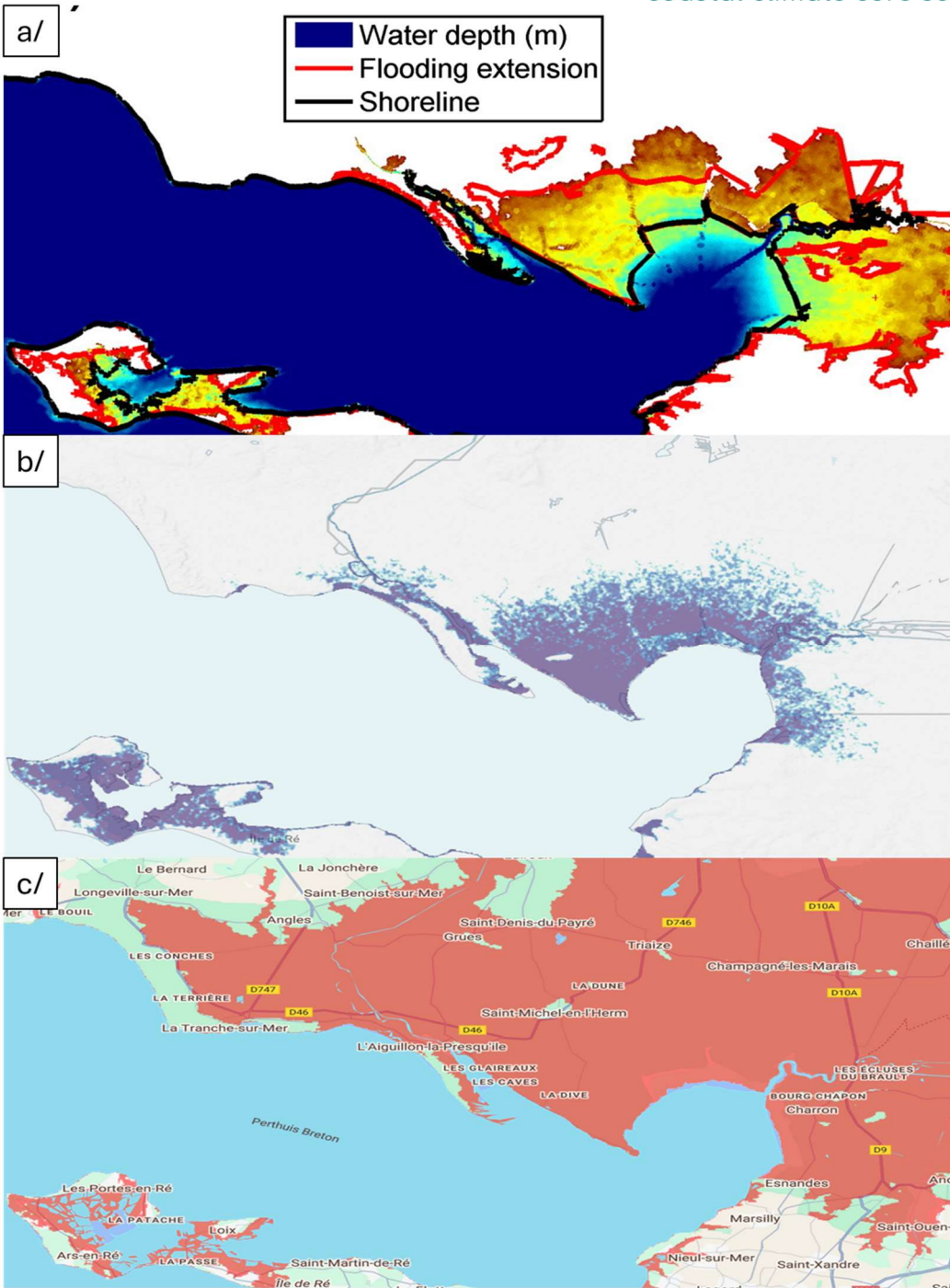


Figure 4. Spatial extent of the flooded area in the sector of La Faute-sur-mer (Charente-Maritime, France) for (a) the Xynthia event modeled by Bertin et al. (2014), (b) a 1000-year return period event modeled by CoCliCo and (c) a 1-year event water level static projection provided by Climate Central.



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3.1 Flood extent

The area exposed to flooding in the sector of La Faute-sur-Mer, which was heavily hit by the Xynthia storm is shown on **Figure 4**. Three approaches are compared: panel a) shows the results of a high-resolution hydrodynamical modelling with boundary conditions observed during Xynthia, panel b) shows the results from the low-resolution hydrodynamical modelling of the CoCliCo project for a 1000-year event under contemporary mean sea level, and panel c) shows the extent of low-lying areas exposed to annual flood event as provided by Climate Central (<https://www.climatecentral.org/>). Note that the Xynthia storm extreme water levels return periods were estimated between 250 years and over 1,000 years in the literature (Bulteau et al., 2015; Duluc et al., 2014). As the CoCliCo flood map library only considers 1-year, 100-year and 1000-year events, the latter is the most relevant for comparison with the Xynthia event.

High-resolution (**Figure 4a**) and low-resolution (**Figure 4b**) modelling reveal comparable flood extent along the Northern flank of “la baie de l’Aiguillon”, where most damaged were recorded (i.e. cities of La Faute-sur-Mer & L’Aiguillon-sur-Mer, André et al., 2013). The comparison at the eastern flank (or bottom) of the bay shows however that the CoCliCo modelling tends to underestimate the flood extent there. Comparatively, the static approach used in Climate Central (**Figure 4c**) shows an important overestimation of the extent of the area exposed to flooding, even considering an annual event.

Flood extent for Johanna and Emma storms are not shown but CoCliCo’s flooding results have been compared with high-resolution flood modelling results. We found that CoCliCo’s flood extent is similar in Gâvre during Johanna compared to the high-resolution modelling (Le Roy et al., 2015), while in Cadiz, the flood extent tends to be underestimated compared to the high-resolution modelling (Duo et al., 2025).

3.2 Damaged buildings and associated costs

The number of damaged buildings and associated costs calculated with CoCliCo data for the three storm events are provided in **Table 2**. In agreement with the flood extent results, the comparison with **Table 3** indicates that the number of flooded buildings tends to be underestimated for Xynthia (by a factor of ~2) and Emma (by a factor of ~8) but shows comparable estimates for Johanna. These comparisons should be interpreted with caution, however, since:

- The total water level boundary conditions are not the same between CoCliCo’s integrated scenario events (i.e. annual, centennial and millennial) and the high-resolution flood modelling that relied on the observed boundary forcing during the storms;
- CoCliCo’s infrastructure dataset is not structured as those used for comparisons, and in particular, the information on building’s type is not directly comparable between the different datasets;
- The flood hazard modelling resolution differs between CoCliCo’s model and the other studies;
- Even the high-resolution studies lack of observed information to firmly validate their results – this is the case e.g. for the Emma storm (Duo et al., 2025).



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Table 2. Modelled impacts of centennial and millennial events under contemporary conditions in La Faute-sur-Mer, Gâvres and Cadiz.

Area (Event)		Flooded building	Total costs	Average costs per building
La Faute-sur-Mer (Xynthia)	RP100	1,472	13.1 M€	8.9 k€
	RP1000	1,968	17.6 M€	8.9 k€
Gâvres (Johanna)	RP100	97	0.5 M€	5.0 k€
	RP1000	152	0.7M€	4.6 k€
Cadiz (Emma)	RP100	23	1.15 M€	50 k€
	RP1000	25	1.25 M€	50 k€

The comparison of the average damage costs per building shows an overall underestimation of the CoCliCo's results by a factor of 2 to 4 for Xynthia and Emma and less than 2 for Johanna compared to high-resolution modelling and observational evidence. It is worth noting that CoCliCo's estimates capture well the regional variations of average costs per building, but the total damage costs per event are underestimated, typically, by one order of magnitude. For the risk assessment analysis that comes in the next section, we therefore focus on the exposed number of infrastructure and population as risk metric rather than the damage costs. The sensitivity analysis, however, relies on damage costs to explore a wider range of uncertain parameters.

Table 3. Independent estimates of impacts of Xynthia (2010) in La Faute-sur-Mer, Johanna (2008) in Gâvres and Emma (2018) in Cadiz.

Area (Event)	Flooded buildings	Average costs per building	Reference
La Faute-sur-Mer (Xynthia)	~3,000 (residential), ~1,000 (commercial/industrial)	20 k€ (residential), 40 k€ (commercial), 100 k€ (industrial).	Duo et al. (2025)
	~4,000	30 k€ (all types)	André et al. (2013)
Gâvres (Johanna)	~120 (all types)	~7 k€ (all types)	André et al. (2013), Le Roy et al. (2015)
Cadiz (Emma)	~200 (all types)	200 k€ (all types)	Duo et al. (2025)



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4. Future projections

This section presents the main results of the projections of the marine flood risk at the pan-European scale and its regional variations. We present first the outcomes of the direct analysis of future projection of infrastructure and population exposure based on CoCliCo state-of-the-art new risk dataset. Then, we explore how these changes could shape adaption decisions.

4.1 Assessment of pan-European exposure changes

4.1.1 Contemporary status

In this part, change in infrastructure and population exposure to flood hazard with sea-level rise is examined. **Figure 5** shows the contemporary status of coastal buildings exposed to various episodes of coastal flood hazards (i.e. permanent inundation and 3 episodic flood events) at the pan-European scale. Considering the scenario without defences, 2.0, 2.9 and 3.4 million buildings in Europe are in the spatial extent of an annual, centennial and millennial flood event, respectively.

Flood event \ Defence scenario	Undefended scenario (all NUTS2)	Undefended scenario (defended NUTS2 only)	Defended scenario (defended NUTS2 only)
Static	0.78	0.57	0
1-yr	1.98	1.58	0
100-yr	2.89	2.34	0.01
1000-yr	3.39	2.76	0.21

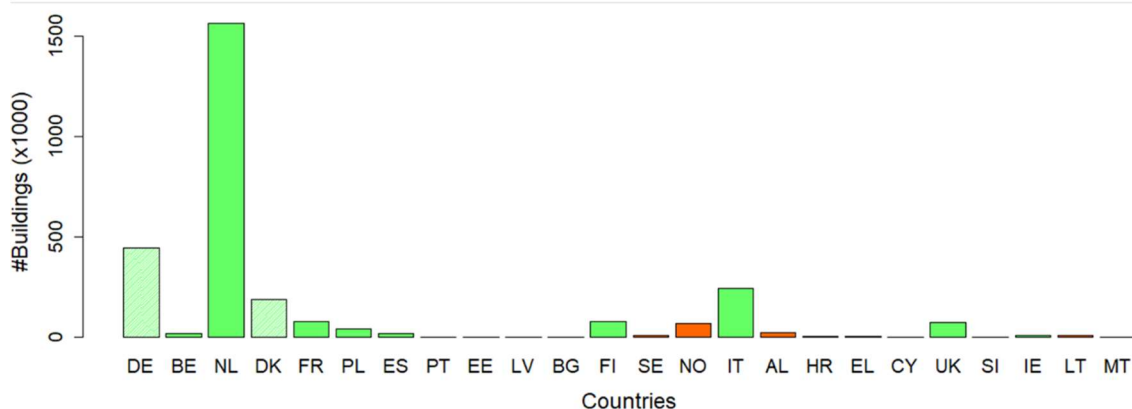


Figure 5. (top) Number of buildings exposed to flooding in Europe as a function of the type of flood event and the consideration of coastal defences. (bottom) Distribution of the number of exposed buildings per country under a 100-yr flood event assuming no defences.



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As shown on **Figure 5**, the buildings exposed (assuming no defences), are not uniformly distributed among European countries. Those with the largest coastal floodplains concentrate most of assets below undefended flood extent: i.e. the Netherlands accounts for more than a half of the total amount of buildings, followed by Germany (dominated by the North Sea coast), Italy (essentially the north Adriatic) and Denmark.

Considering undefended scenario allows appraising the status of assets located in flood prone areas; i.e. the potentially maximum extent of the hazard assuming that all defences would have failed. Although this information is more realistic than what a bathtub approach would provide (see e.g. **Figure 4c**, often used for large scale assessments; i.e. Sanders et al., 2025), it still strongly overestimates the actual exposure as most flood prone areas with assets are defended. The high-defences scenario allows assessing the exposure assuming policy-based protection levels. The table on **Figure 5** shows that the number of buildings exposed is strongly reduced if we consider that high-defence level standards are applied uniformly along the coast: buildings are no longer exposed to annual events, and the exposure is reduced by ~2 and ~1 order of magnitudes for centennial and millennial events, respectively. This strong reduction of exposure reflects the fact that most policy-based protection levels consider a 100-yr event or higher.

Note that the policy-based protection level could not be retrieved and applied for all coastal European NUTS2 regions. This is the case for Norway, Sweden or Greece for instance (marked in orange in **Figure 3** and **Figure 5**). The contribution of these countries on pan-European building exposure remains small, however. For Germany and Denmark, where policy-based protection level could be considered only partially (**Figure 3**), the weight of their contribution on pan-European building exposure is more important. When aggregating country-scale results for the defended scenarios, we therefore discarded NUTS2 regions where policy-based protection levels were not modelled. This represents ~30% of the European coastal NUTS2 regions. The effect of the removal of these regions for the pan-European assessment of assets exposed is shown on **Table 4**.

Table 4. Comparison of the total number (or length) of assets exposed to a 100-yr flood event in Europe (no defence scenario) depending on the availability of information on policy-based protection levels at NUTS2 level.

Type of infrastructure	Buildings	Education	Healthcare	Power	Rail	Road
All NUTS2	2.9 millions	4,600	800	24,300	5,900 km	55,000 km
NUTS2 with defences	2.3 millions	3,800	570	20,700	4,400 km	39,900 km

Table 5 indicates the population exposed to marine flooding in Europe as a function of the flood event and the level of defences assumed. Here the defended scenario corresponds to the high-defence scenario and aggregates the results for 70% of the NUTS2 regions. We find that 4 to more than 6 million persons are currently living in the annual to millennial flood prone



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areas in Europe (assuming no defences). Consistently with infrastructure exposure, accounting for policy-based defences leads to a reduction of 2 and 1 order of magnitude for the centennial and millennial of population exposure, respectively.

Table 5. Population exposed in 2010 in Europe (in millions)

Flood type Scenario	Permanent inundation	Annual	Centennial	Millennial
Undefended	1.7	4.1	5.7	6.6
Defended (high-level)	0	<10 ⁻⁴	2.6x10 ⁻²	0.6

In the following section, we quantify how contemporary exposure is projected to change along with the integrated scenarios defined in CoCliCo.

4.1.2 Projections

4.1.2.1 Global analysis

Table 6 provides projected changes in population and infrastructure exposure to a 100-yr flood event aggregated at pan-European scale for several time horizons and SSPs corresponding to the integrated scenarios. The contemporary values are indicated in the column filled in gray and projections are given as anomalies with respect to the contemporary values. The units corresponding to each type of exposed asset is indicated in the left column. Values for both undefended and high-defence scenarios (in italics) are provided.

As mentioned previously, considering defences under contemporary mean sea levels reduces the exposure of assets to a centennial event by ~2 orders of magnitude, independently of the asset's type. However, the order of magnitude of projected exposure changes – if quantified as the deviation from the contemporary period - is very similar whether considering defences or not: e.g. by 2050, the number of buildings exposed to a centennial event increases by 0.1 and 0.2 million for the defended and undefended scenario, respectively, regardless of the SSP. In terms of relative changes, by 2050, the number of buildings exposed to a centennial event increase by ~1000% for defended scenario versus ~10% for the undefended scenario. This highlights that in protected areas, maintaining and upgrading defences is needed to keep the level of risk as low as possible but this will require massive investment.

Increase in infrastructure exposure significantly depends on the SSP scenarios by 2100. Our results show that the increase in exposure for the SSP5 by 2100 is nearly two times larger than for the SSP1. Note that SSP1 and SSP5 are associated with a median mean sea-level rise of 0.44 and 0.77 m, respectively, by 2100 with respect to the 2010 reference mean sea level. This is consistent with the fact that we obtain an increase in exposure of nearly a factor of 2 between SSP1 and SSP5. Similarly, the high-end scenario leads to ~1.6 m SLR in 2100 and the corresponding exposure increase of infrastructures is twice as large as for the SSP5. This suggests that infrastructure exposure increases proportionally with SLR. **Table 7** further



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reveals that the current degree of building exposure to a centennial - millennial - event today is equivalent to an annual event by 2100 under the SSP5 median – high-end – scenario, respectively.

Let us, however, recall that this result assumes no coastal infrastructure’s development in space and time. It therefore solely reflects the impact of change in coastal flooding hazard’s level.

Table 6. Change in population and infrastructure exposure for 100-yr flood events

Centennial		2010	2050		2100				2150
			SSP2	SSP5	SSP1	SSP2	SSP5	HE	HE
Population (in millions)	undef	5.7	+0.8	+1.5	-0.2	+1.4	+2.4	+4.2	-
	def	0.03	+0.3	+0.4	+0.3	+0.4	+0.6	+1.2	-
Buildings (in millions)	undef	2.9	+0.2	+0.2	+0.6	+0.8	+1.1	+1.9	+7.4
	def	0.01	+0.1	+0.1	+0.2	+0.2	+0.3	+0.6	+4.1
Power (in thousands)	undef	24.3	+1.0	+1.1	+2.7	+3.5	+4.5	+8.0	+32.4
	def	0.04	+1.2	+1.3	+1.8	+1.9	+2.2	+6.0	+27.5
Roads (in 10 ³ km)	undef	55.4	+3.4	+3.9	+7.8	+10.5	+15.1	+28.1	+126.1
	def	0.2	+3.9	+4.2	+5.9	+6.8	+8.5	+17.2	+74.9
Rails (in 10 ³ km)	undef	5.9	+0.4	+0.5	+1.1	+1.5	+2.2	+4.1	+17.3
	def	0.03	+0.3	+0.3	+0.4	+0.5	+0.7	+1.6	+9.4

Table 7. Equivalence in the number of buildings exposed within integrated scenarios.

Hazard level	Present, 100-yr	Present, 1000-yr	SSP5 2100, 1-yr	HE 2100, 1-yr
#buildings	2.9 million	3.4 million	2.8 million	3.6 million

Unlike the infrastructures, the coastal population dataset developed within CoCliCo varies in space and time with SSPs (Bonatz et al., 2025). Under the SSP5 scenario, the population at the coast is projected to strongly increase until 2070 and then decline, while under the SSP2 scenario, the population at the coast is projected to remain nearly constant. This is well reflected in **Table 6**, where the exposed population in 2050 for the SSP5 is found to be twice as large as for the SSP2, despite no significant changes in hazard level. It is also worth noting



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that, in the scenarios where defences are considered, the increase of population exposure (0.3 to 0.4 million) in 2050 in Europe is consistent with estimates of the AR6, which obtained +0.38 million by 2040 (IPCC, 2023).

In 2100, the SSP1 scenario results in a decrease in population exposure. This means that the coastal flood hazard increases under a moderate SLR is compensated by the population dynamics, which tend to reduce the level of coastal flood risk on population. Under SSP3 - not retained as an integrated scenario - the large increase in projected population should lead to a substantial increase in population exposure. This highlights that socioeconomic development throughout the 21st century is having a major impact on the evolution of coastal risk, including the decisions to be made over the coming three decades.

4.1.2.2 Regional analysis

It is important to note that the increase in asset's exposure to coastal flooding is not uniform in Europe as shown on **Figure 6**, which presents a country-scale map of the contemporary state (panel a) and the evolution of exposed buildings by 2100 under the SSP5 scenario (panel b). The European countries with the largest number of buildings exposed to flooding (assuming no defences) are the Netherlands, first, followed by Germany and then Italy (see also **Figure 5**). The relative increase in building's exposure in 2100 is however much more important for France, Spain and Belgium (> 80% increase), and comparatively, much less pronounced for Germany, Finland and Norway (< 20% increase) or Italy (< 40% increase).

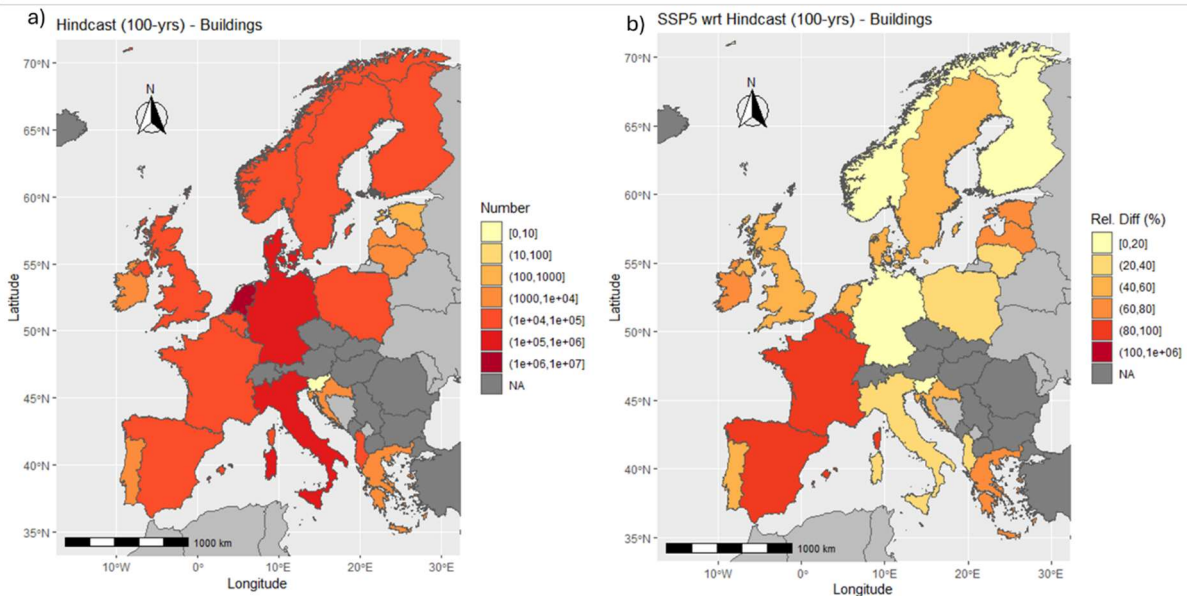


Figure 6. (a) Contemporary number of exposed buildings to centennial event per country. (b) Relative change (in %) in the number of exposed buildings in 2100 following the SSP5 scenario compared to the reference period. Undefended scenario is shown.



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Figure 7 highlights the evolution of building exposure relative increase from 2030 to 2150 under the SSP5 and assuming a high-end SLR in 2150. The evolution through time of the spatial distribution of the exposure increase is overall consistent with the one already discussed in 2100 (**Figure 6b**), with France, Belgium, Spain, Ireland but also the Baltic countries showing the largest relative increase. Note that according to the high-end scenario in 2150, more than 10 times more buildings will be located in a centennial coastal floodplain in France and Spain than under current conditions. Interestingly, only Finland shows a reduction of buildings exposure in 2030 and 2050, which is the result of the projected mean sea-level fall due to the glacial isostatic adjustment.

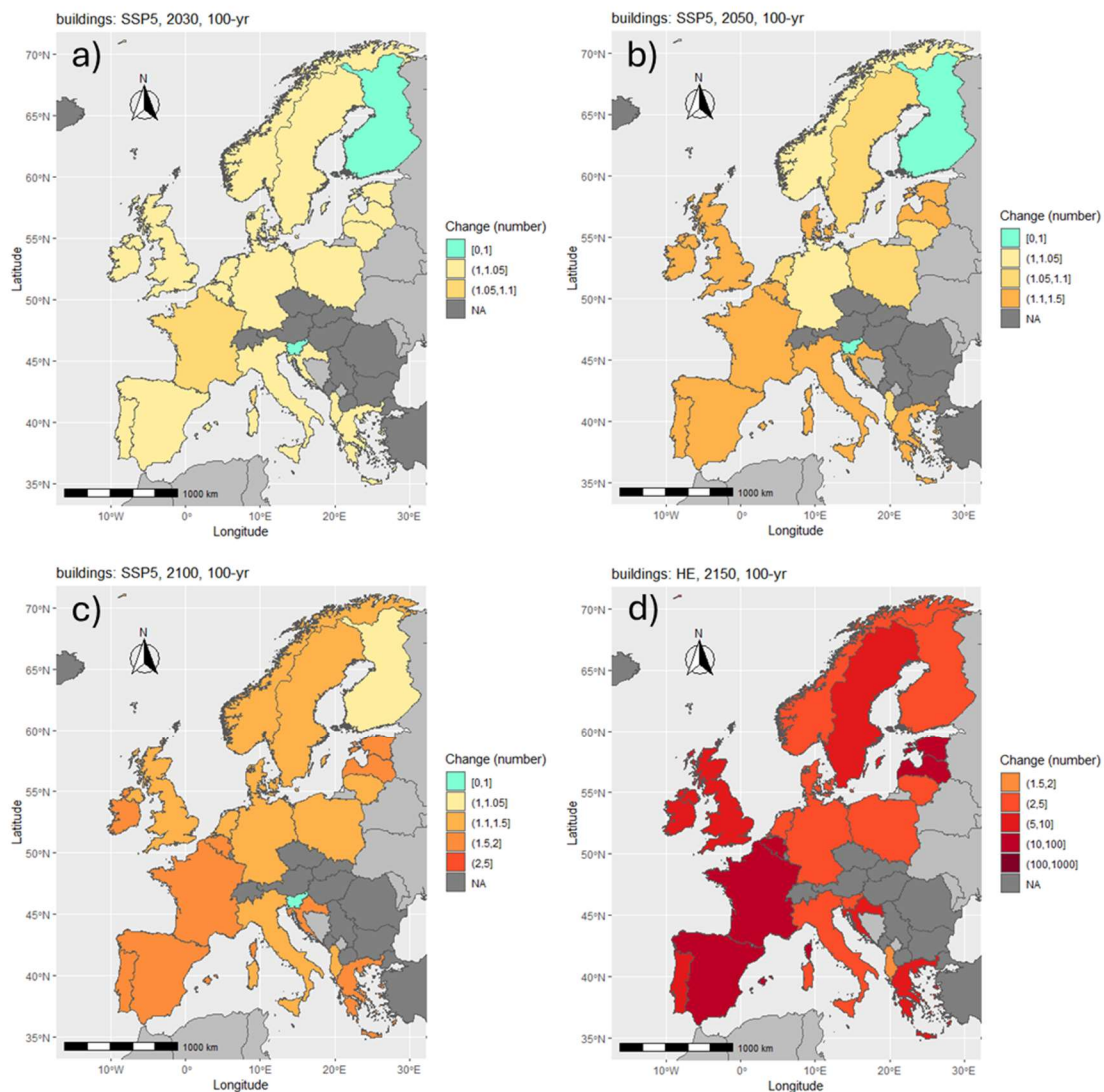


Figure 7. Relative change (ratio with respect to the reference period) in the number of exposed buildings in (a) 2030, (b) 2050, (c) 2100 and (d) 2150 for the (a-c) SSP5 and (d) high-end scenario. The undefended scenario is shown.



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The same analysis has been repeated for the remaining assets' type (i.e. rail, roads, ...) and the results yield similar conclusions (see Figures A and B in the appendix).

Overall, this analysis suggests that European countries that are already well prepared and/or defended against coastal flooding – i.e. the Netherlands or Germany – will experience a certain but rather gentle and progressive increase of their asset's exposure in comparison with the contemporary situation. Conversely, for countries such as France or Spain, the increase of coastal asset's exposure will be more abrupt. This further supports the statement that coastal adaptation needs to start today, especially in those countries such as France and Spain where impacts will emerge most rapidly.

4.2 Implications for adaptation

In this section, the results are presented and framed to address the challenges that Europe will face to adapt to sea-level rise. The results are first analysed at the LAUs scale and then aggregated at national-to-European scale following different assumptions.

4.2.1 How many more buildings will be protected in the future?

To estimate the number of buildings protected in Europe against coastal flooding under present forcing conditions, we consider the undefended scenario. We then make assumptions at the scale of LAUs and associate a level of defence with respect to the population density:

- Coastal LAUs are considered rural if the population density is lower than 50 inhabitant/ km². We assume that rural LAUs are protected against annual flood events;
- Coastal LAUs with a population density comprised between 50 and 1,000 inhabitants/km² are assumed to be defended against centennial flood events;
- Densely populated cities (i.e. greater than 1,000 inhabitants/km²) are considered as protected against millennial flood events, such as e.g. Nice and Marseille in France or San Sebastian and Santander in Spain;
- Finally, Germany, Netherlands, Denmark and Belgium LAUs are all assumed to be protected at a minimum level of 100-yr event, even in rural areas.

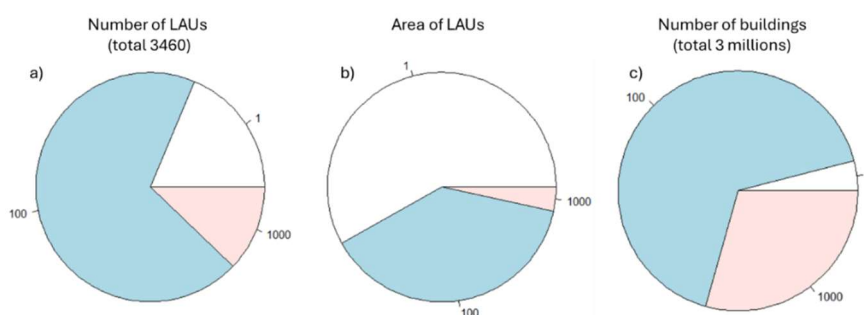


Figure 8. Distribution, expressed as (a) the number of exposed LAUs, (b) area of exposed LAUs and (c) Number of exposed buildings within LAUs, with respect to the protection level (1-yr, 100-yr or 1000-yr) assumed at the LAU scale.



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As shown on **Figure 8**, among 12,000 coastal LAUs in Europe, 3,460 LAUs embed a total of 3 million buildings that are currently protected against coastal floods. Following the defence level hypotheses described above, 70% of LAUs (**Figure 8a**) associated with more than 1.8 million buildings (**Figure 8c**) are assumed to be protected against centennial events, although this corresponds to only ~40% of protected coastal LAUs in terms of spatial extent (**Figure 8b**). Conversely, only ~20% of coastal LAUs embedding less than 5% of buildings are in rural areas and considered to be protected against annual events (**Figure 8a and c**), but this represents the largest land domain in Europe (**Figure 8b**). Finally, more than 25% of buildings in Europe are located in densely populated cities and assumed to be protected against millennial events, although this represents a very small portion of land (less than 5%, **Figure 8b**). The country-scale deviation is however very substantial: i.e. more than a half of the total protected buildings in Europe are located in the Netherlands and one sixth in Germany, then followed by Italy, Denmark and France.

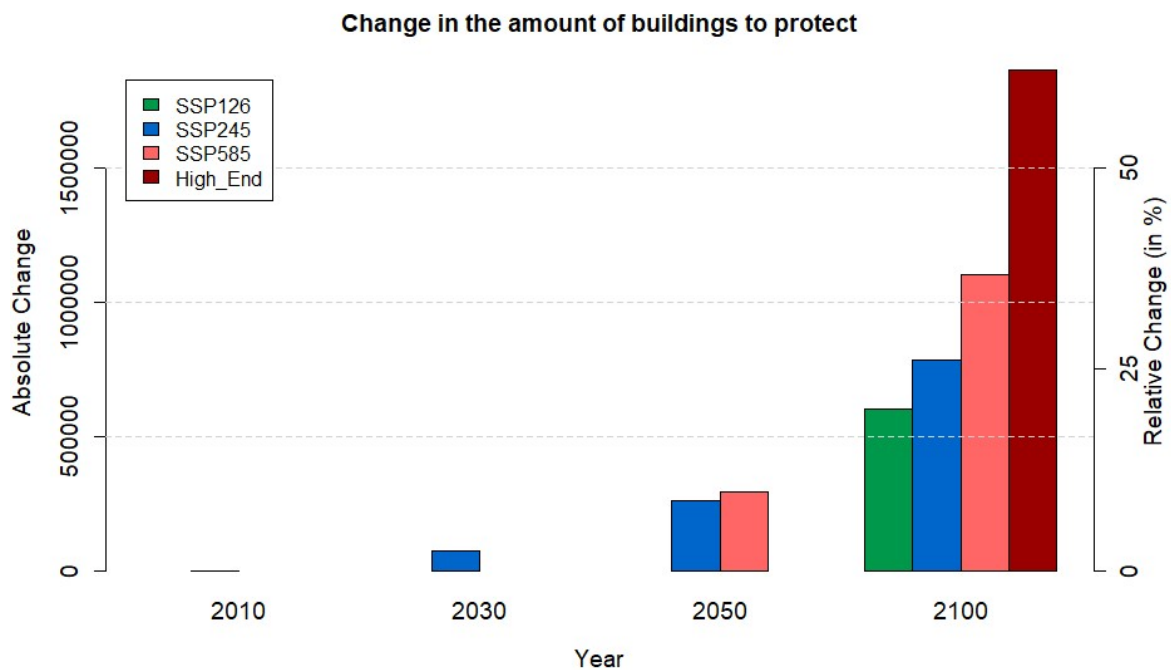


Figure 9. Absolute and relative change (i.e. projection minus reference period) in the number of buildings that will need to be protected against coastal flooding as a function of SSP scenario at the scale of Europe.

Following the same assumptions on protection levels, we now project how many more buildings will need to be protected with rising sea level. Changes with respect to the reference period (year 2010) are shown on **Figure 9**. At the scale of Europe, ~70,000 and ~280,000 more buildings will need to be protected against coastal flooding by 2030 and 2050, respectively, corresponding to an increase of ~3% and ~10% compared to the reference period. At these short-to-midterm time horizons, the climate change scenario has a small influence. The influence of climate change becomes substantial in 2100, where the projected



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number of buildings to be protected is nearly two times larger for the SSP5 (36% increase) than the SSP1 (20% increase). Considering a high-end sea-level rise scenario could lead to an increase greater than 60% by 2100. This suggests that the uncertainty of knowledge on ice-sheet processes driving SLR rates has an impact as large as climate change trajectory on future coastal exposure reduction.

Again, examining the regional variations of these changes is very informative. For example, **Figure 9** indicates that considering the SSP2 scenario leads to a 25% increase of buildings to protect by 2100 in Europe. However, this relative change yields more than 50% for France, Ireland, Spain and Belgium while it remains below 20% for Germany, Poland or Norway, and is even negative for Finland (-10%). It is also interesting to remark that the relative increase for France or Ireland by 2100 for a SSP2 scenario is equivalent to the relative increase for Netherlands by 2100 but considering the high-end SLR scenario. This reflects well the imbalance between country within Europe in the efforts that will be required to reduce their coastal exposure.

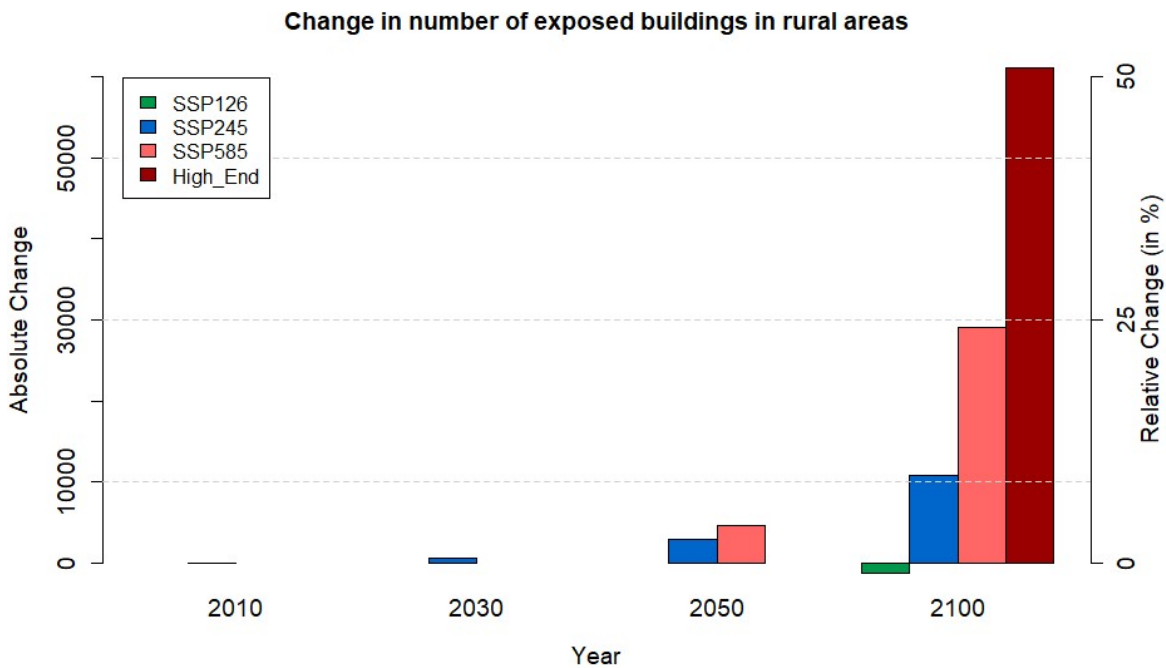


Figure 10. Same as Figure 9, but restricted to rural LAUs; i.e. where population density < 50 inhabitants/km² excluding the Netherlands, Germany, Belgium and Denmark.

So far, we assumed that rural LAUs are protected against an annual event and that this will remain the case in the future. However, one could alternatively assume that buildings located in such areas may not be protected further and therefore abandoned: this concerns 120,000 buildings in Europe for the reference period. **Figure 10** shows exposure change of buildings in rural environments. It is noteworthy that exposure increase remains moderate until 2050



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but exhibits a very strong dependence to SLR trajectory in 2100, going from an exposure decrease for the SSP1 to a 50% increase in the event of a high-end SLR trajectory. The analysis at the national level (not shown) reveals that the rural LAUs of Norway, Italy, France, Poland and UK will face an increase buildings loss aligned with the global SLR. Conversely, Finland - and to some extent Sweden - may experience either a strong risk reduction of their rural built environment under the SSP1 scenario in 2100 (-12,000 buildings) or a strong increase under the SSP5 scenario (+5,000).

4.2.2 Impact of SLR on population displacement

Following an approach like the one used to assess change in built environment exposure in rural LAUs, we assess projection of population displacement (from rural areas) over the 21st century in Europe. More specifically, we used the same hypotheses as Ballesteros et al. (2025); i.e. we assume that displacement of population occurs in unprotected areas when land becomes flooded annually. Therefore, we assume (i) that coastal areas are unprotected if the population density is lower than 50 inhabitants/km² and (ii) that population in these unprotected coastal areas is uniformly distributed in sectors that are not exposed to a 1-in-1-year flood event under current forcing conditions. Displacement is derived as the number of people that become located within a 1-in-1-year flood event extent with SLR. Results are shown on **Figure 11**.

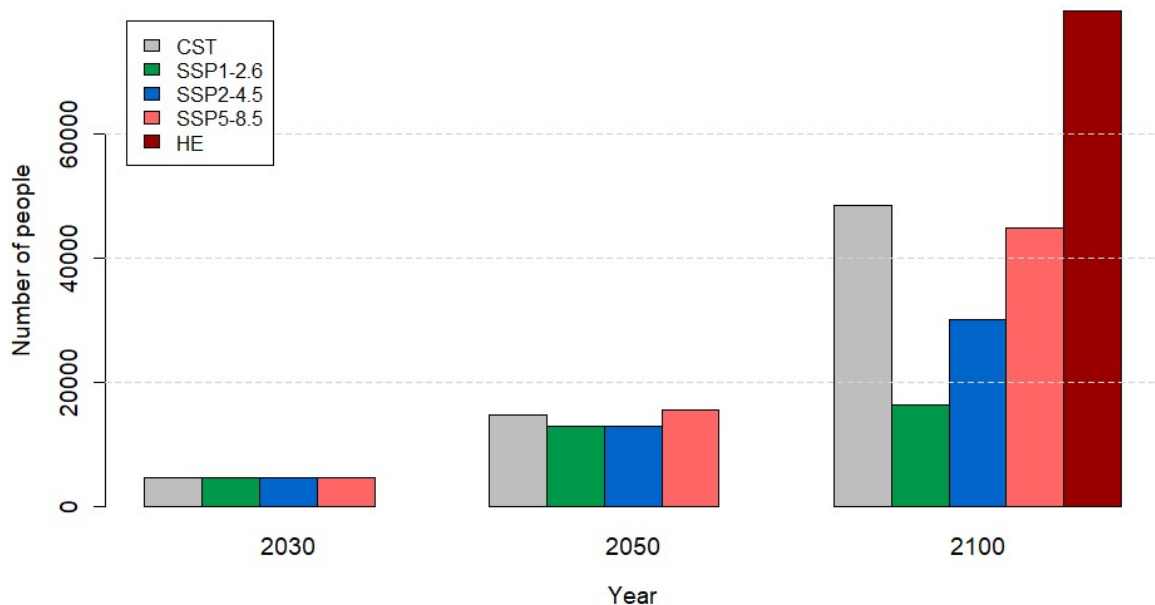


Figure 11. Projection of population displacement from rural coastal LAUs (i.e. < 50 inhabitants/km²) in Europe in 2030, 2050 and 2100 as a function of the SSP scenario. The CST is a scenario assuming no population changes but consider a SSP5 hazard change.



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In the short-to-midterm horizon, the projected population displacement is not sensitive to the integrated scenario, reaching 5,000 and 15,000 people in 2030 and 2050, respectively. By the end of the century, the projected population displacement varies between 18,000 people and 45,000 for the SSP1 and SSP5, respectively. The high-end scenario, which considers a SSP5 population projection, reaches up to almost 80,000 people migrating. Note that these orders of magnitude are consistent with the analysis of building exposed in rural environment (section 5.2.1). They are however much lower (by ~one order of magnitude) than the estimates of Ballesteros et al. (2025), who used a different coastal risk modelling framework and different datasets. More work is needed to better understand these differences.

Interestingly, if we consider no change in the population in the future but still apply a hazard change according to the SSP5 scenario (CST, gray bar), we find that the projected population displacement remains similar to the SSP5 integrated scenario (red bar). This suggests that despite the overall increase in coastal population in the SSP5 (Bonatz et al., 2025), the rural areas could still experience a decrease of population. Note that these numbers remain quite sensitive to the threshold applied to the population density to define unprotected coastal areas. For example, if we applied a threshold of 100 inhabitants/km², the impact on projected population displacement is overall multiplied by factor 3 compared to when we apply a threshold of 50 inhabitants/km², whatever the scenario (see Figure C in the appendix).

4.2.3 Impact of current defences

In section 5.2.1 and 5.2.2, the risk metrics and indicators were derived from undefended scenarios. Here, we make use of policy-based defences level to assess how many buildings are currently at risk of coastal flooding and how this could change if the defence standards are not upgraded. In line with previous analysis, we assume that LAUs with a density of population lower than 50 inhabitants/km² are unprotected, except in the Netherlands, Germany, Denmark and Belgium, where even rural environment is protected following policy-based standards. For LAUs with a population density comprised between 50 and 1,000 inhabitants/km², we assume that the coastal is protected under low defence standards. Finally, densely populated LAUs (> 1,000 inhabitants/km²) are considered to be protected following high-defence standards. Through these assumptions, we refine the consideration of defences at the LAU scale and adjust the level of defence to the current coastal exposure to seek at getting close to the real state of coastal defences in Europe.

Table 8. Number of buildings exposed (in million) to annual, centennial and millennial coastal flood events, assuming defences are maintained but not upgraded.

Flood event	2010	2050		2100				2150
		SSP2	SSP5	SSP1	SSP2	SSP5	HE	HE
Annual	0.12	0.13	0.14	0.15	0.19	0.27	0.45	3.68
Centennial	0.22	0.31	0.31	0.36	0.48	0.56	0.86	4.50
Millennial	0.37	0.48	0.49	0.56	0.62	0.73	1.14	4.87



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As shown on **Table 8**, 0.12, 0.22 and 0.37 million are exposed to annual, centennial and millennial flood events, respectively, in Europe over the reference period. Let us remind that for a centennial event exposure over the reference period, we obtain 2.9 million buildings exposed if we assume no coastal defences and. Conversely, only 0.01 million buildings are exposed if we assume that the coasts in Europe are uniformly protected according to the policy-based levels. The former hypothesis leads to strongly overestimate the buildings exposure, while the second strongly underestimates the exposure. In this regard, the 0.22 million buildings exposed to a centennial event obtained based on the LAUs-scale defence assumptions likely better represents the actual buildings exposure. **Figure 12** shows that, among the 0.22 million buildings exposed, ~70% are located in rural LAUs and ~30% in LAUs of medium population density.

By 2050, the number of buildings exposed to annual events increases very slightly (~10,000), while a substantial increase of ~100,000 is projected for centennial and millennial events. This suggests that, considering current defence levels, LAUs of medium-to-high population density will remain protected against annual events but will start to be increasingly exposed to centennial events. In 2100, if protections are not upgraded, the buildings exposure to flood events will be multiplied by ~2 and ~4 under the SSP5 (+80 cm SLR) and high-end scenario (+1.6 m SLR), respectively, in comparison with the contemporary period. As shown **Figure 12**, 70% of the increase in buildings exposure mostly concerns LAUs of medium population density in 2100 (panel b), while densely populated cities increased exposure becomes more prominent for high SLR (panel c). This implies that massive investments will be required to protect or relocate in populated areas to adapt to sea-level rise.

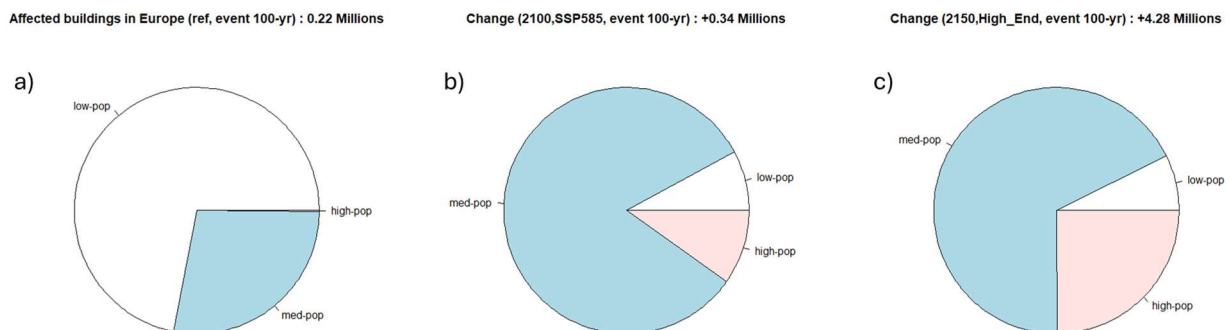


Figure 12. Distribution as function of population density in the LAUs of (a) the buildings exposed to a centennial coastal flood event and its changes under (b) the SSP5 scenario in 2100 and (c) a high-end scenario in 2150.

5. Analysis of uncertainty

In the CoCliCo project, the design and use of integrated scenario allows exploring future coastal risk through various but consistent socioeconomic and climate change future evolutions. Comparing the results obtained for these different scenarios therefore provides a first estimate of the uncertainty range. In this part, we first describe the difference sources of



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uncertainty and their impact. Then, we present the results of the sensitivity analysis (see section 2.3), which allows quantifying how uncertainties of each component of the risk calculation workflow contribute to the integrated risk uncertainty.

5.1 Comparison of integrated scenarios and sources of uncertainty

5.1.1 Uncertainty related to the hazard level

In 2050, our results revealed that the increase in number of infrastructures (of any type i.e. buildings, networks, ...) exposed to coastal flooding is rather insensitive to SSP scenarios (e.g. **Table 6** or **Table 8**). This is also true whatever the flood event analysed: i.e. the centennial and millennial events both result in the same increase in exposure for SSP2 and SSP5 scenarios by 2050. This non-dependence to SSP scenario in 2050 is not a surprised, however, since the projected median sea-level rise used as a boundary conditions for flood modelling is similar (+ 20 cm) for both scenarios (see D3.2 or Fox-Kemper et al., 2021) and since other components of risk remain unchanged. Indeed, total water level components (i.e. tides, surges or waves) used as boundary conditions for flood modelling are derived over the hindcast period and kept fixed in the future. Similarly, the infrastructure dataset is computed over the contemporary period and then fixed in space and time. Although it is already clear that a simple comparison between integrated scenarios is insufficient for an exhaustive uncertainty assessment, these assumptions (i.e. fixed infrastructures and climate boundary forcing beside SLR) remain relevant at short-to-mid time horizon. Nonetheless, even if the median SLR of SSP2 and SSP5 is similar in 2050, the likely range is comprised between 15 and 30 cm (D3.2). As we found that increase in infrastructure exposure in Europe is nearly proportional to mean sea-level changes (see **Table 6**), increase infrastructure exposure estimates may deviate by ~50% in 2050 if we consider SLR uncertainty solely as provided by the likely range.

Our results also revealed that considering coastal defenses or not has a major impact on flood hazard level, and therefore on risk. For instance, we found that the number of infrastructures exposed to coastal flooding is reduced by ~2 and ~1 orders of magnitudes for centennial and millennial events, respectively, over the reference period. While this is not surprising, it remains highly challenging to determine which parts of the European coast is effectively defended, what is the level of protection and how it will evolve with sea-level rise. In section 5.2.3, we made several hypotheses that allow linking the level of defences with exposure to try approaching the real state of defences in Europe. As a result, we obtained that 0.22 million buildings are presently exposed to a centennial event in Europe, versus 2.9 million if we consider that coasts are uniformly undefended or 10,000 buildings if we assume that the whole European coast is protected following high-defences policy standards. In this regards, 0.22 million seems a reasonable number, but remains largely sensitive to assumptions made.

Finally, note that flood event return periods correspond to a spatially varying total water level (one per coastal target point) used (i) as boundary forcing of the flood modelling and (ii) to define the policy-based level of defences. Uncertainty on water level for a given return period can however be very large, especially for long return period events (e.g. millennial). It is sensitive to several factors, such as e.g. the quantity and quality of water level data, the



number of data sources, the extreme value analysis assumptions (Wahl et al., 2017), etc. This is well illustrated for the Xynthia event, which, depending on the data (systematic measurements and/or consideration of historical storms) and methods used, has been associated with a return period of ~1,000 years (Duluc et al., 2014) or ~200 years (Bulteau et al., 2015).

5.1.2 Uncertainty related to the exposure changes

Unlike infrastructures, population projections are changing substantially in space and time already by 2050 with respect to the reference period (**Table 6**). Despite no significant changes in median SLR, uncertainty associated with SSP scenario leads to a doubling of population exposure between the SSP2 and SSP5 in 2050. This indicates that future socio-economic development of coastal regions will have a major influence on the future risk level, although quantifying its weight remains highly challenging and requires more research.

5.1.3 Uncertainty related to integrated scenario in 2100 and beyond

Scenarios of sea-level rise projections start diverging after the mid of the 21st century (Fox-Kemper et al., 2021). The sensitivity of coastal risk change to future sea-level rise is accordingly well captured in our analysis in 2100, when the choice was made to provide 4 integrated scenarios: SSP1 – sustainability – leading to +0.44 m median SLR, SSP2 – middle of the road – leading to +0.56 m median SLR, SSP5 – fossil-fuelled development – leading to +0.77 m median SLR, and finally a high-end scenario, relying on the 83rd percentile of an SSP5 scenario including ice-sheet collapse, leading to a +1.6 m SLR. Our results reveal that, between the SSP1 and the SSP5, the change in infrastructures exposed to SLR in 2100 is multiplied by two. Furthermore, considering a high-end sea-level rise scenario could lead to an increase greater than 60% by 2100. This suggests that the uncertainty of knowledge on ice-sheet processes driving SLR rates has an impact as large as climate change trajectory on future coastal exposure reduction. The event of a high-end would dramatically enhance coastal flood exposure by 2150, as revealed by the projected increase by almost one order of magnitude compared to 2100 (see e.g. **Table 6** or **Table 8**).

Again, as the infrastructure dataset remains static in space and time, it is not possible within the CoCliCo framework to assess how future infrastructure developments would impact the coastal risk evolution by the end of the 21st century. The SSP-driven population projections, however, show that by 2100, the population dynamics could counteract or, conversely, amplified the coastal risk very substantially.

In summary, section 5.1 provides an overview of what are the major sources of uncertainty in the risk assessment and quantifies their impact when data produced allows it. For obvious computational cost reasons at such large (continental) scale, a detailed analysis of each uncertainty sources and their respective weight is not possible. Nonetheless, we had sufficient data and information to perform a sensitivity analysis involving several uncertainty sources and modelling choices. The results applied to damage costs are described in the following section.



5.2 Sensitivity analysis

The sensitivity analysis described in Sect. 3.3 was conducted for all LAUs of five countries: France, Spain, Italy, UK, and Finland.

Figure 13 gives an example of results for LAU #17486 located in Charente-Maritime on the French Atlantic coast. This shows the distribution of the damage costs in the form of boxplots for all 368 computer experiments conducted by varying the values of the considered uncertain factors. The visual inspection of these results suggests that the level of defence has the largest impact on the damage costs because setting this level to 'UD' (undefended) results in high changes in the distribution compared to the other levels, HD and LD – the resulting distribution being highly skewed towards large damage cost values. The second most impactful factor appears to be the choice in the scenario, where the selection of the high-end scenario also results in a skewed distribution.

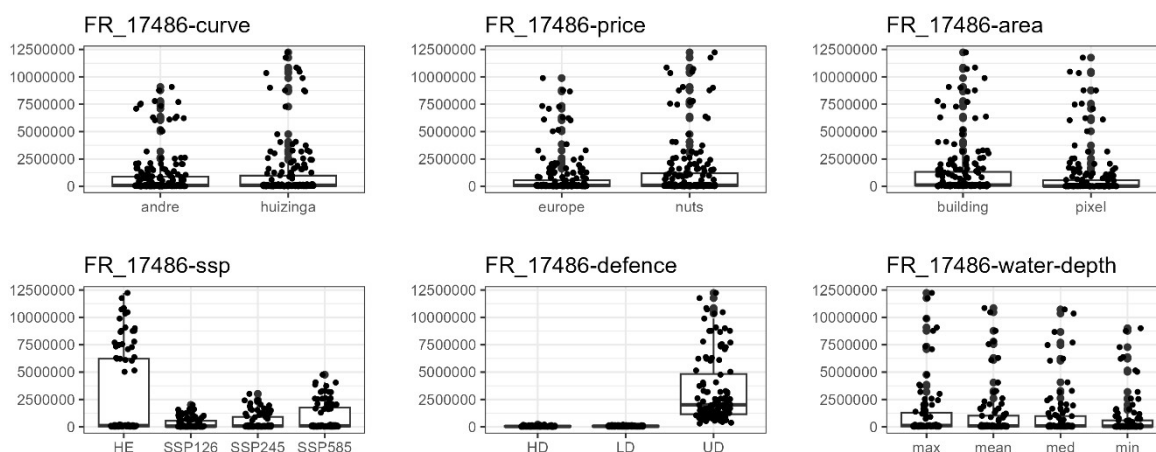


Figure 13. Distribution in the form of boxplots of the damage costs (expressed in euros) depending on the value taken by each uncertain factor (indicated in the title of each panel) for LAU 17486 (France).

This qualitative analysis is confirmed by computing the sensitivity indices using the HSIC-based approach. **Figure 14** shows that the level of defence has in this case the highest index of 40%, which means that this modelling choice has here the highest impact on the damage cost estimation. The choice in SSP has here the second highest index of 10%, which means that its influence is lower by a factor 4 than that of level of defence. The other uncertain factors have HSIC indices of low values. A complementary hypothesis testing procedure shows us that the remaining factors can be considered of negligible influence.



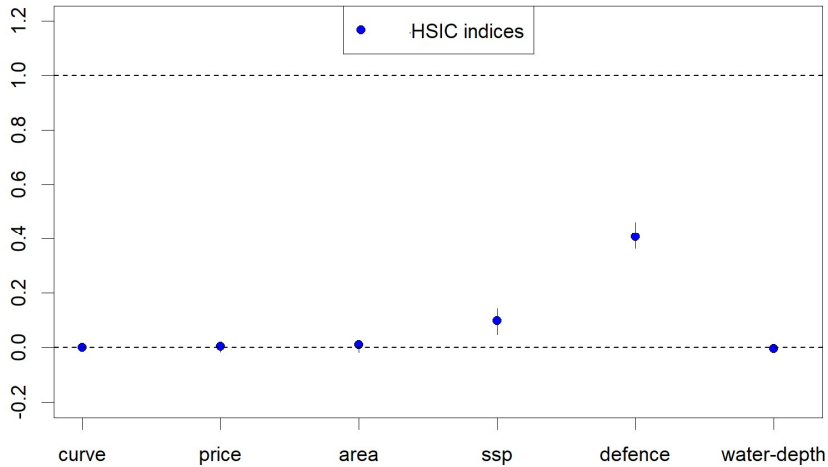


Figure 14. Sensitivity indices HSIC for each uncertain factor for LAU 17486. The higher the index, the higher the influence of the considered factor on the damage costs.

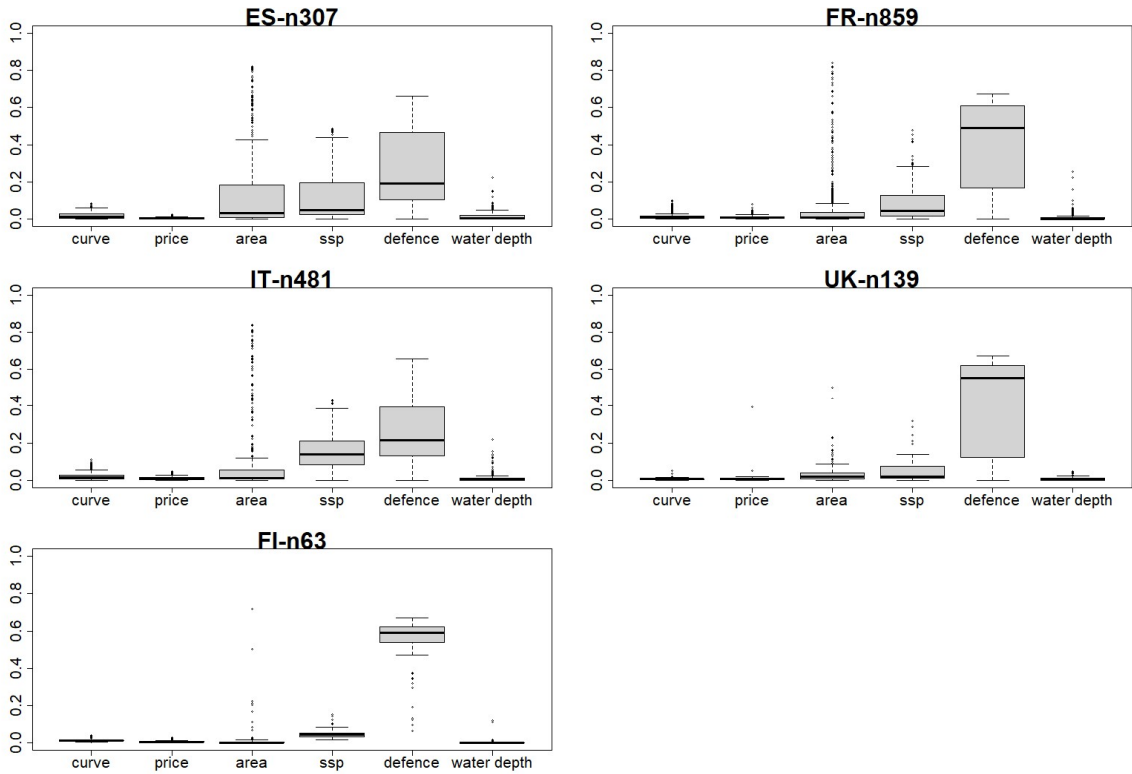


Figure 15. Distribution in the form of boxplots of the sensitivity indices HSIC for each uncertain factor considering all LAUs for five countries. The number *n* of LAU per country is indicated in the title of each panel.



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The afore-described analysis is then conducted for all LAUs. **Figure 15** shows boxplots of HSIC sensitivity indices aggregated per country. As expected, the level of defences has the largest influence on damage costs for all countries, followed by the choice of SSP, which directly relates to the magnitude of sea-level rise. It is worth noting that the primary influence of the level of defences differs between countries, e.g. in Finland, the median HSIC reaches 60%, while in Italy or Spain, the median HSIC drops to 20%. Overall, the modelling choices related to the damage curve, the asset’s repair price or the flood water depth are very small. The influence of the method used to compute asset’s area hit by the flood is significant, especially in Spain.

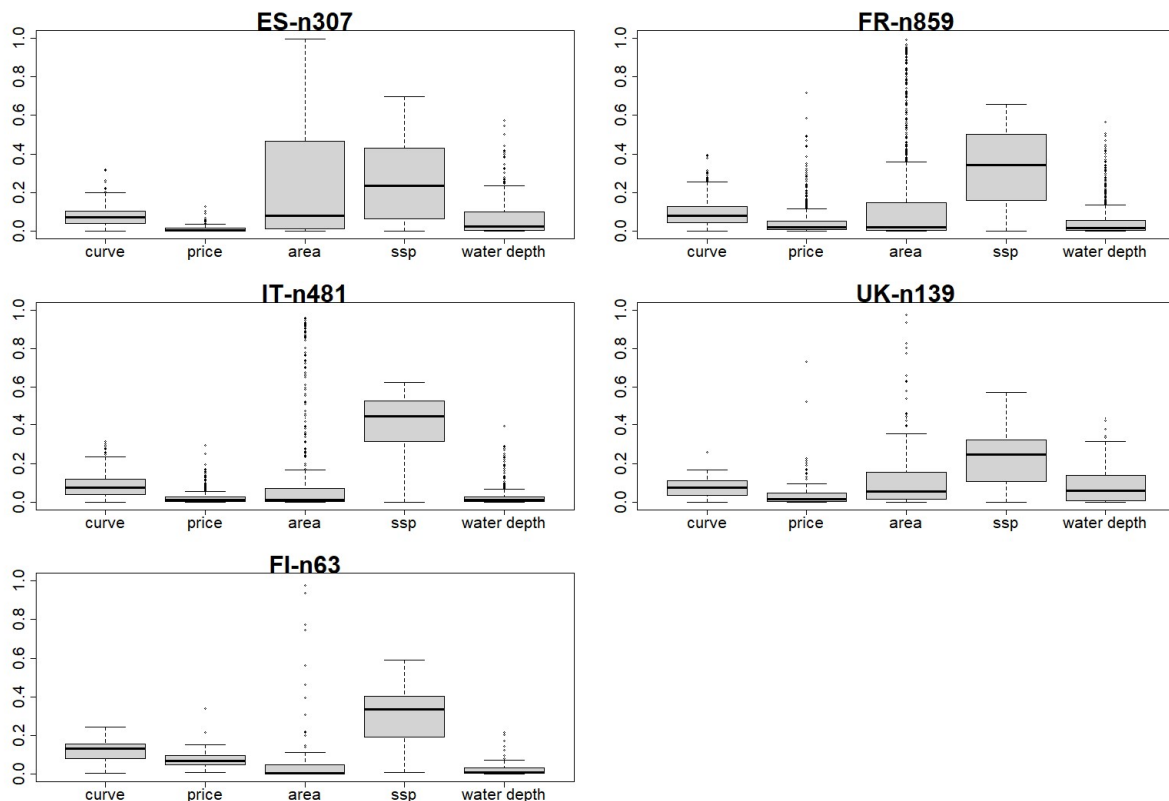


Figure 16. Distribution of the sensitivity indices HSIC or each uncertain factor considering all LAUs for five countries. Here the analysis is focused on undefended cases only. The number *n* of LAU per country is indicated in the title of each panel.

Next, we repeated the sensitivity analysis but focusing only on experiments that are ‘undefended’ to better quantify the influence of each factor besides defences. **Figure 16** shows, as expected, that the SSP choice dominates overall, particularly in Italy, France and Finland, where the median HSIC index reaches ~40%. The second most important factor is the choice of the damage curve, which is consistent over all countries with a median HSIC value of ~10% and a similar spread. Conversely, the method used to compute asset’s area hit by the flood shows a very contrasted influence. While its influence is very small in most LAUs



as revealed by the median HSIC value that falls below 5% in France, Italy, UK and Finland, the boxplots show a high level of skewness toward upper HSIC values.

Figure 17 illustrates the spatial distribution of the factor with the highest sensitivity index per LAU in coastal regions of Spain. As expected, the choice of the SSP (in pink) appears to be the most influential factor in most LAUs for the three regions. We note also several clusters of LAUs where the area factor (in violet) is the most influential: this is the case e.g. in the northern part of Galicia (Figure 17a), between Alicante and Murcia (Figure 17b) or between Gibraltar and Marbella (Figure 17c). The coast of Galicia (Figure 17a) shows also several LAUs where the flood water-depth (in green) is the factor with the largest weight in uncertainty. Other examples are shown in the appendix (Figure D to F).

Overall, this quantitative sensitivity analysis performed on the flood damage costs on buildings shows that the most influential drivers of uncertainty are first the level of defences and second the magnitude of sea-level rise. The analysis reveals also substantial variations in the order of importance of these factors at the scale of LAUs. Further analysis would be needed to better understand these regional disparities, however.

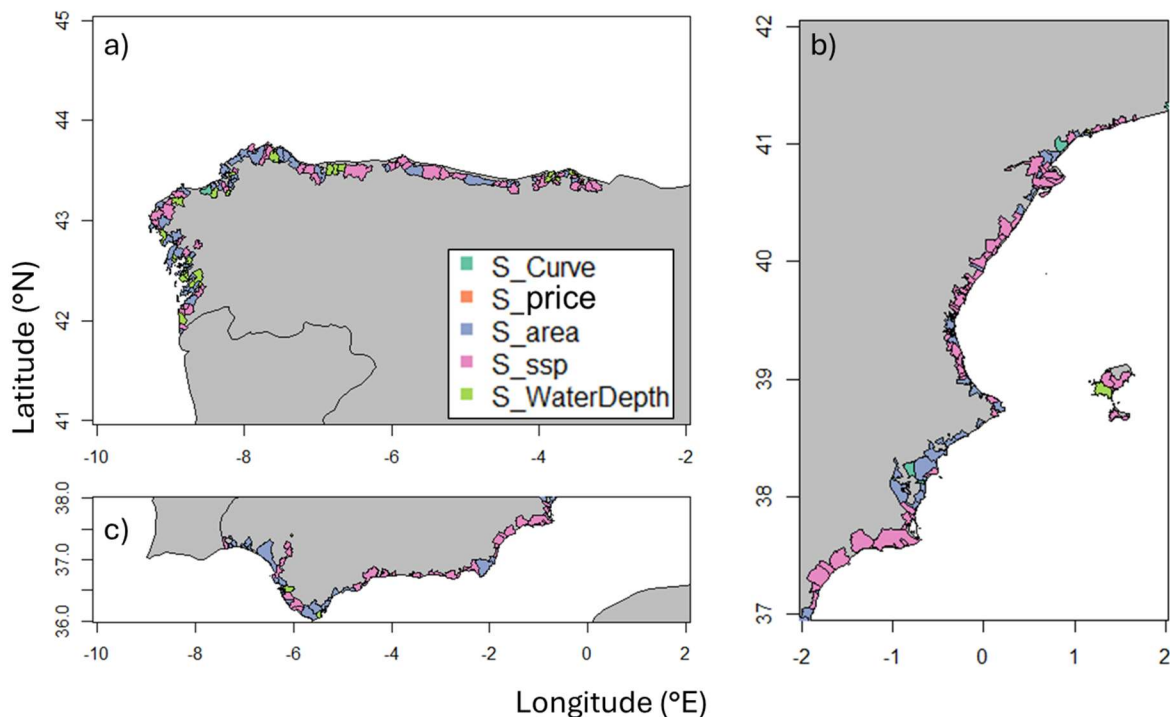


Figure 17. Map across Spain of the most influential uncertain factor, i.e., with the highest sensitivity index. The map is divided into three large coastal regions: (a) the North-Northwest Atlantic coast, (b) the East Mediterranean coast and (c) the South Atlantic and Mediterranean coast.



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6. Conclusion

In this deliverable, we presented a new coastal flood risk assessment that provides a cutting-edge, validated coastal risk database for projecting future risks across Europe and supporting climate services. In particular, the risk analysis highlights the urgent need for immediate coastal adaptation, especially in countries like France and Spain, where impacts from sea level rise (SLR) will appear soonest, even under moderate SLR. This requires that policy-makers make decisions now about adaptation, including relocation, accommodation, upgrading or abandoning coastal defenses, despite the social and governance difficulties involved and investments needed. Furthermore, we found that socioeconomic development strongly shapes future coastal risks and that the related impacts are already expected over the coming decades. Finally, as illustrated through the various caveats or the discussion on uncertainties, the CoCliCo coastal risk assessment is a first effort that provides a strong foundation for future developments in coastal climate services.

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8. Appendix

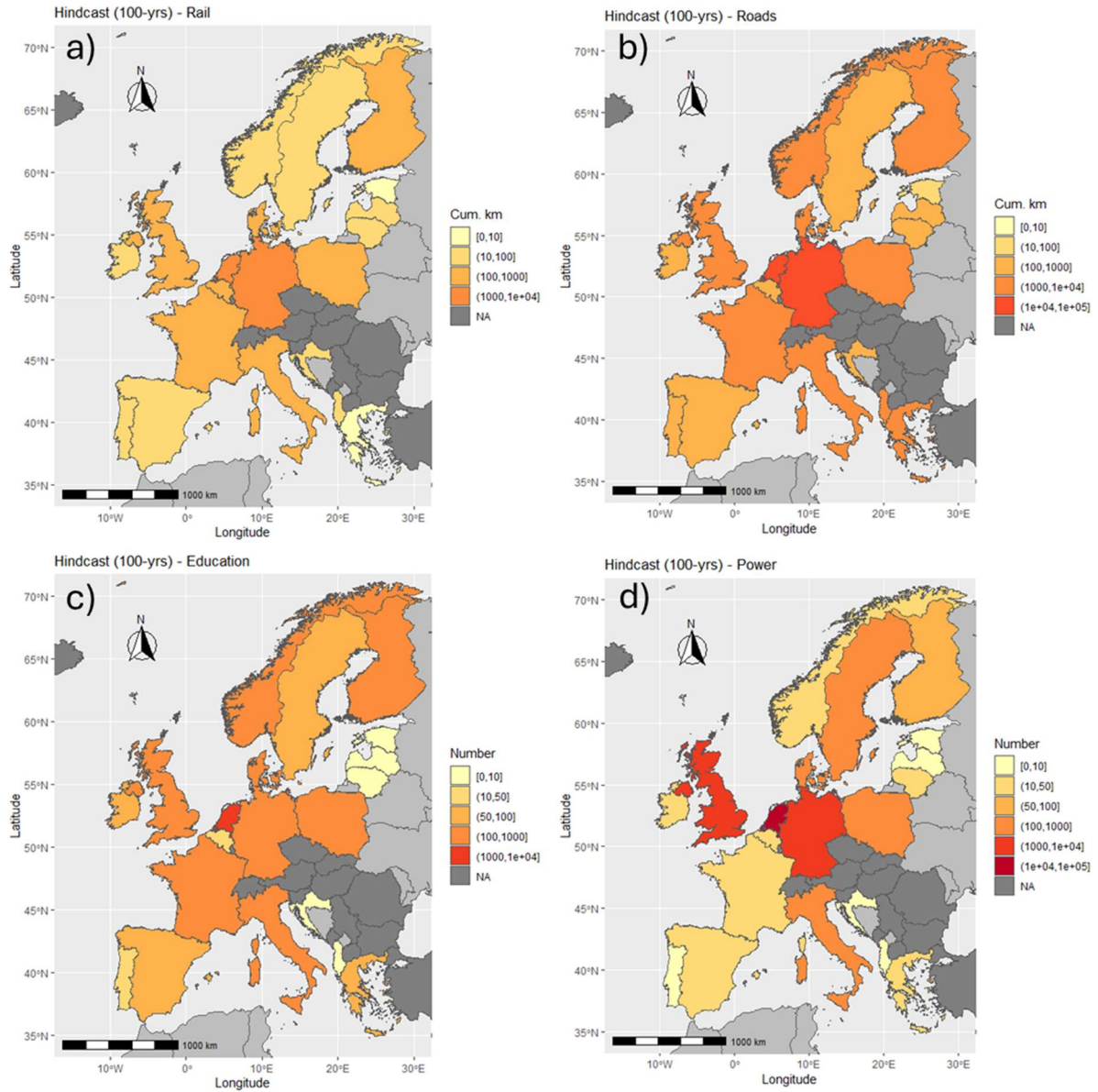


Figure A. Contemporary (a,b) length and (c,d) number of exposed (a) rail, (b) roads, (c) education buildings and (d) power infrastructures to centennial event per country. Undefended scenario is shown.



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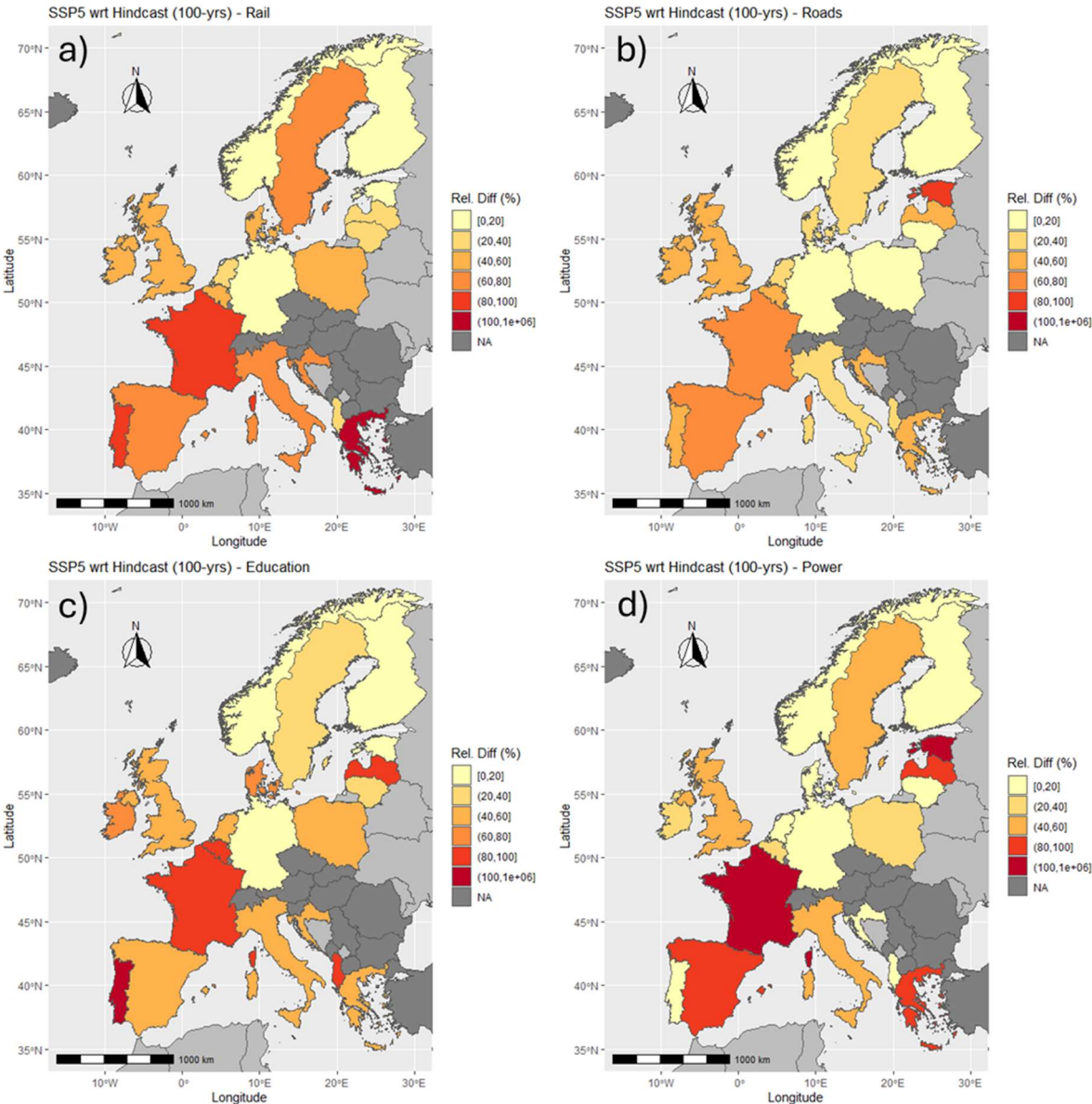


Figure B. Relative change (in %) in the (a,b) length and (c,d) number of exposed (a) rail, (b) roads, (c) education buildings and (d) power infrastructures to centennial event per country in 2100 following the SSP5 scenario compared to the reference period. Undefined scenario is shown.



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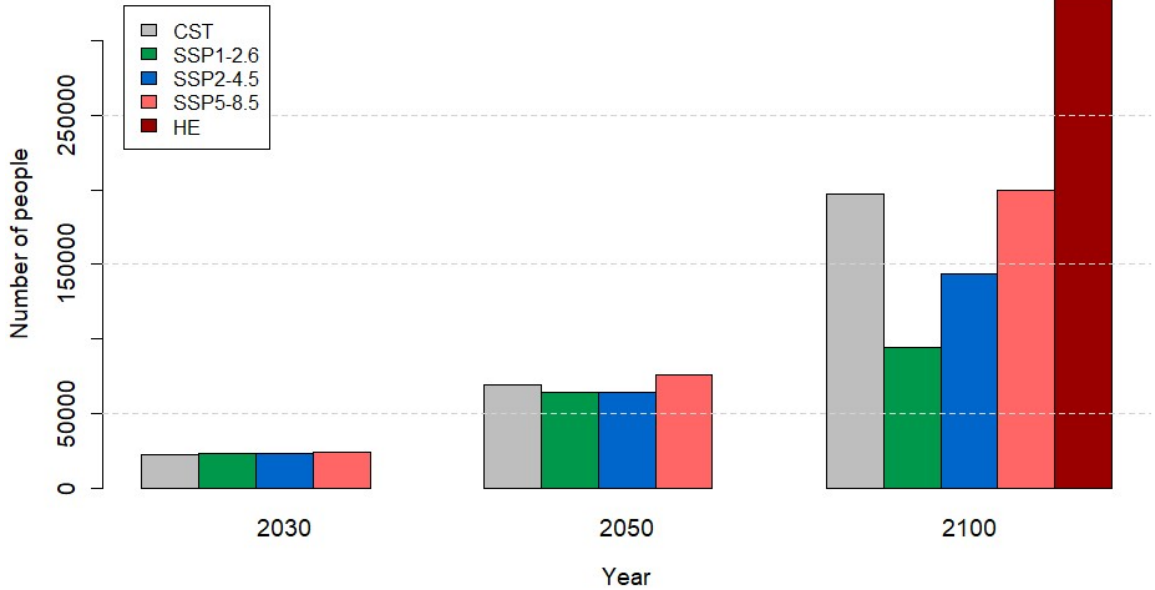


Figure C. Projection of population displacement from rural coastal LAUs (i.e. < 100 inhabitants/km²) in Europe in 2030, 2050 and 2100 as a function of the SSP scenario.



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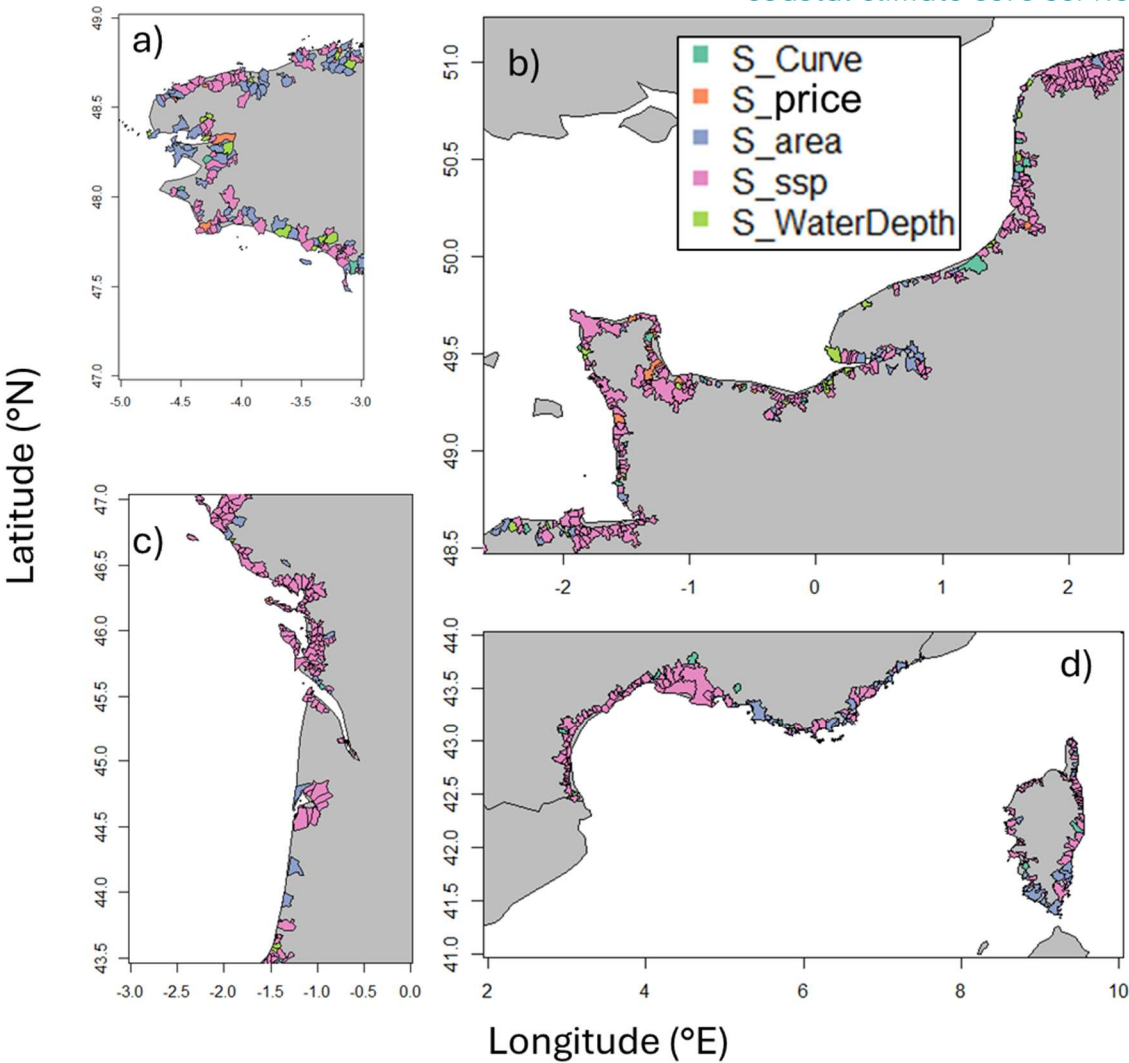


Figure D. Map across France of the most influential uncertain factor, i.e., with the highest sensitivity index. The map is divided into four large coastal regions: (a) the Brittany coast, (b) the Channel's and North Sea coast, (c) the Bay of Biscay and (d) the Gulf of Lion.



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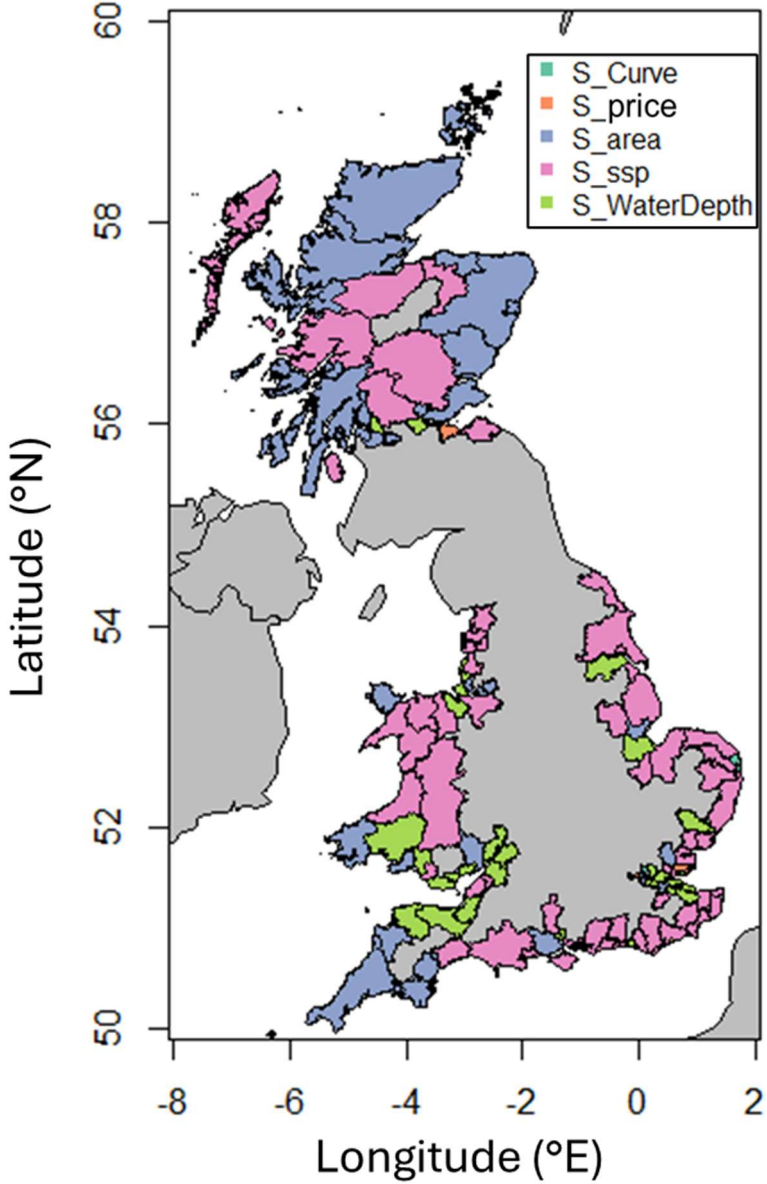


Figure E. Map across United Kingdom of the most influential uncertain factor, i.e., with the highest sensitivity index. Note that LAUs are missing in the between 54° and 56°N.



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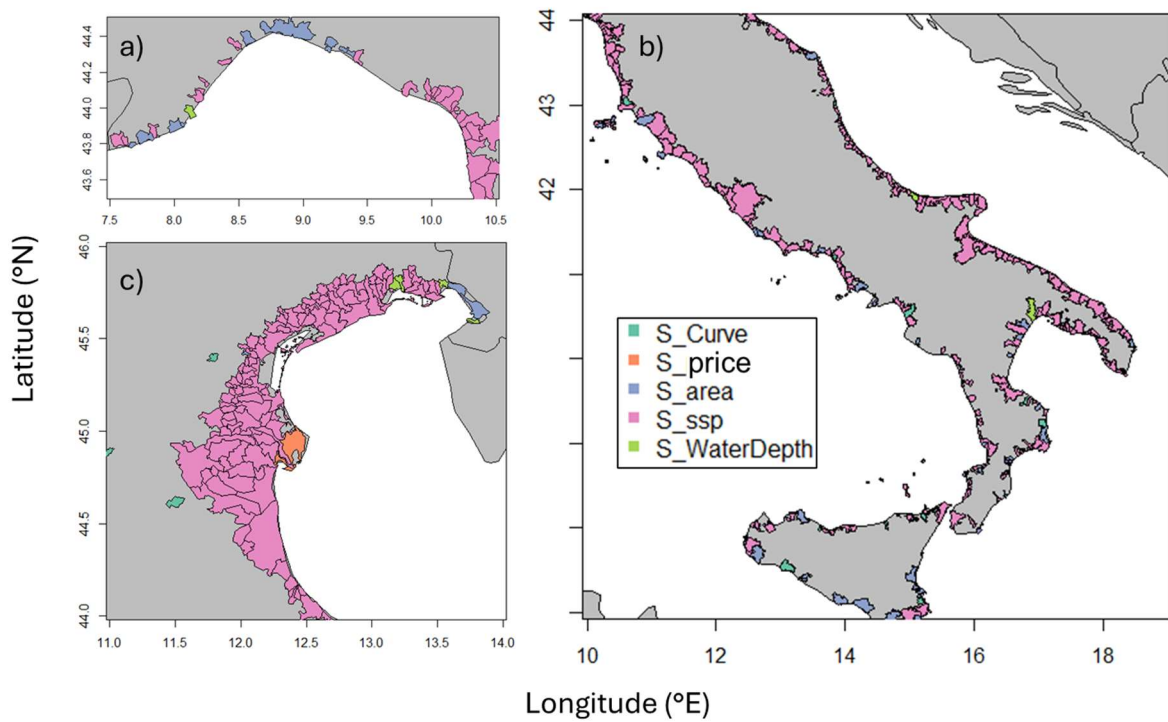


Figure F. Map across Italy of the most influential uncertain factor, i.e., with the highest sensitivity index. The map is divided into three large coastal regions: (a) the Ligurian Sea coast, (b) the coast of the boot of Italy and Sicily and (c) the North Adriatic Sea coast.



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