

# ARIES for SEEA

## Global runs

# Coastal Protection Services

Deliverable 3: Global results

under the KM-GBF Project between UN-DESA and BC3

Author:

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# 1. Coastal Protection Services

## Overview

Coastal protection services include ecosystem contributions to mitigating the impacts of tidal surges, sea level rise, erosion and storms on local communities and coastal infrastructure (United Nations *et al.* 2021). Coastal ecosystems, including mangroves, salt marshes, coral reefs and seagrass, provide these essential coastal protection services (Barbier *et al.* 2011). For example, mangroves have been shown to reduce wave heights by 13–66% over a 100-meter-wide forest (McIvor *et al.* 2012). This service is increasingly critical as sea level rise and extreme weather events accelerate under climate change. Protecting and restoring healthy coastal ecosystems is crucial to enhancing the resilience of coastal communities and reducing damage costs.

Near-coastal zones, all land within 100 km of the coast at elevations up to 100 m, were home to over 27% of the global population (~ 1.9 billion) in 2010 (Kummu *et al.* 2016). Over 10% (634 million) of the global population lived in low-elevation coastal zones, land with an elevation of up to 10 m in hydrological connection with the sea, in the year 2000 (Balk *et al.* 2009; MacManus *et al.* 2021; McGranahan *et al.* 2007). Protecting and enhancing coastal protection services is therefore vital to maintaining and improving the livelihoods of billions globally.

The provision of coastal protection services by natural ecosystems depends on several factors. These include the extent, structure, and health of coastal ecosystems, as well as their proximity to coastal populations and infrastructure. The protection and restoration of these ecosystems offer opportunities to advance nature-based solutions for climate change adaptation and curb biodiversity loss.

## Objective of the module

The coastal protection module assesses the role of ecosystems in risk reduction, as determined by hazard (in this case, coastal flood hazard), exposure, and vulnerability. Specifically, risk results “from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards” (Intergovernmental Panel on Climate Change [IPCC] 2022; Figure 1). In this module there have been novel efforts in linking the ecosystem services dimension and the local population risk dimension using an accounting framework (La Notte *et al.* 2025). The model quantifies the population benefiting from reduced hazard exposure by comparing hazard



levels with and without ecosystem protection, focusing on populations and areas prone to coastal flooding. The resulting outputs represent the supply of ecosystem-based hazard mitigation and the demand for such protection among human communities. This module produces spatially explicit indicators of hazard proneness, exposure, vulnerability, and avoided risk. Avoided risk is quantified as the human population benefitting due to the presence of a particular coastal protective ecosystem, in ecosystem service supply-use accounts.

## Methodology

The methodology underlying this module estimates the biogeophysical exposure-vulnerability of coastal areas to flooding from wind waves, storm waves, and surge potential (i.e., coastal hazards). The hazard component, which estimates how hazard prone areas are (hazard proneness) to coastal flooding, draws conceptually on the InVEST Coastal Vulnerability model (Natural Capital Project 2020) but has been substantially adapted to integrate new geophysical variables, ecosystem parameters, and spatially explicit datasets suited for SEEA-EA accounting. We interpret this index as representing hazard proneness, aligned with the IPCC definition<sup>1</sup>.

To assess the mitigating effect of coastal ecosystems (the potential supply of the Coastal Protection Ecosystem Service, CP-ES), hazard proneness is computed with and without the presence of mangroves, salt marshes, seagrasses, and coral reefs. The spatial distribution of the difference between these two conditions represents the potential supply of the coastal protection in hazard prone areas (i.e., the ecosystem-supplied reduction in hazard proneness of different areas). The demand for coastal protection corresponds to the number of people in areas prone to coastal flooding that require protection. The final output layer and summary statistics reveal the local population benefiting from the service. It also reveals the local populations who's demand for this service areis not currently being met.

### Hazard proneness to coastal flooding

The hazard proneness index is derived as a combination of 7 sub-indices (Table 5):

1. The geomorphology index represents the landform's proneness to erosion and assigns a score to each landform type accordingly. The geomorphology index will be estimated based on biogeophysical characteristics of the areas. Geomorphology represents the physical characteristics of the coastline that influence its sensitivity to wave action, erosion, and flooding. Geomorphology was derived from the CCI

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<sup>1</sup> According to the IPCC, "hazard refers to the possible future occurrence of natural or human-induced physical events that may have adverse effects on vulnerable and exposed elements"

CORINE Land Cover dataset, which provides detailed classifications of coastal landforms, including beaches, rocky shores, dunes, wetlands, and artificial structures. These classes were translated into geomorphology exposure ranks where more erodible features (e.g., sandy beaches, wetlands) receive higher vulnerability scores, and resistant features (e.g., rocky cliffs, armored coasts) receive lower scores.

2. The relief index represents the land's proneness to flooding due to variations in terrain elevation. Higher elevations are at lower risk of inundation than lower elevations (Natural Capital Project 2020). The relief index was estimated using the global 30 m Digital Elevation Model (DEM) derived from ASTER and SRTM data, which provides high-resolution elevation information suitable for global terrain and relief analyses (NASA/METI/AIST/Japan Space Systems, and U.S./Japan ASTER Science Team, 2019).
3. The natural habitats index represents the relative level of protection provided by different coastal ecosystems (Mangrove, seagrass, salt marsh and corals) (see Table 6 for a detailed description of the datasets, crosswalk between the datasets and IUCN GET Typology, as well as potential future applications).
4. The wave exposure index is a semi-quantitative indicator of potential for shoreline erosion (Natural Capital Project 2020). It is calculated using ECMWF-ERA5 data by integrating significant wave height and wave direction to quantify the intensity and directionality of wave impact on a given region.
5. Wind exposure represents the relative susceptibility of coastal segments to powerful waves generated by strong winds (CMEM, 10 km resolution).
6. The surge potential index represents the relative exposure to storm surges (ECMWF-ERA5).
7. Sea-level rise input to the model was obtained from ECMWF ERA5 reanalysis data, which provides high-resolution global estimates of ocean surface height and long-term sea-level trends.

According to the rules in Table 5, a sub-index is found for each variable, and the final hazard index (*H*) is obtained by a geometric mean of the seven sub-indices, ranging from 1 to 5.

*Table 5. Modelled hazard sub-indices inspired by Natural Capital Project (2020).*

Rank	1 (very low)	2 (low)	3 (moderate)	4 (high)	5 (very high)
Geomorphology	Rocky; high cliffs; fjord; fiard; seawalls	Medium cliff; indented coast; bulkheads and small	Low cliff; glacial drift; alluvial plain; revetments; rip-rap walls	Cobble beach; estuary; lagoon; bluff	Barrier beach; sand beach; mud flat; delta



		seawalls			
Relief	>20 meter	15 to 20 meter	10 to 15 meter	5 to 10 meter	0 to 5 meter
Natural Habitats	Coral reef; mangrove; coastal forest	High dune; marsh	Low dune	Seagrass; kelp	No habitat
Wind Exposure	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Wave Exposure	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Surge Potential	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile

By denoting the set of studied coastal ecosystems as  $E$  ( $E = \{\text{mangroves, saltmarshes, seagrasses, corals}\}$ ), then  $\forall e \in E$ :

$$\Delta H_e = H_{\text{without } E} - H_{\text{with } e} \quad (1)$$

where  $H_{\text{without } E}$  represents the hazard proneness index in the absence of all protective ecosystems, and  $H_{\text{with } e}$  the hazard proneness index when only one ecosystem, ecosystem  $e$ , is included. To isolate the protective effect of each individual ecosystem type, the model is run under the assumption that when evaluating a given ET, all other ecosystem types present along the same coastal segment are replaced by a neutral baseline surface such as the waterbody in this module. This ensures that the estimated reduction in hazard reflects only the contribution of the focal ET rather than the combined influence of multiple co-occurring habitats.

A positive  $\Delta H_e$  indicates a reduction in hazard proneness attributable to ecosystem  $e$ . To isolate the contribution of individual ecosystems, the model is run iteratively. In each iteration, the hazard is modeled by comparing the baseline (no ecosystems) against a scenario where a single ecosystem layer is present (Equation 1). It serves as an indicator of the potential spatial supply of the coastal protection service by ecosystems and is

calculated as the mean of the spatial hazard reduction across each area of influence of each ecosystem.

### Exposure and Vulnerability to Coastal Flooding

Exposure is defined as the presence of people, infrastructure, and economic activity in areas that may be affected by coastal hazards. In the supply–use ecosystem modelling framework, we quantify who/what needs protection and who/what benefits from the presence of the ecosystem. Vulnerability<sup>2</sup> assesses the sensitivity or susceptibility of exposed elements to harm and their lack of capacity to cope with or recover from hazard impacts.

In this model, exposure and vulnerability are combined to create a layer that represents the population living in flood–prone areas most likely to be affected by coastal flooding. Population data (which represents exposure, or the potential users of the coastal protection service) is overlapped with two vulnerability layers: a deprivation index, which serves as a stratifier of the results, and a layer defining low–elevation coastal zones. The resulting layer serves as a foundation for assessing both the demand for and the supply of coastal protection services. The vulnerability aspect acts as a stratifier for exposure, to identify the least, moderately, and highly vulnerable populations.

$$EV = f(Pop, LECZ, GRDI) \quad (2)$$

Where *EV* is the Exposure–vulnerability layer, *Pop* refers to the population, Low–Elevation Coastal Zone (*LECZ*) delimits the low elevation coastal zones, and Global Relative Deprivation Index (*GRDI*) integrates the different levels of deprivation (i.e., vulnerability) of the population. The WorldPop population grid provides a spatially explicit representation of population density. At the same time, the *LECZ* dataset specifies which portion of that population lives within physically flood prone places (exposure). When these are combined with the *GRDI*, the result is a stratified population layer that includes both the number of exposed individuals and the degree to which their socioeconomic circumstances heighten their exposure to flooding (exposure and vulnerability). The stratification of the *GRDI* covers three classes: “High vulnerability” (for values  $\geq 67$ ), “Medium vulnerability” (for values between 34 and 66) and “Low vulnerability” (for values below 33). Accordingly, *EV* is an area–based, deprivation–stratified population estimate in low–lying coastal regions, and is a combined single layer of physical exposure and social vulnerability for subsequent estimation of both demand for and supply of coastal protection ecosystem services.

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<sup>2</sup> “Vulnerability refers to the propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events (UNDRO, 1980; Cardona, 1986, 1990)”.



## Ecosystem Service Demand

The demand for coastal protection (*CP-ES demand*) comes from the number of people living in areas prone to coastal flooding (*EV*) that might be affected by the hazard (*H*). In this case, it corresponds to the population in areas at risk of the hazard.

The baseline population at risk is identified by spatially intersecting the population layer with the hazard extent modeled in the absence of ecosystems (i.e.,  $H_{without E}$ ), to identify the potential beneficiaries of the protection. At the same time, the exposure–vulnerability (*EV*) component is stratified by vulnerability classes, to differentiate among the levels at which levels of social deprivation influence the levels of impact. This stratification enables a more accurate identification of population groups (low, moderate, or highly vulnerable) and estimates which group is likely to benefit most from the presence of coastal ecosystems.

Demand (*D*) is therefore a function of population, vulnerability and hazard:

$$D = f(EV, H_{without E}) \quad (3)$$

*Table 7 illustrates the details of the datasets included as inputs for developing the demand and supply tables*

Dataset	Description	Source	Purpose	Temporal coverage	Spatial resolution
Population count	Gridded population counts and densities based on census + remote sensing	WorldPop	Counting population	Annual (2000 – 2020)	100 m (~0.0009°)
				Annual (2025 – 2100)	100 m* (~0.0009°)
Global Gridded Relative Deprivation Index (GRDiv1)	Relative level of multidimensional(6 dimensions) deprivation and poverty in each pixel	NASA Socioeconomic Data and Applications Center (SEDAC)	Stratifying the results by vulnerability level	Static baseline (2010–2020)	30 arc-seconds (~1 km)

	represented as an index from 0 to 100 where a value of 100 indicates the highest level of deprivation and zero the lowest				
Low Elevation Coastal Zone (LECZv3)	Urban, quasi-urban, and rural populations in <10m elevation coastal zones for 234 countries and territories	NASA Socioeconomic Data and Applications Center (SEDAC)	Define the hazardous area	1990, 2000, 2015	9 arc-seconds (~300m)
GLC_FCS30D Global 30-meter Land Cover Change Dataset (1985-2022)	Global land cover layer classified into 35 land cover classes.	Zhang <i>et al.</i> (2024)	Delineate presence of Mangroves, Salt marshes and Waterbodies	Annual (1985-2022). Further updates TBC	30m
Allen Coral Atlas	High-resolution Global coral reef habitat maps (benthic and geomorphic classes)	High-resolution Global coral reef habitat maps (benthic and geomorphic classes)	Delineate presence of Seagrasses and Corals	Annual (2018 - 2020)	5 m

\*new worldpop layer to be integrated for upgrading the model

### Ecosystem Service Users, Potential Supply and Use

The Coastal Protection Ecosystem Service (CP-ES) model generates complementary indicators to quantify both the potential supply of the service and the actual users



benefiting from it. A dual-indicator approach is necessary because a single metric cannot fully capture the nuances of risk mitigation. Specifically, an indicator focused solely on the number of users communicates the spatial extent of the beneficiaries but fails to convey the level of protection each individual receives. Conversely, an indicator detailing the magnitude of hazard reduction illustrates the biophysical effectiveness of the ecosystem but lacks demographic context regarding who is actually benefiting.

To resolve this and provide a comprehensive understanding of whether exposed and vulnerable areas are benefiting from nature-based protection, the model computes three distinct, spatially explicit metrics that are designed to be evaluated in combination:

- **Ecosystem Service Users, or Beneficiary Count (BC)**

The Ecosystem Service Users represent the specific subset of the exposed population (Demand,  $D$ ) that actively experiences a reduction in physical hazard due to an ecosystem's presence. This is measured as a discrete count of the number of people in hazardous areas who benefit from the protective habitat. The Beneficiary Count ( $BC$ ) is calculated by spatially intersecting the population that is potentially exposed and vulnerable to coastal flooding (the  $EV$  layer) with areas where the ecosystem actively reduces hazard proneness (i.e., where  $\Delta H > 0$ ).

- **Protection Magnitude or Hazard Reduction**

This metric serves as an indicator of the physical biophysical benefit provided by the ecosystem. It is calculated as the mean spatial reduction in the hazard index ( $\Delta H_e$ ) across the ecosystem's area of influence.

- **Population-weighted impact**

Is a metric that definitively links the biophysical supply of the service with its human use, and represents the total magnitude of protection delivered to society. This is achieved by aggregating the individual hazard reductions across all ecosystem service users. For each grid cell, the actual service flow is calculated as the product of the hazard reduction and the population density:

$$S_e = \Delta H_e \cdot BC \quad (4)$$

To ensure these metrics capture the social dimension of risk, this calculation is further stratified by vulnerability classes (derived from the GDRI).

## Notes on global runs

To translate pixel-level spatial data into national accounting tables, the global results are aggregated at the country level. The aggregation process stratifies the spatial data into a 16-category matrix based on two intersecting dimensions: human vulnerability and ecosystem type.

### 1. Vulnerability Stratification

Exposed populations are categorized into four distinct vulnerability classes using the Global Disaster Risk Index (GRDI):

- Low: GRDI < 33
- Medium: GRDI 33 to 65
- High: GRDI > 66
- Unknown: Areas lacking GRDI data coverage (to ensure no beneficiaries are dropped).

### 2. Ecosystem Classification & Overlap Rules

Coastal protection is attributed to four specific habitats derived from Coral Systems and Global Wetlands datasets. Because these biophysical layers occasionally overlap, a strict spatial hierarchy is applied to prevent double-counting beneficiaries. Pixels are assigned a single, mutually exclusive ecosystem type, prioritising the more fine Coral Systems dataset.

### 3. Final Accounting Outputs

For each country, the intersection of the 4 vulnerability levels and 4 ecosystem types yields 16 distinct reporting categories per year. Within each category, the model aggregates four primary indicators to populate the accounting tables:

- Demand: Total number of people in baseline hazardous areas (Sum).
- Beneficiary Count (BC): Total number of people physically protected by the ecosystem (Sum).
- Hazard Reduction ( $\Delta H_e$ ): The biophysical magnitude of hazard mitigation (Mean).
- Population-weighted impact: as mentioned above, combines beneficiary count and hazard reduction. (Mean)

This structured aggregation ensures that the final accounting tables provide a precise, non-duplicated breakdown of who benefits from specific coastal ecosystems, and to what



extent.

These results are aggregated (sum or mean) by country.

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