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A4.3: Risk assessment protocol applicable to estuarine areas considering sea-level rise and potential habitat under different Climate Change scenarios

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1 INTRODUCTION

According to its 5th Report (IPCC, AR5, 2014), the combined effects of changes in hazard associated with extreme events, climate variability and long-term changes, the increase in exposed assets and activities, and the increased vulnerability of human settlements and coastal ecosystems are the main causes of the growth in risk levels.

Furthermore, the need to address decision-making requires more reliable and robust methodologies and analytical tools than ever before to help ensure efficient and equitable use of resources. To establish effective options and measures, it is essential to understand the risks at the scale at which they are managed, and the uncertainty associated with them. The consideration of uncertainty in the framework of analysis therefore plays an essential role, as it allows policy and decision makers to consider the full range of possibilities that could occur in the future.

Considering all of the above, it is necessary to have a risk analysis methodology that allows us to study in the necessary detail the different components that influence the determination of the level of risk: impacts derived from hazards, exposure and vulnerability.

This report presents a methodology proposal to achieve this goal. This methodology has been applied in this research project to the assessment of climate change risks on estuaries of Mondego (Portugal), Oyambre (Spain), Westerschelde (The Netherlands), the Bay of Santander (Spain) and the Santoña Marhs (Spain), considering the impacts of coastal flooding on the socio-economic system (see report "*A 4.2: Economic costs derived from flooding in the estuarine areas of study under different scenarios of Climate Change*").

2 RISK FRAMEWORK

For the development of the risk analysis, this study proposes to follow the general risk framework developed by the Intergovernmental Panel on Climate Change (IPCC) (Figure 1).

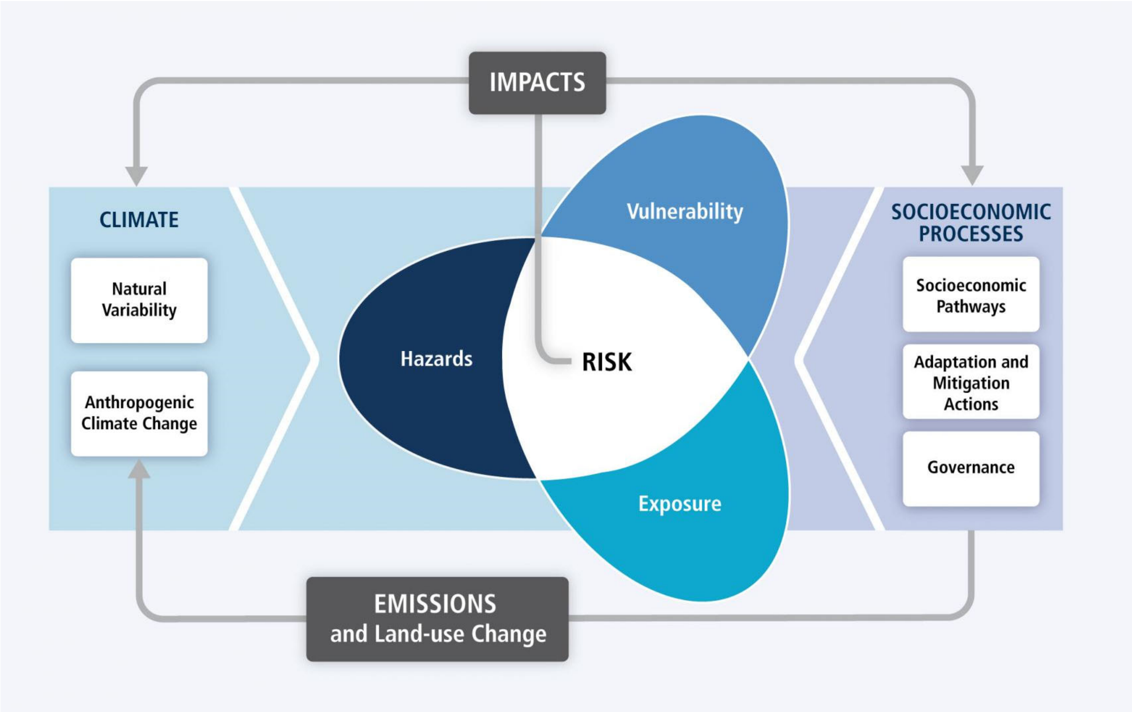

Figure 1. General risk framework proposed by IPCC (IPCC, AR5, 2014)

This framework establishes that the risk of climate-related impacts derives from the interaction of hazard, represented by the meteo-oceanographic and hydro-meteorological dynamics that generate impacts (e.g. flooding, beach erosion or changes in species distribution), exposure, defined by the sectors and sub-sectors of the socio-economic and natural systems that may be affected by the impacts, and vulnerability, related to the susceptibility of exposed elements to damage. Thus, if any of these factors change, so does the risk.

The analysis of the impacts is carried out using process models using historical data and climate change projections of mean sea level, meteorological tide, astronomical tide, waves and sea surface temperature as forcings.

The hazard level of each impact is given by the combination of some of these variables and can be expressed in terms of intensity, e.g., associated with a flood elevation, and probability, corresponding to return periods. Climate change projections, both of climate variables and of the impacts they produce, are always associated with scenarios of greenhouse gas emissions and aerosol concentrations (RCPs), climate models and climate periods (historical period and medium and long-term future periods).

The result of the impact analysis is then combined with exposure data and vulnerability functions. The former is commonly characterised through geospatial databases of present population and buildings. Regarding the characterisation of vulnerability, damage functions are usually defined for the different elements of the socio-economic system.

The consequences integrate the previous components of risk and can be expressed with various indicators to obtain the level of risk for each unit under analysis.

2.1 Temporal horizons

When preparing this risk analysis, it is necessary to establish the period of time for which it is to be valid and, on the other hand, the time horizons for which the risk is to be analysed.

The period of validity of risk analysis varies between 5 or 6 years, highlighting the importance of repeating the analysis carried out with this frequency, so that changes in the projections can be implemented, as well as improvements that appear in terms of methodology and availability and quality of the data. It is important to note that this is the period recommended by most international bodies and especially by the European Commission.

In determining the time horizons of analysis, however, the vision must be broader and is more complex. In this case, it is necessary to consider that coastal ecosystems and many of the infrastructures built along the coast have a long life span as shown by the fact that many of them have been built several decades ago. Moreover, there is nothing to indicate that some ecosystems, thanks to their levels of protection, and many infrastructures and facilities will not extend their lives into the 21st century, so it will be necessary to analyse: 1) the time scales in which the effects of climate change may lead to unacceptable risk thresholds for these natural and socio-economic systems, 2) the time period for adaptation measures to be effective, which is strongly conditioned by the adaptive capacity of the system.

On the other hand, there are other important factors that condition the analysis of the time horizons to be considered. The first of these is the availability of climate information.

Generally, climate projections are defined for climatic periods of 30 years, which means that their availability is limited to that considered by the international centres that produce climate projections. The second factor is associated with the uncertainty surrounding the analysis. Obviously, as we move further out in the time horizon, the level of uncertainty increases.

Considering that ecosystems and fundamental infrastructures present on the coast will foreseeably have a useful life that will extend throughout this century, that all projections indicate a sharp acceleration in the rise in mean sea level from the middle of the century and especially at the end of the century, and that the available projections of climate variables relevant for risk analysis are for the future periods (2026-2045) and (2081-2100), commonly two risk assessment time horizons are suggested:

- Medium term: 2050 as representative of the projection of climate variables for the period 2026-2045.
- Long term: 2100 as representative of the projection of climate variables for the period 2081-2100.

It is important to determine the reference or base period, which is the period to which changes in future risk are referenced. For consistency with the most available climate databases, the reference period is set at 1985-2005.

Note that, for consistency with the climate analysis, the time horizons correspond to 30-year climate periods, so changes in risk will be representative of these time horizons.

2.2 Working scenarios

In the face of uncertainty and the lack of ability to assign probabilities to changes that may occur in the future, scenarios allow for the exploration of possible futures. It is therefore advisable to work with more than one scenario, thus broadening the spectrum of possible futures for better risk assessment.

When establishing the scenarios, it is necessary to distinguish between emission scenarios, which will give rise to climate scenarios, and scenarios relating to the exposure and vulnerability of the estuaries.

Through the Paris Agreement, countries agreed to take action to keep the global average temperature increase well below 2ºC and to continue efforts to limit warming to 1.5ºC. These temperature targets can be translated into other types of quantities such as: balance of cumulative future greenhouse gas (GHG) emissions and stabilisation levels of atmospheric concentrations of GHGs or, equivalently, the anthropogenic radiative forcing of the climate system.

To classify the different warming boundaries, the concept of representative concentration pathways (RCPs) has been introduced, representing projections of GHG emissions and concentrations and their combined radiative forcing.

Originally comprising four projections, ranging from RCP2.6 to RCP8.5, they were augmented after the adoption of the Paris Agreement with RCP1.9 to represent mitigation pathways compatible with the 1.5ºC warming limit. The values refer to radiative forcing in W/m^2 at the end of the century compared to pre-industrial times, e.g., 2.6 W/m^2 in the case of RCP2.6, where W stands for Watts and m for metres.

As an example, doubling the atmospheric concentration of CO2 from pre-industrial times, e.g., from about 280 parts per million (ppm) of air molecules to 560 ppm, would be equivalent to a radiative forcing of 3.7 W/m^2.

A simplified relationship between existing RCPs, radiative forcing (W/m2), temperature increase (ºC) compared to pre-industrial times and emission trends (associated with mitigation policies) is shown in Table 1.

RCP	Radiative forcing (W/m^2)	Temperature increase	Emissions policies
1.9	1,9	~ 1,5°C	Powerful emissions reduction

RCP	Radiative forcing (W/m²)	Temperature increase	Emissions policies
2.6	2,6	~ 2,0ºC	Strong emissions reduction
4.5	4,5	~ 2,4ºC	Slow emissions reduction
6.0	6,0	~ 2,8ºC	Emissions stabilization
8.5	8,5	~ 4,3ºC	Emissions increase

Table 1. Relationship between RCPs, global mean temperature increase and emissions policies.

The relevant RCPs for the Paris Agreement are RCP2.6 which would lead to a warming of less than 2ºC and RCP1.9 which would lead to a warming of 1.5ºC or less.

However, in terms of risk management, considering the political and socio-economic situation and the great inertia of some of the climate forcings such as the rise in mean sea level, it is more common to apply two conservative emissions scenarios in terms of risk by selecting the following: RCP4.5 and RCP8.5. Thus, the first one corresponds to a policy scenario with a slow reduction of emissions and the second one to a continuous increase of emissions. The latter is an undesirable but possible scenario.

For RCP4.5 and RCP8.5, emissions scenarios are generated that feed into general circulation climate models (GCMs) or regional climate models (RCMs) that allow different simulations of future atmospheric climate to be obtained. This information is then regionalised to generate the high spatial resolution climate data needed to feed models of marine dynamics and, ultimately, coastal impacts.

Among the marine dynamics, it is the future projection of mean sea level rise that presents the greatest uncertainties, especially due to the possible response of large ice masses in the Arctic, Antarctic and Greenland to global warming. It is therefore standard practice to construct scenarios of mean sea level rise to help better inform risk management. Therefore, in addition to considering different percentiles of the mean sea level projections indicated by the IPCC (5%, 50% and 95%), it is a good and common practice to consider a scenario from the high end of the distribution known as H++, intended to show very low probability and very high impact, but possible, scenarios.

In terms of climate scenarios, it is also important to note that for risk management purposes it is not only necessary to deal with long-term changes that show slower variations, but also with changes in extreme events or their combined action, as they may require reactive interventions.

Therefore, several climate scenarios can be constructed in which, on the one hand, long-term changes induced, for example, by mean sea level rise (permanent inundation or structural erosion of the coastline) and also those produced by extreme events have to be analysed. In the latter case, extreme events have to be characterised using the commonly used concept of return period.

Finally, and contextualising the definition of risk, the analysis should also require the use of future scenarios of the other two components of risk, e.g., exposure and vulnerability. In general, the emission scenarios generated by the IPCC are associated with global socio-economic scenarios.

3 METHODS

This section describes in detail how to work with the different risk components: hazard and the related impacts, exposure and vulnerability. A final subsection on obtaining risk indicators completes the necessary stages to develop a risk analysis.

3.1 Hazard and Impact

The term impact refers to the effects on natural and human systems (IPPC, AR5, 2014). Impact is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change.

In this project, the main impact considered is coastal flooding and its effects on population and built capital around estuaries. Figure 2 shows a schematic representation of the methodology used to carry out the analysis of the flooding areas in the analysed estuaries.

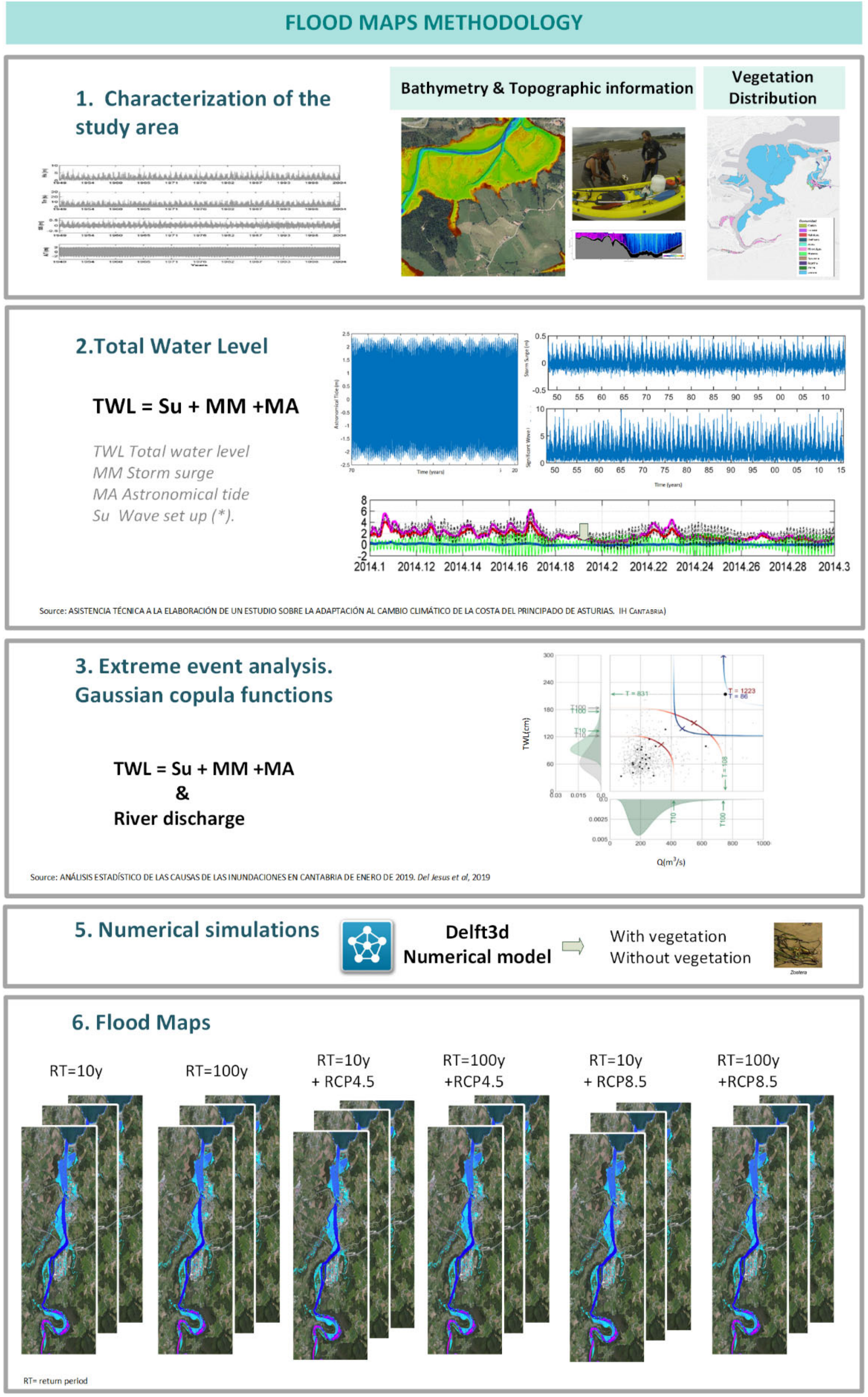

Figure 2. Methodological scheme for the calculation of flooding area

For the analysis of flood maps (considering the role of estuarine vegetation), the following methodological steps must be carried out:

1. **Gathering of information and analysis of main dynamics.** The gathering of information is an essential step in order to obtain flood maps that provide robust and reliable information. Therefore, in order to be able to approach this type of study, at least the following information is required.

   Bathymetric information. A compilation of bathymetric information of the study area will be collected. If different bathymetric maps are available, the one with the highest spatial resolution will be used. The vertical reference levels (which are crucial to obtain robust results) at which bathymetric measurements are made must be known.
   Digital Terrain Model. A compilation of topographic information of the study area will be collected, using the information available from the source with the highest spatial resolution. When assembling the bathymetric information with the topographic information, all the information must be homogenized to the same reference level, making the necessary corrections.
   Information of Estuarine Vegetation. A proper assessment of the role played by coastal vegetation in coastal protection involves representing the behavior of the vegetation in the development of the flow. A physical description of the different plant species to be considered is necessary. This includes the spatial distribution of the different species, their physical characteristics (height and diameter) and the drag coefficients of each species typology (obtained from bibliographic information).

   Analysis of dynamics. It is necessary to identify the dynamics that cause flooding in the study areas. Once identified, a statistical analysis of each one of the dynamics must be carried out in order to know the role played by each one of them and to be able to characterize their average behavior. This analysis will dilucidated whether the most important dynamics are marine or continental.

The analysis of the dynamics will be accompanied by a study of climate change projections in order to capture the long-term behavior.

2. **Computation of the Flooding indicator: Total Water Level (TWL).** Although the total water level is not a marine dynamic *per se*, it is an indicator of coastal inundation that combines the three most important marine dynamics (astronomical tide, storm surge and waves). Its quantification is important for the assessment of the role of coastal dynamics in the total inundation of estuarine environments.

3. **Extreme event analysis of dynamics.** As mentioned above, inundation events are linked to extreme events. For this reason, an extreme event analysis of the dynamics that produce flooding in the study area should be carried out.

   Univariate analysis. If the flood events have only a coastal origin (aggregated in the TWL), it will be considered a univariate flood. Those events are induced mainly by one mechanism that can be easily analyzed by means of an extreme value analysis using the Generalized Extreme Value (GEV) distribution.

   Multivariate analysis. If the flood events are the result of the combination of coastal (TWL) and continental dynamics (river discharge), a multivariate analysis using Gaussian copulas should be performed.
   From this analysis the different extreme scenarios to be simulated with the numerical model are obtained.
4. **Numerical model.** Process-based models for flooding analysis rely on the description of the underlying physical processes that derive from the dynamics of the estuaries. At the estuarine scale, finite differences or finite elements, grid-based models such as Delft3D, Telemac and MIKE21 can be applied. These models are based on considerable simplifications that allow for fast computations but limit the range of problems they can solve. Generally, hydromorphodynamic models involve a combination of different interconnected models that are called from a control module. This control module successively calls hydrodynamic, sediment transport and bed level update modules, linked through a feedback loop (Lesser et al., 2004). The hydrodynamics are solved using the unsteady shallow water equations for currents and the spectral wave action balance equation for waves (Booij et al., 1999). Biogeomorphic models add a fourth -biology- module to this scheme. Various types of biology modules exist: rule-based cellular automata, physics-based habitat models and individuals-based models (Hidralab+, 2016). In this study, the Delft3D model will be used to combine the behavior of the hydrodynamic and the wave module, incorporating the spatial interaction of vegetation species.

5. **Flood maps.** The results obtained from the numerical model will serve to perform the analysis of flood maps considering different climatic scenarios. The comparison of the maps considering a vegetated or unvegetated estuary will allows to quantify the protective role provided by these vegetated ecosystems.

3.2 Exposure

Exposure is defined as the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC, AR5, 2014). The objective of this step is then to characterise the spatial distribution of people and man-made assets (built capital) likely to be affected by the coastal flooding considered in the estuaries under analysis.

The effects on the above exposure categories have effects that can be considered in two different ways. On the one hand, the actual effect on the asset (people or buildings) can be quantified as direct damage. On the other hand, there are indirect effects related to the displacement of the population and the cessation of economic activities that have effects on the general behaviour of the economy, which can be deferred in time and have indirect effects affecting other sectors not directly involved.

These magnitudes are analysed in two very different ways. In the first case, we should have to analyse an exposure that is spatially dispersed in a variable way. In the second, however, the elements of the exposure must be analysed as a network, a model of nodes and links, whose impact causes a chain effect whose consequences move through the elements of the network. Damage in a basin causes local industrial damage in the basin, but also possible sectoral damage in the country due to industrial shortages, with local damage being negligible.

Indirect damages have not been considered in this methodology. The objective of the methodology has been to determine the numerical quantification and spatial distribution of existing assets susceptible to direct damage from the flooding impacts considered in this project.

To characterise the exposure (population and built capital), the following methodological steps must be carried out:

1. **Definition of the analysis unit.** The evaluation of the consequences will be carried out at a defined spatial scale. This first step must determine the resolution and shape of this grid which should cover all the area under analysis. As a working reference, in this project, a hexagonal grid with polygons of about 15.000 square meters was created in each estuary under analysis.
2. **Gathering exposure information.** A critical point in exposure characterization processes is to find and gather all available information. The best, most updated and more detailed information is recommended to be used. For population this normally includes working with census, usually at city or district level. For other assets (built capital, economic

activity) it is rare to have the information at the same level, so regional disaggregation can be used.

3. **Homogenisation and downscaling.** When analysing different hotspots, is usual to have different sources of data, with different variables and spatial resolution. It is therefore necessary to carry out a process of homogenisation of variables and scale adjustments so that similar information is available at all study points to enable the results obtained to be compared. This work will be carried out at this stage, using the polygons developed in step 1 as spatial aggregation elements.

Once these three steps are carried out, the study of exposure is complete, and the quantification of the exposed assets (namely population and built capital) should be available at each analysis unit.

3.3 Vulnerability

The objective of this phase of the methodology is the characterisation of the sensitivity or fragility of system components and flows exposed to hazards, and their adaptive capacity or resilience. In this methodology, vulnerability is characterised by introducing individual functions that act as attributes of the exposed elements.

Vulnerability assessment consists of identifying the magnitude of expected change through an indicator that, when applied to exposure, determines the expected damage due to the impact of a given hazard intensity. The population and assets identified above have been subjected to a "simulated experiment" in which their expected response to the physical conditions created by the events has served as a prediction of the expected damage.

To this end, a set of damage and loss prediction functions have to be generated to predict the average damage for different hazards. These functions, called vulnerability curves or damage curves, are specific to each case, both for exposed elements and for hazards. Vulnerability curves quantify the level of damage suffered by the exposed asset for a certain level of hazard, and are also capable of assessing the losses caused by the disruption of economic flows.

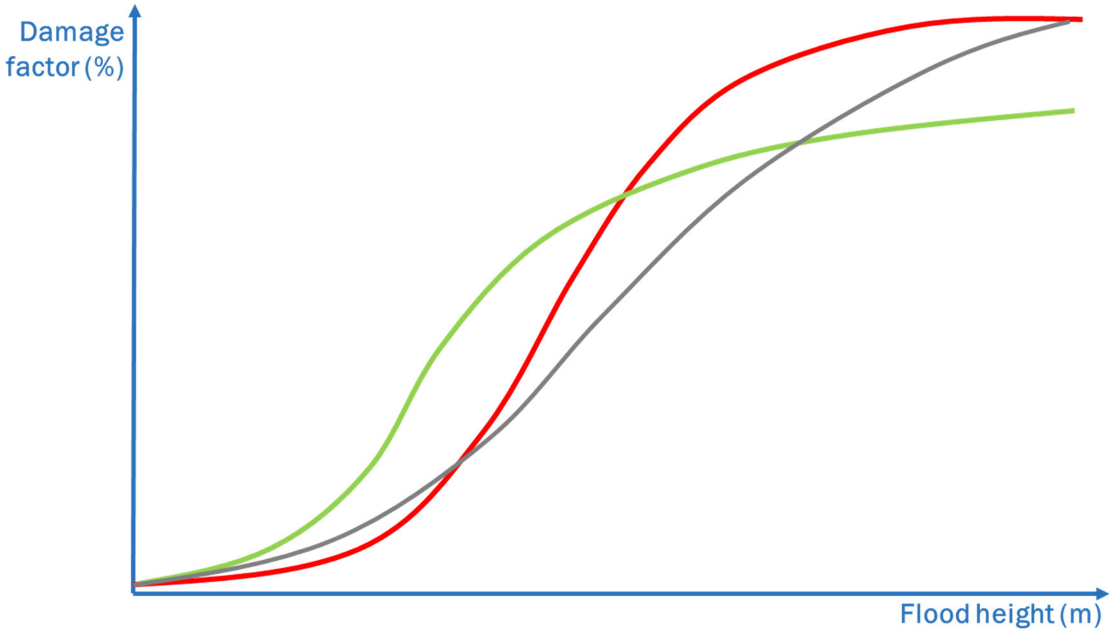

Figure 3. Example of a vulnerability function

The process of constructing vulnerability curves for population and built capital is described below.

1. **Population.** When it comes to people, it is not reasonable to express the impact of the hazard as a gradual damage; the damage is no different when a person is affected by a flood of 0.5 m depth than when they are affected by a flood of over 1 m depth. Therefore, the vulnerability curve of the population generally does not have an increasing shape as a function of the hazard, but instead uses "threshold" type curves, in which a point is simply determined at which the population is considered to be "affected" by the hazard. The objective at this point in the methodology is to determine the threshold at which the population is considered to be affected.
   In this case we obtain a damage function that only counts the people affected. It is important to note that this method does not determine the damage to people, but simply counts the number of people who, at a certain intensity of the hazard (in this case coastal flooding), are affected in their daily lives and have to leave the place where they are.
2. **Built capital**. In the case of the physical built stock, two options can be followed. First, to develop ad hoc vulnerability curves to characterise the impact on the buildings. Second, follow existing databases such us Huizinga et al. (2017), developed by the JRC (Joint Research Centre). This database is a global database that includes flood damage functions for 214 countries and six damage categories (residential buildings, commerce, industry, transport, infrastructure and agriculture).

This phase of the methodology has sought to generate damage-loss functions that present the consequences of different hazard levels (height or depth of flooding), to allow the estimation of local damage. The analysis has to focus on quantifying the damage suffered by the different hazard levels (height or depth of flooding), and has to be expressed as loss functions. Vulnerability curves derives from these relationships, and quantify the level of damage suffered by the exposed asset for a given level of impact.

3.4 Risk

The objective of this step of the methodology is to define the spatial and temporal distribution of risk, the magnitude of which is determined by the distribution of the probability of damage existing in the different exposure categories.

As defined at the beginning of the document, risk results from the interaction of vulnerability, exposure and hazard, and is associated with a certain probability of occurrence (return period, Rp). Thus, once the flood maps were obtained, they were crossed with the exposure data. The values of the flood height reached in each of the pixels of the flood map are grouped in the exposure analysis units, and then introduced into the corresponding vulnerability curves, obtaining a damage factor, which, combined again with the exposure, finally gives the expected result of the consequences of the impact.

By crossing the flooding layers with the exposure layers and applying the vulnerability function, a set of spatial maps of flood risk is obtained, as well as a set of numerical indicators on the population and the built capital for the climate scenarios of flooding considered.

It is usual to represent the above information in a graph like the one shown in Figure 4, in which, for a given asset, time horizon and scenario, the damages for each return period are obtained. As can be seen in this case, events with longer return periods are more improbable, but produce greater damage. From this graph, synthetic indicators can be obtained that allow a more synthetic comparison of risk. One of the most widely used indicators is the Annual Expected Damage (AED), which expresses the damage observed for different return periods on an annualised basis, and which is calculated by integrating the area under the curve.

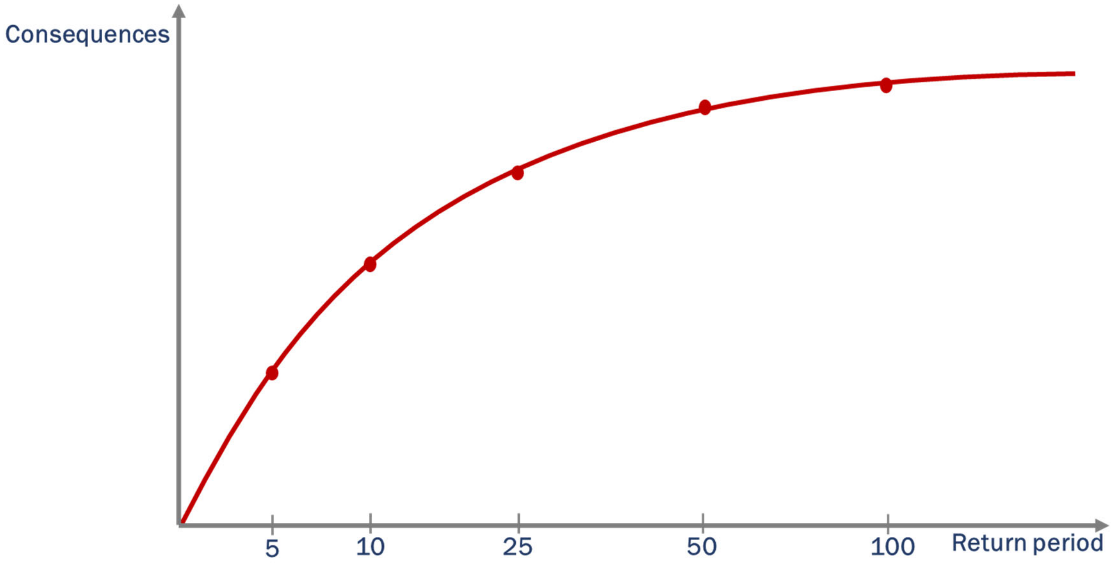

Figure 4. Theoretical representation of the consequences produced by events of different return periods on a given asset for a given time horizon and scenario

4 REFERENCES

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.