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Cost-benefit coastal adaptation model

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This report presents a cost-benefit coastal adaptation model designed to support decision-making on economically optimal adaptation pathways in response to rising sea levels across European coastal floodplains. Given the projected increase in sea levels and intensifying flood risks, the model provides a time-dependent, data-driven approach to assess and optimise adaptation strategies over time from an economic perspective. The model incorporates three primary adaptation options: protection, such as dikes and storm surge barriers; accommodation, including flood-proofing buildings; and retreat, which involves relocating from high-risk areas. It will be applied to 41,327 coastal flood risk management units across Europe, integrating hazard assessments, vulnerability analysis, and cost functions to determine the economically optimal adaptation actions. The methodology builds on previous deliverables and employs a multi-stage cost-benefit optimisation to account for long-term economic feasibility. Unlike traditional models that focus solely on protection, this approach dynamically sequences adaptation actions over time, ensuring that they are implemented at the economically optimal moments in time. By incorporating adaptation tipping points, the model enables policymakers and planners to develop strategies that minimize long-term costs while strengthening coastal resilience across Europe. The results will be integrated into the CoCliCo project to support user stories on adaptation and will also be analyzed in forthcoming research publications.

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Table of Contents

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1. Introduction

Coastal areas across Europe face escalating risks due to sea level rise, a consequence of accelerating climate change. Projections indicate that sea levels could rise by at least 30 cm by the latter half of this century, potentially exceeding 1 meter by 2100 under high greenhouse gas emission scenarios (Fox-Kemper et al., 2021). This poses a severe threat to approximately 50 million people living in Europe's low-lying coastal regions, where flood risks are expected to intensify (Neumann et al., 2015).

To address these challenges, substantial investments in coastal adaptation will be required in the coming decades. Although the European Flood Directive advocates for a risk-based approach to flooding, most countries have yet to fully integrate actual flood risk assessments into their coastal management and adaptation strategies. Notable exceptions include the UK and the Netherlands, which have established risk-based approaches to inform coastal management and adaptation decisions (Blazey et al., 2021). However, current decisions largely emphasize protection measures (i.e., physical measures like dikes and storm surge barriers), often neglecting accommodation (i.e., measures that reduce vulnerability, such as flood-proofing buildings) and retreat (i.e., planned relocation of people and assets away from high-risk areas) (Esteban et al., 2020; Glavovic, B.C. et al., 2022). This context underscores the need for an economic adaptation model that integrates all adaptation options.

This report provides an in-depth overview of the cost-benefit model for coastal adaptation developed within Work Package 6. The model’s primary goal is to determine economically optimal adaptation pathways for addressing sea level rise across Europe’s coastal floodplains. A key innovation of this model is its capacity to dynamically sequence and economically optimize diverse adaptation options over time, thereby identifying adaptation tipping points. To our knowledge, no global or continental scale coastal impact and adaptation assessment has considered economic adaptation tipping points by incorporating the timing of adaptation actions (Anthoff et al., 2010; Bachner et al., 2022; Brown et al., 2021; Diaz, 2016; Hinkel et al., 2014; Lincke & Hinkel, 2021; Vousdoukas et al., 2020).

Building on the methodologies presented in previous deliverables, the model incorporates investment cost estimates for adaptation measures outlined in D6.3, current adaptation practices described in D6.1, and applies its optimisation to all 41,327 coastal flood risk management units identified in D6.2. While the baseline adaptation models developed in D6.3 provide a descriptive analysis of existing practices, the normative cost-benefit model presented here contrasts this perspective by presenting economically optimal adaptation pathways to inform future adaptation decisions.

2. Cost-benefit coastal adaptation model

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The cost-benefit optimisation model consists of several core components: a hazard component for modelling extreme sea levels, an exposure component to evaluate populations and assets at risk, a vulnerability component to assess the susceptibility of assets to hazards, an adaptation state space to chart potential adaptation pathways, and cost functions to estimate the costs of adaptation measures. The multi-stage cost-benefit optimisation is conducted individually for each coastal flood risk management unit.

2.1 Adaptation options

We consider three distinct coastal adaptation options to address coastal flooding: (i) the use of hard protection infrastructure, such as dikes or storm surge barriers, (ii) the accommodation of buildings within the one-metre floodplain by implementing flood-proofing measures up to one metre, and (iii) the (planned) retreat from coastal areas.

2.1.1 Adaptation state space

Let $d_t = (d_t^p, d_t^r, d_t^a)$ represent the adaptation state space over time, where d_t^p represents the protection height, d_t^r represents the retreat height, and d_t^a represents accommodation. Protection is given in absolute protection heights above mean sea level in meters, retreat is given in absolute elevation heights in meters below which all assets and people will retreat, and accommodation is given in absolute elevation heights in meters below which all buildings will be flood-proofed. The adaptation action $u = (u^p, u^r, u^a)$ can increase each adaptation option independently of each other by

$$d_{t+1} = d_t + u = (d_t^p + u^p, d_t^r + u^r, d_t^a + u^a),\ u^r \geqq 0,$$

where the protection height and accommodation can be decreased to zero, because we assume only retreat is an irreversible adaptation option. The state space allows combinations of protection and retreat at the same time, if the protection height is higher than the retreat height. The following ATP types are considered in the adaptation state space over time: switching from protection to accommodation, retreat or protection and retreat; switching from accommodation to protection, retreat or protection and retreat; and switching from retreat to protection and retreat. By modifying the adaptation state space and its transitions, the scope of adaptation options and ATP can be readily tailored.

2.1.2 Costs of adaptation options

We use country-specific unit costs for coastal protection sourced from D6.3, adjusting these costs from EUR 2014 to USD 2024. This adjustment is made using the U.S. Bureau of Labor Statistics CPI inflation calculator and historical exchange rate data from https://www.exchange-rates.org/exchange-rate-history/eur-usd-2014. Additionally, we incorporate a fixed cost component for protection, making smaller upgrades proportionally

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more expensive than larger ones. This approach aligns with findings from previous studies (Eijgenraam et al., 2017; Völz et al., 2024):

$$I(d, u) = 0.3 * c * 1 * l + 0.7 * c * u * l,$$

where u is the height upgrade, c the unit cost factor and l the length of the protection action. Consistent with previous studies (J. Aerts, 2018; J. C. J. H. Aerts et al., 2013; Mooyaart et al., 2014), we assume that maintenance costs for coastal protection infrastructure amount to 1% of the initial investment costs, as suggested in D6.3.

In line with previous research by Lincke & Hinkel (2021) and the forthcoming work by Sayers, Penning-Rowsell, Nicholls, and Le Cozannet (2024), we estimate retreat costs at three times the local GDP per capita per migrant, assuming no maintenance costs for the retreat. It is important to note that the detailed retreat model outlined in D6.3 accounts for the costs of physical works, compensation payments, and habitat creation, which depend on factors such as the number of residential and non-residential properties being relocated. While such detailed retreat costs are appropriate for specific case studies, they are not suitable for the continental cost-benefit model developed here, as parameters like the number of properties are not included. Therefore, we rely on aggregated retreat cost estimates from similar models.

For accommodation, we use average unit costs for flood-proofing buildings, as derived in D6.3. The estimated average unit cost for flood-proofing buildings across countries is USD 5,467 (2016) per person per metre, adjusted to 2024 values using inflation rates from the Consumer Price Index (CPI) inflation calculator provided by the U.S. Bureau of Labor Statistics. Maintenance costs for accommodation are assumed to be zero, as suggested in D6.3.

2.1.3 Current protection levels

We utilise current coastal flood protection levels at the NUTS2 level, derived from a European survey (De Plaen et al., 2024) conducted with coastal experts across Europe as part of D6.1. This survey provides the only systematic empirical evidence of coastal flood protection levels at a continental scale (Hermans et al., 2023; Hinkel et al., 2021). When multiple protection levels are reported for a NUTS2 unit, we distinguish between them based on population density (people per square kilometre), classifying areas as uninhabited (<10), sparsely populated (<300), or densely populated (>300). For regions where the survey lacks data on current protection levels, we supplement with modeled estimates (Tiggeloven et al., 2020) and assume no protection where such estimates are unavailable.

2.2 Flood damages

2.2.1 Exposure and vulnerability: DIVA

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We adopt the general approach of the Dynamic Interactive Vulnerability Assessment (DIVA) framework (Hinkel et al., 2014), which has been widely used to assess flood damages at both continental and global scales (Bachner et al., 2022; Diaz, 2016; Jevrejeva et al., 2018; Kirezci et al., 2023; Lincke & Hinkel, 2018, 2021; Schinko et al., 2020). Building on this prior work, D6.2 has enhanced the analysis by expanding its scale and dividing the European coastal zone into 41,327 coastal floodplains (Lincke and Hinkel, in preparation), compared to the 1,810 floodplains in the original DIVA model. These floodplains are defined as hydrologically connected regions below the 1-in-100-year flood level, with an additional 2-meter allowance for sea level rise, and are further subdivided by NUTS2 administrative units. The floodplains are derived from the Copernicus digital elevation model (DEM) (European Space Agency & Airbus, 2022) and extreme water level data from COAST-RP (Dullaart et al., 2021).

For each coastal floodplain, we create a hypsometric profile by overlaying the Copernicus DEM (European Space Agency & Airbus, 2022) with population data from the Global Human Settlement Layer (Schiavina et al., 2023), following the methodology outlined in Freire et al., 2016. Asset exposure is calculated by multiplying local GDP per capita (Kummu et al., 2018) by a factor of 2.8 (Hallegatte et al., 2013) and the population data. To estimate future asset exposure, we apply population and GDP growth rates from the SSP scenarios (Moss et al., 2010) to the current asset exposure until 2100, and use linear interpolation for growth rates beyond 2100. In the case of retreat, we modify the hypsometric profile by removing all assets and people below a certain elevation d^r_t, resulting in $H_t^{d^r_t}$.

We calculate the flood damage $\phi_t(H_t, x, d)$ on the hypsometric profile H_t under extreme water level x and adaptation state d using a bathtub flood model and a logarithmic depth damage function $\frac{w}{w+1}$ for inundation depth w, following the approach in (Hinkel et al., 2014). These functions enable the explicit solution of the flood damage integral, eliminating the need for numerical approximation methods and thereby reducing computational resource requirements.

2.2.2 Hazards

We use regional mean sea level projections provided by the 6th Assessment Report of the IPCC (Garner et al., 2023). Notably, we replace the low-confidence vertical land motion (VLM) estimates from AR6 (Kopp et al., 2014) with improved Glacial Isostatic Adjustment (GIA) model results (Caron et al., 2018).

For hotspot regions in Europe where significant vertical land motion, aside from GIA, has been observed, remains robust, and is still being recorded (e.g., the north-east Netherlands, north-west Germany, the north Italian Adriatic coast, and the vicinity of Thessaloniki in

Greece), we assume a linear extrapolation of the VLM contribution based on the Copernicus European Ground Motion Service (EGMS) vertical velocity estimates from the Ortho product for the period 2015-2021 (Costantini et al., 2021). Specifically, we derive the spatially averaged EGMS vertical land velocity every 1 km along the shoreline of these hotspot regions. The spatial average is computed over a 10 km radius around each 1 km-spaced shoreline point to smooth out fine-scale VLM variations. In line with Thiéblemont et al., 2024 and D3.2, the VLM estimates are then adjusted to the geocentric reference frame ITRF2014 to prevent overestimating subsidence. We also subtract the GIA contribution, as it is already included in the mean sea level projections. Finally, the obtained VLM estimates are linearly extrapolated for the entire time horizon and added to the coastal sea level projections. This approach results in a near 2 mm/yr relative sea level rise enhancement in the hotspot regions, with up to 4 mm/yr locally in some coastal floodplains along the north Italian Adriatic coast.

Extreme water level distributions are derived by fitting a Generalized Extreme Value (GEV) distribution to the extreme water level return periods provided by COAST-RP (Dullaart et al., 2021). While extreme data from Work Package 4 could not be used due to time constraints and delays in data handover, a sensitivity analysis indicated that the pathways from the cost-benefit analysis are highly robust, and significant changes in model output are not expected. The COAST-RP return periods offer a high spatial resolution of 1.25 km along the European coastline. To assign each coastal floodplain its corresponding extreme water level return period, we perform a nearest-neighbour matching based on the midpoint of the coastline for each floodplain. If the shape parameter of the fitted GEV distribution is negative, we interpret this as a sign that the GEV model is unsuitable for representing the underlying return periods, and instead, we fit a Gumbel distribution. This process produces an extreme value distribution $f(x)$ with its maximum value x_{max} for each location. Extreme water level distributions are modified over time by sea level rise l_t^p and vertical land motion v_t. We implement this by shifting the location parameter μ of the extreme value distribution function $f(x)$ upwards with $\mu + l_t^p - v_t$, resulting in $f_t(x)$.

2.3 Multi-stage cost-benefit optimisation

The multi-stage cost-benefit optimisation can be applied to each coastal floodplain individually and minimise the expected costs over time by choosing the optimal adaptation pathway π, which defines which adaptation action u should be taken at the adaptation state d_t,

$$\min_{\pi \in \Pi} \mathbb{E} \sum_{t_0}^{T} \beta^t C(d_t, \pi_t(d_t)),$$

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where β is the discount rate and $C(d, u)$ is the cost function. Let $I(d, u)$ be the investment cost function and $m(d)$ the annual maintenance cost function. Using the flood damage function $\phi_t(H_t, x, d)$ we can then write our objective function as

$$\min_{\pi \in \Pi} \mathbb{E} \sum_{t_0}^{T} \beta^t \left[I\left(d_t, \pi_t(d_t)\right) + m(d_t)\Delta t + \int_{max(d_t^p, d_t^a)}^{x_{max}} \phi_t \left(H_t^{d_t^r}, x, d_t \right) f_t(x)\, dx \Delta t \right],$$

where we integrate over the flood damages multiplied by the probability distribution function of the extreme water levels $f_t(x)$ to consider the expected annual flood damages times Δt, the number of years between two time steps. The lower bound of the integral is set to $max(d_t^p, d_t^a)$, because we assume that for extreme water levels below the protection height or the accommodation height no flood damage occurs. This also means that as soon as the protection or accommodation height is exceeded by an extreme water level, flood damage is considered as if there were no adaptation action in place, i.e. a complete failure of coastal protection or accommodation.

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3. Discussion

Flood risk assessments rely on different modeling approaches, each with distinct strengths and limitations, and they serve different purposes in flood risk and adaptation planning. Here, we compare the DIVA model with the 30 m Global Flood Inundation Model developed by Wing et al., 2024. While Wing et al.'s model provides highly detailed flood hazard maps, DIVA is designed for large-scale cost-benefit analyses of coastal adaptation.

One of the fundamental differences between these models lies in their approach to flood modeling. DIVA employs a simplified bathtub flood model combined with an analytical solvable depth-damage function to estimate flood damage and adaptation costs efficiently. In contrast, Wing et al.'s model uses detailed hydrodynamic modeling, capturing coastal, pluvial, and fluvial flooding at 30 m resolution worldwide. This high-resolution approach allows for greater accuracy in flood extent and depth estimation but comes at a significantly higher computational cost.

Another major distinction is how each model accounts for vulnerability and exposure. DIVA integrates economic considerations, including adaptation costs, adaptation benefits, and asset exposure, making it a valuable tool for policymakers evaluating different adaptation strategies. Wing et al.'s model, however, focuses solely on flood hazard mapping and does not incorporate information on economic losses, population exposure, or asset damage. While its high-resolution flood maps provide a detailed understanding of flood extent under different climate scenarios, they lack the economic framework necessary for cost-benefit assessments.

Computational efficiency is another crucial factor differentiating these models. DIVA is designed to be computationally efficient, solving flood damage integrals analytically rather than relying on numerical approximation. This allows for the full integration of extreme value distributions and enables large-scale, long-term scenario modeling. In contrast, Wing et al.'s model computes flood depths for only 10 extreme events due to the immense computational resources required for its hydrodynamic simulations, which can take months to run. This limitation makes it difficult to integrate a full range of extreme flood scenarios into broader risk and adaptation assessments.

Adaptation representation also differs significantly between the two models. DIVA in combination with the multi-stage cost-benefit model dynamically models adaptation strategies over time, explicitly considering time-dependent sea level rise and incorporating different response options such as protection, accommodation, and retreat. In contrast, Wing et al.'s model includes adaptation only in post-processing and only at a single future moment, meaning it does not account for how adaptation strategies evolve over time.

While Wing et al.'s model provides more detailed flood hazard data, the use of such detailed flood hazard data within DIVA assessments is only practical under specific conditions. First, it would only make sense to integrate such high-resolution flood maps into DIVA if exposure data on people and assets is available at the same level of detail. Since DIVA relies on economic loss assessments, it requires similarly detailed vulnerability and exposure data to make full use of the flood hazard information. Second, due to the high computational costs of Wing et al.'s model, such detailed data would only be useful for DIVA if the analysis is focused on specific extreme flood events rather than full risk distributions. Alternatively, an emulator trained on the 10 extreme events modeled by Wing et al. could be used to approximate results for a broader range of scenarios without the need for running full hydrodynamic simulations.

4. Conclusion

The cost-benefit model developed for coastal adaptation provides a comprehensive framework for identifying economically optimal adaptation pathways to manage flood risk across more than 41,000 coastal flood risk management units in Europe. By addressing the impacts of sea level rise, this model enables policymakers to make informed decisions about long-term coastal resilience strategies.

A key innovation of this approach is its ability to conduct continental-scale economic optimisation, which allows for a systematic evaluation of adaptation costs and benefits across diverse coastal regions. Unlike previous models that often focused on static adaptation measures, this framework integrates adaptation tipping points, ensuring that adaptation actions are timed optimally to maximize effectiveness while minimizing costs. This dynamic approach acknowledges that different regions will reach critical risk thresholds at different times, requiring tailored responses rather than a one-size-fits-all strategy.

For the first time, this model incorporates protection, accommodation, and retreat as viable adaptation options within a unified cost-benefit analysis, offering a more flexible and realistic representation of adaptation pathways. By considering multiple adaptation strategies rather than focusing solely on hard protection measures, the model better reflects the complex trade-offs between economic, social, and environmental factors in flood risk management. This holistic perspective ensures that adaptation decisions are not only cost-effective but also sustainable in the face of uncertain future climate conditions.

This modeling framework marks a significant advancement in coastal flood risk management by offering a scalable, data-driven approach to adaptation planning. It will be applied to all European floodplains identified in D.2, with the resulting insights informing WP1 and WP2 to develop a user story on adaptation within CoCliCo. Additionally, the quantitative findings will be analyzed in forthcoming research papers (e.g., Völz et al., 2025). By integrating economic principles with dynamic adaptation strategies, this model serves as a valuable tool for policymakers, planners, and researchers striving to strengthen coastal resilience across Europe.

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