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METHODS FOR ASSESSING CURRENT AND FUTURE COASTAL VULNERABILITY TO SEA LEVEL RISE. A REVIEW FOR A CASE-STUDY IN EUROPE.

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Abstract

Sea level rise is on of the main hazards caused by climate change. Although there is a strong scientific consesous regarding the occurrence of ths topic, there is still an important uncertainty about the local effects on the coasts all over the world. The aim of this paper is to review different data sources and methodologies to assess coastal vulnerability to sea level rise for an exceptionally complex and large area such as Europe. The lack of high resolution data for the whole area is one of the key issues, needing to use spatial data covering all the territory. The reviewed techniques include relative indexes, focusing in the Coastal Vulnerability Index, and different models, from very simple approaches like bathtub models, to other approaches like SLAMM, DIVA or SimCLIM. The discussion made should be helpful for those interested in assessing coastal vulnerability to sea level rise in large areas o in countries with poor spatial data.

Keywords: *climate change, coastal vulnerability, sea level rise, models.*

1. INTRODUCTION

Coastal environments are characterized by high geomorphological dynamics. Changes in the equilibrium of the processes that model the coast can produce observable changes in short time scales, making them especially sensitive to disturbances of natural (Carter, 1990) and anthropic origin (Cowell and Thom, 1995).

Highly diverse ecosystems bring important ecosystem services to society and other species communities. However, these ecosystem services could be threatened by the current climate change and the consequence sea level rise (Nicholls et al., 2007).

Increases in sea-level are projected to increase intensity and frequency of storm surges and coastal flooding, and to increase salinity intrusion in rivers, bays and coastal aquifers. In general terms, without adaptation, a rise in sea-level will inundate and displace wetlands and lowlands, exacerbate coastal storm flooding, increase the salinity of estuaries, threaten freshwater aquifers, and otherwise impact water quality alter natural sedimentary dynamics, erode shorelines, and intervene in the decline of their resilience and adaptive capacity of the coasts as natural systems (Janssen et al., 2006). In addition, urbanized coastal environments have a tendency towards narrowing (coastal squeeze) due to the action of sea level rise and human occupation and transformation of the coastal strip (Fraile-Jurado & Rey-Romero, 2018). The impacts would vary from place to place and would depend on coastal type and relative topography. Areas most at risk are considered to be tidal deltas, low-lying coastal plains, beaches, islands (including barrier islands), coastal wetlands, and estuaries. In this sense, coastal areas around the world are highly vulnerable to disturbances caused by climate change, such as sea level rise (Fraile-Jurado, 2018).

In this context, the Intergovernmental Panel on Climate Change (IPCC) defined vulnerability specifically to climate change (e.g. in its fourth Assessment Report of 2007). There is uncertainty regarding future climate change, impacts, vulnerability and adaptation processes especially for long term scenarios (e.g. up to 2100) (Downing *et al.*, 2005). The most authoritative and widely quoted definition of vulnerability in the context of climate change is from the Fourth Assessment Report (2007): “Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity” (IPCC 2007a, p.883).

Various different methods have been developed for assessing vulnerability of different coastal systems to the projected range of climate change impacts. One challenge of measuring vulnerability is that vulnerability is temporally dynamic and context specific, because exposure, sensitivity and adaptive capacity vary by type, by stimulus and are place and system specific (Smith*et al.*, 2006). Vulnerability is unevenly distributed and will vary depending on experience, income levels, age or the strength of social, cultural or linguistic networks. Additionally, the aggregation of variables and indicators is controversial (Harvey *et al.*, 2009; Hinkel, 2011).

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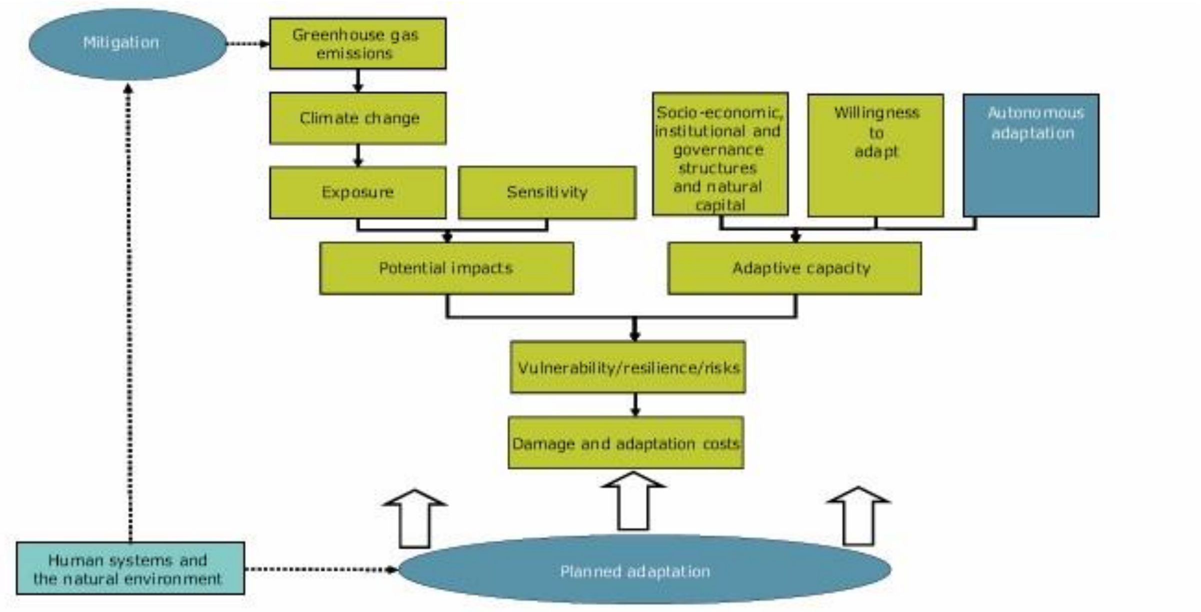
In general terms, without adaptation, a rise in sea-level would inundate and displace wetlands and lowlands, erode shorelines, exacerbate coastal storm flooding, increase the salinity of estuaries, threaten freshwater aquifers, and otherwise impact water quality. The impacts would vary from place to place and would depend on coastal type and relative topography. Areas most at risk are considered to be tidal deltas, low-lying coastal plains, beaches, islands (including barrier islands), coastal wetlands, and estuaries.

For assessing vulnerability of different coastal systems to the projected range of climate change impacts various different methods have been developed, presented in this paper. However in addition to vulnerability and risk assessments also cost/benefit analyses of adaptation responses to climate change impacts are needed. However such analyses and models used were beyond the scope of this working paper.



Source: Isoard, 2010; IPCC, 2007; Füssel and Klein, 2006.

Figure 1. Conceptual framework for climate change impacts, vulnerability, disaster risks and adaptation options (EEA, 2010b)

Coastal erosion is a natural process, which has contributed throughout history to shape European coastal landscapes. Coastal erosion and soil erosion in water catchments are the main processes which provide terrestrial material to the coastal systems including beaches, dunes, reefs, mud flats, and marshes (Roig i Munar et al. 2019). In turn, coastal systems provide a wide range of functions including absorption of wave energy, nesting and hatching grounds for fauna, protection of fresh water, or sites for recreational activities.

However, migration of human population towards the coast, together with its ever growing interference in the coastal zone has also turned coastal erosion into a problem of growing intensity (Eurosion, 2004). Depending on the sediment balance, the loss of important coastal wetlands might be expected.

Vulnerability understood as a change in the condition of natural systems has a direct impact on the ecosystem functions that humans depend upon for their socio-economic wellbeing (Bowen and Riley 2003). Therefore, better understanding of the linkages between socioeconomic conditions and coastal environmental dynamics is a prerequisite that will lead to more sustainable management of the coastal zone.

The aim of this paper is to review the main techniques to improve the understanding of the dynamics of the coastal systems, to identify hotspots and to raise awareness of the problems causing vulnerability in the coastal areas in Europe. There is a potential need of decision makers to compare and prioritize the different vulnerable locations for developing sectoral and integrative plans to reduce vulnerability.

2. SEA LEVEL CHANGES AND COASTAL VULNERABILITY.

From the point of view of coastal vulnerability, it is necessary to use the concept of relative mean sea-level changes. This concept describes any change in mean sea-level measured at the coast (usually by tide gauges). Relative sea-level change can be split into two components i) global sea-level change (eustasy), which depends on the volume of liquid water in the oceans basins, and ii) local sea-level changes, related to the local sea-level fluctuations but also to the vertical local movements of the continental side.

Eustatic rise of global sea-level cannot be measured directly, due to a high spatial variability (Pugh, 2004), excepting for remote sensing techniques. Pugh (2004) defines the eustatic changes of sea-level as the change in seawater volume divided by the ocean's surface area. Two general factors contribute to eustatic change of sea-level: expansion due to warming, and an increase in mass of the ocean due to the melting of land-based ice.

During the 20th century, tide gauge data show that the global sea level rose by an average of 1.7 mm/year (IPCC, 2007a). This was due to an increase in the volume of ocean water as a consequence of temperature rise, although inflow of water from melting glaciers and icesheets is playing an increasing role. For the period 1961–2003, thermal expansion contributed about 40 % of the observed sea-level rise, while shrinking mountain glaciers and ice sheets contributed about 60 % (Allison et al. 2009; IPCC, 2007a). Sea-level rise has been accelerating over the past 15 years, 1993–2008, to 3.1 (± 0.6) mm/year, based on data from satellites and tide gauges, with a significantly increasing contribution of ice-sheets from Greenland and Antarctica.

In the past, the main cause of sea-level fluctuations during the Quaternary period was the melting of glaciers, small ice caps and the ice sheets of Antarctica and Greenland (Lowe, 1997). The estimated current contribution from Greenland is 0.7 mm/year and the estimate for Antarctica is almost the same, according to observations from 2002 to 2009 (Allison et al., 2009; Scientific Committee on Antarctic Research, 2009), although the role of certain areas in which an accelerated melting has been proved is still unclear (Khazendar et al. 2016; Ferrero et al. 2018).

In the middle of the past decade, there was a scientific agreement about the range of projected future sea-level rise. Most of the general circulation models (GCMs) showed a range of sealevel rise of 20-60 cm by the end of the 21st century (IPCC 2001, 2007a). In 2007 the IPCC projected a rise of 0.18–0.59 m above the 1990 level by the end of the 21st century (IPCC, 2007a). However, the models used in developing these projections did not include representations of dynamic ice sheets. In the last few years some experts have remarked that these types of GCM models (such as the modelled used by the IPCC) are underestimating the contribution of ice caps, especially the contribution of Greenland (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009; Lowe *et al.,* 1997; German Advisory Council on Global Change, 2006, Rahmstorf *et al.*, 2007). According to these experts, the mean sea-level might rise by 100 cm before the end of this century. More monitoring and more accurate modelling of the processes of ice cap melting will inform this discussion further during the next years. The last IPCC report (Field et al., 2014) could not state an agreement between the two opposite points of view.

For local sea-level fluctuations, it is necessary to consider the importance of local factors to inform studies about the risk of coastal hazards or about coastal vulnerability to sea-level rise. Even if some factors have no importance at a global scale, they can be the main drivers of local relative mean sea-level changes, such as the construction of coastal human infrastructures or changes in the coastal land uses. From a local point of view, a vertical water level rise of 1 meter is equivalent to a descent of 1 meter of the emerged land side. In order to make a comprehensive analysis, these matters can be distinguished into i) local fluctuations of mean sea-level and ii) vertical movement of emerged land áreas (Fraile, 2011).

Other oceanographic causes of local sea-level fluctuations are related to the ocean circulation and its configuration. For example, changes in the currents or in the air pressure, which means a response of 1 cm per hPa (Yanagi *et al*., 1993). It appears that there is a positive correlation between those variables and climate change (Tel and García, 2003).

At the continental scale, there are different kinds of vertical movement capable of causing local sea-level changes. Postglacial rebound caused by isostasy covers the largest areas (in fact, it can also be considered as a "regional" factor). Although its effects are very clear in the highest latitudes (causing sea-level declines), their effects in the middle and lower latitudes (and in the mean sea-level time series) are not so evident (Mitrovica *et al.*, 2002, Tel and García, 2003, Pugh 2004, Fraile and Fernández, 2016).

On a local scale, tectonic movements are one of the main causes of relative mean sea-level changes, having in some cases more influence on the local seal level change than any global or regional cause. In particular subsidence in delta areas can lead to significant local changes in sea-level rise (Figure 2).

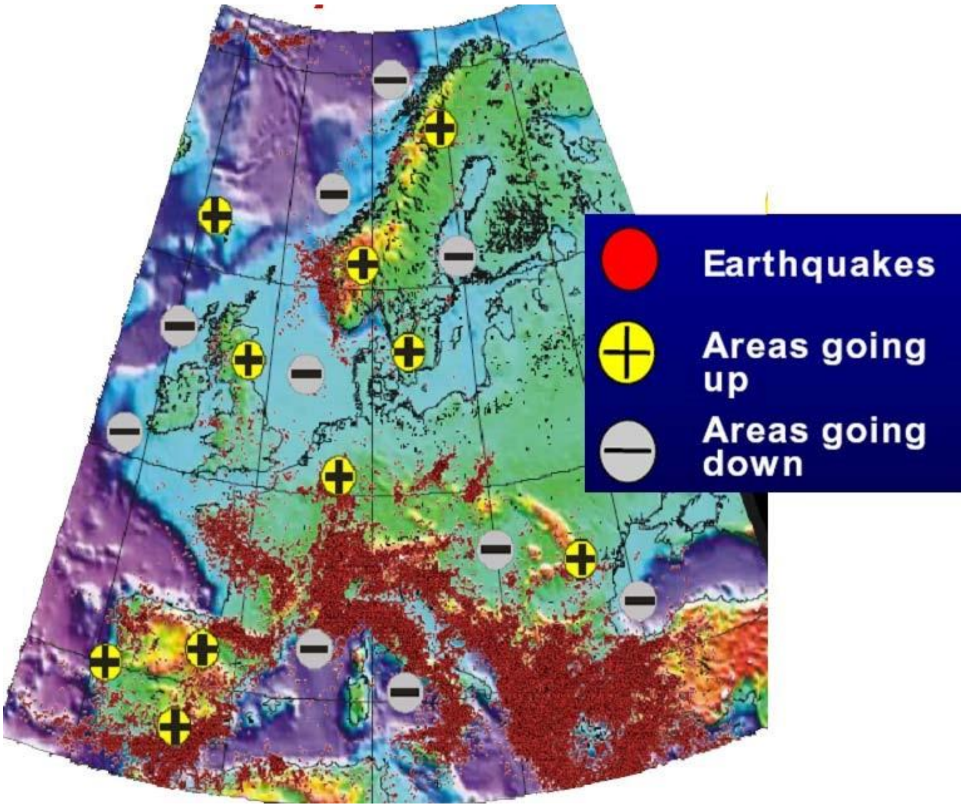


Figure 2. Regional techtonics in Europe. *Source: Topo-Europe – PICASSO Workshop*

In Europe, the projected regional mean sea level rise can be up to 50% higher than the global due to regional influences, including the enhanced melting of the Greenland ice. Other climatic phenomena, such as the sea surface temperature coupled ocean-atmosphere phenomenon El Nino and La Nina, also are important and can introduce additional uncertainty in projected sea-level rise estimates for Europe's coasts (IPCC 2007a).

The Baltic and the Arctic sea-level rise projections under the IPCC SRES scenarios, indicate an increased risk of flooding and coastal erosion for this century. In other low tidal range regions (coastal wetlands and sandy beaches) sea-level rise will increase the damage potential of storm surges. The same indications emphasize that the coastal retreat rates are currently 0.5 to 1.0 m/yr for parts of the Atlantic coast which are the coasts most affected by storms (IPCC 2007a).

Satellite observations indicate a large spatial variability of sea-level rise across the European seas, for example with increases of 3.4 mm/yr for the North Atlantic (50 °N to 70 °N) and 1.7 mm/yr on average for the Mediterranean Sea. In part of the eastern Mediterranean, sea-level rise has been higher than this average, while in the west it was lower. These local variations can be explained by variability of the North Atlantic Oscillation (NAO), inter-annual wind variability, changes in global ocean circulation patterns, or specific local structures of the circulation such as gyres, or isostatic uplift (EEA, 2010). Many European cities could be affected, multiplying the effects of a potential sea-level rise due to high population concentration (Figure 3).

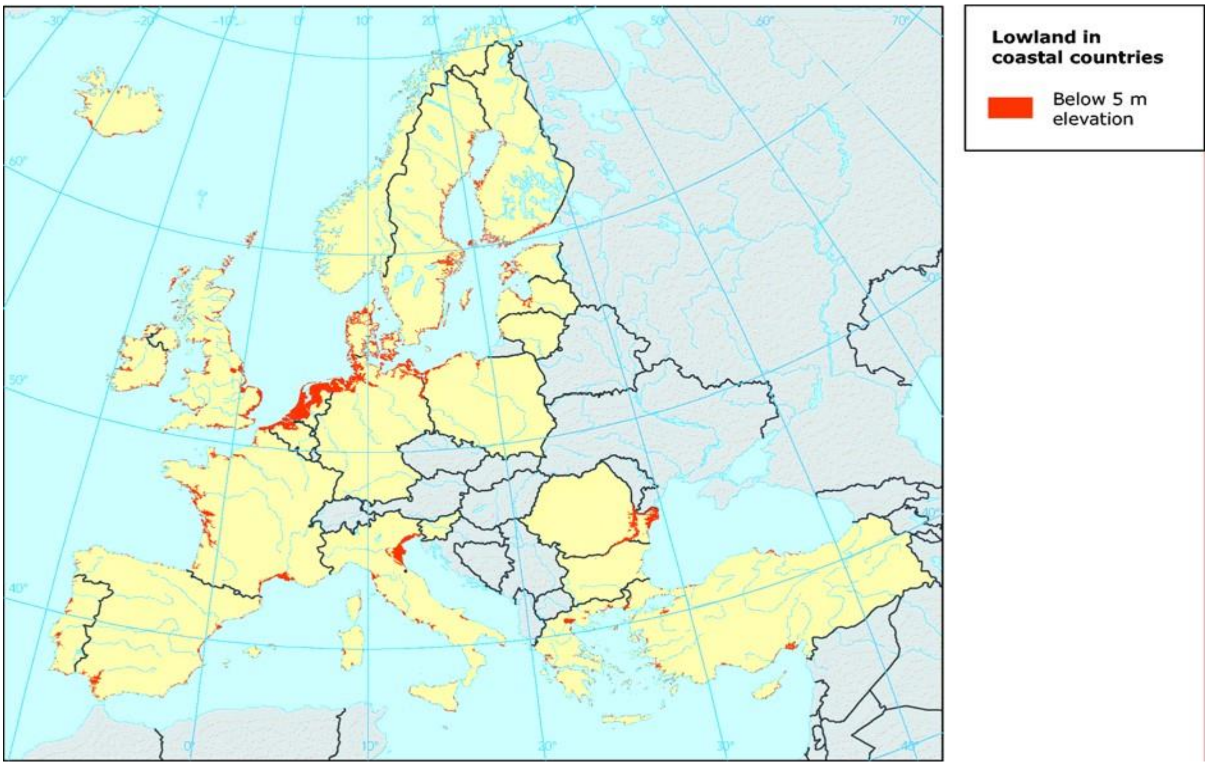


Figure 3. Lowland in Coastal Countries. *Source: EEA, 2006*

Changing sea level could significantly raise efforts and cost requirements for the protection of terrestrial drainage. Currently, many floodgates allow the natural drainage of inland waters at low tide cycles. Rising sea level would require the introduction of pumping drainage stations (as currently found in The Netherlands).

3. ASSESSING IMPACTS OF AND VULNERABILITY TO SEALEVEL RISE AT THE COAST

3.1. Data

Coastal data accommodate widely varying information from diverse disciplines and sectors of society, business and government. Typically, a number of local, national and regional government agencies are responsible for different aspects of the same physical areas and uses of the coastal zone, e.g. fisheries, environment, agriculture, transport (terrestrial and marine) and urban planning.

Due to such complex institutional roles, responsibilities and relationships, it is often not possible to access many homogeneous datasets covering the European continent. This is shown by a review of the coastal components of several data sets that are useful for developing and applying methods and models.

The most significant Digital Elevation Model (DEM) fot the planet is the SRTM30. The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data for over 80% of the globe. These data are currently distributed free of charge by the U.S. Geological Survey (USGS) and are available for download from the National Map Seamless Data Distribution System, or the USGS file transfer protocol (ftp) site. The SRTM data is available as 1 arc second (approximately a 30m resolution). The vertical error of the SRTM30 is reported to be less than 16m.

A DEM derived from the GTOPO30 dataset was compiled by EEA (http://edcdaac.usgs.gov/gtopo30/gtopo30.html). The DEM was converted to raster (georeferenced tiff) using Arcview and Grid Pig extension. The Caspian Sea border, the SyroAfrican depression and some areas from the Netherlands, all under sea-level were corrected.

The JAXA's Global ALOS 3D World is a 30-meter resolution digital surface model (DSM) captured by the Japan Aerospace Exploration Agency's (JAXA). The neat thing about is that it is the **most precise global-scale elevation data** now.

Other examples at national or regional level have detailed DEM with better resolution for assessing coastal vulnerability, like the DEM Andalusia (10, 5 and <1 meter resolution), an example of good practices of land and sea data integration (Fraile and Ojeda, 2013).

With regards to relevant socio-economic data, demographic tables were compiled from data provided directly by the national statistical offices to Eurostat, especially total population living in coastal regions, population type classes and population projections. The data are collected each year through a joint questionnaire on demography, managed by Eurostat in conjunction with the Council of Europe and the United Nations Statistical Division.

At European level, this data is only available by NUTS0 (EU Member State national level) and NUTS2 (Regions) administrative units extracted from National Statistics and National Census, with the complication that not all the European Member States follow the same methods for collecting the statistical information; especially those countries that have joined the EU more recently use different methods.

Besides the socio-economic statistics of Eurostat, the JRC in collaboration with the EEA calculated the population density disaggregated/in connection with the Corine land cover classes for the year 2006 (Figure 4). Population data in the European Union Member States are available at municipal level (NUTS5). More detailed data are available only for a few countries. CORINE Land Cover (CLC) provides land cover information with a medium resolution (100 meters). This methodology provides approaches to combine municipal population data with CLC to produce an EU-wide population density grid at scale 1:1.000.000. Using this methodology, each pixel value is the estimated density of inhabitant per km^2. Each pixel has a size of 100 m x 100 m including the data in integer values (Gallego, 2010).

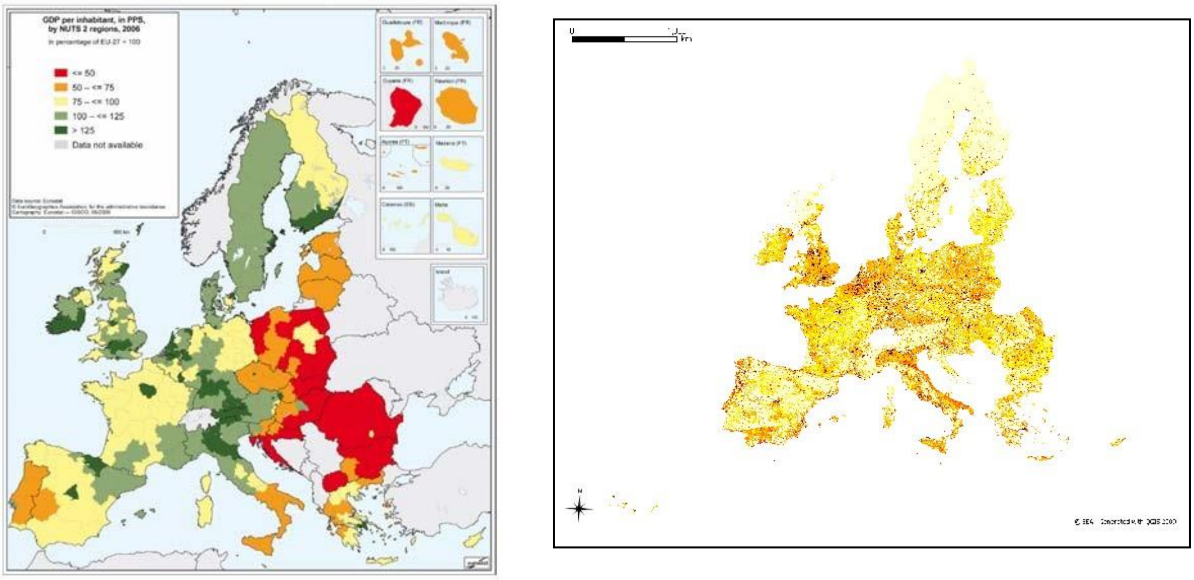


Figure 4. GDP Indexes and Population Density GRID disaggregated with Corine, *Source: Eurostat and JRC*

Corine is the only homogenous dataset at European scale on land cover. There are 3 different versions dated in 1990, 2000 and 2006, all of them available and accessible at the European Environment Agency's website (Figure 5).

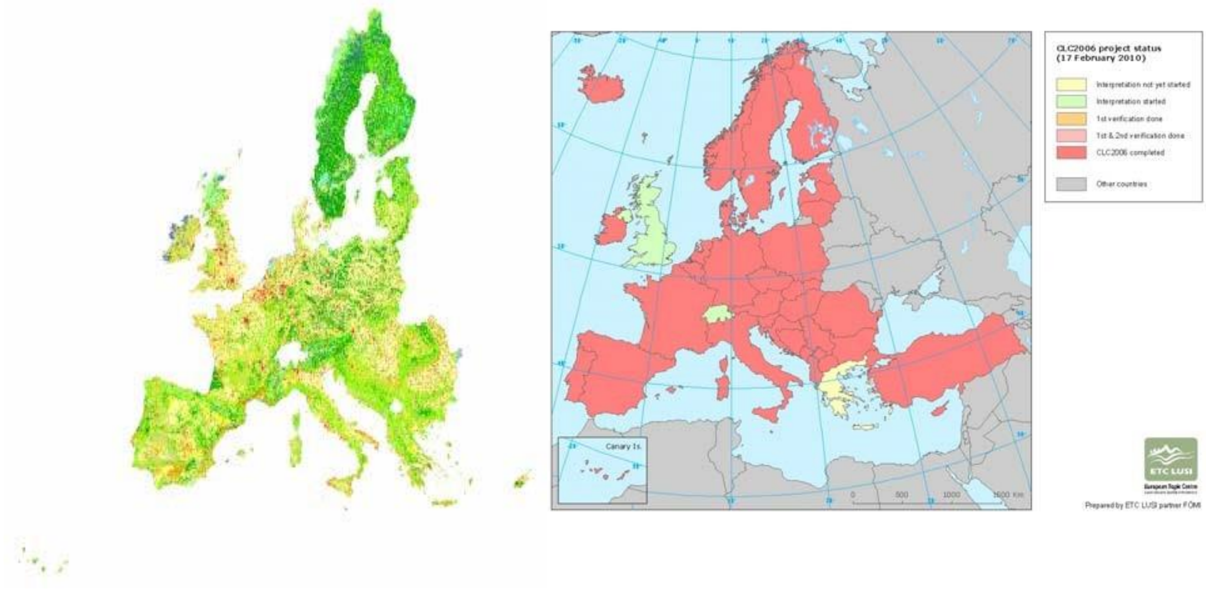


Figure 5. Corine Land Cover 2000 and Corine Land Cover 2006 Implementation. *Source: EEA – ETCLUSI, 2010*

3.2. Climate change vulnerability indicators

For measuring vulnerability, indicators can be used. A working definition of a vulnerability indicator is an observable variable that indicates the possible future harm a system (or entity) of interest is facing. Thus, there is clear need to define the system and its troubles before trying to measure the harm by indicators (Hinkel, 2011).

The Pressure-State-Response (PSR) model developed by the Organisation for Economic Corporation and Development (OECD) (Levrel, H, *et al.*, 2008), is an example framework for environmental evaluation. The main limitation of the PSR model is its limited focus on anthropogenic factors. It does not effectively address pressures resulting from environmental change. Despite the incompleteness or complete lack of measurable data-sets for some indicators at the global level, the Driving forces-Pressures-State-Impacts-Response framework (DPSIR) appears to be a practical approach for describing dynamic linkages between socioeconomic and environmental indicators of coastal vulnerability.

Increasing human presence in the coastal zone, coastal land use and land cover patterns, and the growth of cities all increase the demand for coastal resources, leading to the potential degradation of coastal ecosystems. Environmental factors are mainly related to environmental hazards and climate change resulting from human actions and/or natural trends.

The EEA core set of indicators (CSI) comprises indicators representing different categories that could be useful for developing such as the DPSIR framework. Nevertheless, the use of this general overview for Europe also presents many differences in geographical coverage and in the applied methodologies.

Gornitz *et al*. (1991) developed a Coastal Vulnerability Index (CVI) to identify areas that are at risk of erosion and/or permanent or temporary extreme climatic events (storms, floods, etc). Grid cells and/or line segments with low reliefs, erodible substrates, histories of subsidence and shoreline retreat, and high wave and tide energies, will have high index values indicating high vulnerability.

Variables such as mean elevation, local subsidence trend, geology classifications, geomorphology classifications, mean shoreline displacement, maximum wave height and mean tidal range are used to create a basic coastal vulnerability database to formulate a coastal vulnerability index (Gornitz *et al.*,1991) which has been modified for large areas purposes (Ojeda-Zújar, J *et al.*, 2009). (Figure 6). The comparison applications of CVI with more detailed local studies (Fraile and Ojeda, 2012, Fraile et al. 2014) showed the accuracy of this method for open coastal áreas.

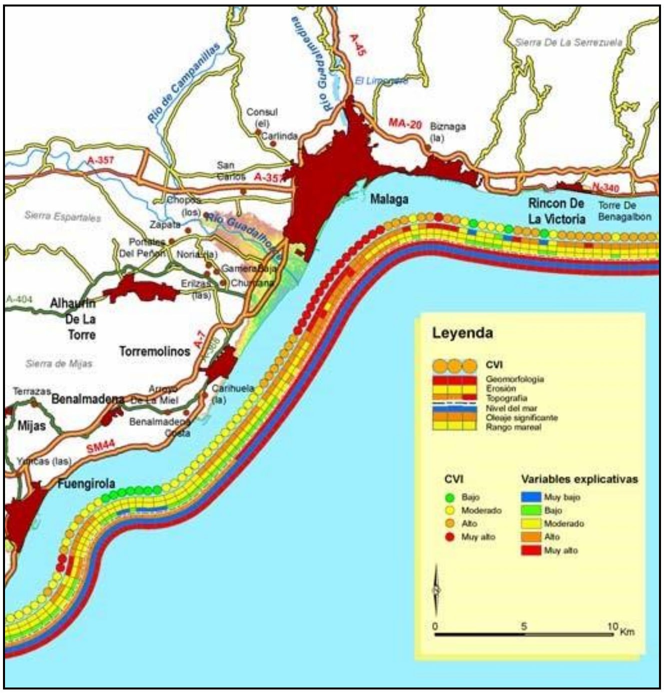


Figure 6. Coastal Vulnerability Index applied to the coast of Andalusia (Spain). *Source: Junta de Andalucía – Regional Ministry of Environment – REDIAM, Spain*

However, different studies conclude that there is a need for additional socio-economic variables (i.e. demographic and economic factors) to complement the environmental variables used so far (Cooper *et al.*, 1998, Gornitz *et al.*, 1993).

The CVI could be applied to various European coastal areas in order to assess the coastal cities and ecosystems vulnerability. At European level, data on reference layers of geomorphology and erosion (Eurosion, 2004), topography-DEM (SRTM, EEA), sea-level rise scenarios (IPCC), tidal ranges (National Hydrographic Institutes) and extreme wave situations (National Meteorological Institutes) are available.

3.3. Assessing coastal vulnerability through the use of models

In this section the models that are available for assessing coastal vulnerability to sea-level rise, including a consideration of adaptive capacity, are discussed. The use of models facilitates the coastal and flood awareness not only from a research point of view but also to policy makers (Meehl *et al.*, 2007, Nicholls *et al.*, 2007). The accuracy of the results of the different models and methods depends on many factors, as described in each model review section.

The models presented here raise problems of scale; some are good for local purposes and not very good for large study areas and others vice versa (Fraile-Jurado et al., 2018). In the case of large coastal areas, the lack of good quality and homogeneous data among regions-countries is a key bottleneck, for instance meteorological data or consistent and high accurate height information (DTM) for Europe (Vaze *et al.*, 2010, Horritt *et al.*, 2001).

3.3.1. GIS Inundation Model – Bathtub

The Bathtub or Inundation model can be better described as a set of tools (i.e. GIS software) which allows the mapping of sea-level rise in all studied locations (NOAA, 2010) rather than a model to simulate flooding along the coast or rivers. The intersection of this surface with a Digital Elevation Model provides a predicted planar surface. All areas below this surface are classified as flooded (Priestnall, 2000; Yunus et al., 2016).

There are three main advantages of using bathtub inundation models (Table 1). The tools do not require high expertise, so the analysis is cheaper in terms of man hours. Furthermore, this ease of use is complemented with fast production of vulnerability maps of the coastal areas. The final advantage is that policy makers can easily understand and interpret the model results.

The disadvantages of this sort of model are also clear. There is a lack of inclusion of urban infrastructures (i.e. dikes), sediment data, storm tide, waves, wind, and precipitation information and also, feedback systems on hydrological and ecological issues. All this makes the model not very accurate, especially for local purposes. Thus, the inundation model commonly overestimates the flooding areas due to sea-level rise.

One step forward with Bathtub is the modelling combining a DEM with others sources of information such as remote sensing and/or meteorological data to develop a simplified flood inundation simulation. The purpose of this is to obtain results of vulnerability to flood hazards in river catchments, urban areas, etc (Zheng *et al.*, 2008). One well known model is LISFLOOD-FP. It has evolved from a simple raster-based model to a simplified two dimensional hydrodynamic model designed to simulate floodplain inundation over complex topography using new sources from remote sensing such us LIDAR information. It can simulate dynamic propagation of floods due to prediction in each grid cell at each time step (Bates *et al.*, 2005, Bates *et al.*, 2000). Other approaches based on this methodology lie in assessing the hazard of sea level rise through the calculation of the probability of flooding in each cell of a DEM (Purvis et al. 2008, Fraile-Jurado et al., 2017).

Table 1. GIS Inundation Model – Bathtub

GIS Inundation Model – Bathtub	
Impacts considered	Inundation
Drivers	Relative sea-level rise
Appropriate scale	From local to global
Spatial resolution	Varies depending on the input parameters
Temporal scale	Defined by the user
Input parameters	DEM, sea-level rise, scenarios and socio-economic data among other datasets.
Output products	Maps of flooding potential
Example of areas of application	Concrete coastal area, cities, River Basin Districts, regions, countries, regional seas, Europe and neighbouring countries.
Technical information	Inundation models are based in GIS tools that could be used with commercial or open-source software (ESRI, gvSIG, GRASS), the cost is low and there is no need of high expertise for technicians to use it.
Additional information	Status: Operational Purpose/Policy: Developed to create easy and understandable flooding maps from basic sources, DTM, river and sea-level. Test Areas: Global and U.S. Coastal areas

3.3.2. Sea-level Affecting Marshes Model (SLAMM)

Research studies show that wetlands are a key natural habitat with high biodiversity of flora and fauna (EPA, 2009). Besides this environmental value, they play a crucial role to control natural floods and provide goods and services to the society (Maltby, 1991). External pressures like intense agriculture, urban society or global climate change (Kracauer *et al.*, 1997, Winter., 2000) make wetlands are among the most threatened ecosystems (Mitsch, 2009).

SLAMM allows researchers to understand the process behind wetland vulnerability (Park *et al.,* 2003). The Sea-level Affecting Marshes Model (SLAMM) simulates the dominant processes involved in marsh ecosystems to understand wetland conversion and shoreline changes during long term sea-level rise (Park *et al.,* 1989). The model can be applied from local, such as small test sites, to the regional scale ((Table 2).

The model is based on a decision tree where quantitative and qualitative relationships are established to represent the transfer of land cover coastal classes according to different variables such as elevation, type of habitat, sediments, erosion degree, etc (SLAMM, 2010). The variables are aggregated per grid cell level for each site and each time slice. It includes the summary of the historic trend, the rate of change and the special adjustment depending on the scenario chosen (Titus *et al.,* 1991; IPCC, 2001).

There are five primary processes within SLAMM which can influence wetland dynamics under different scenarios of sea-level rise: inundation, horizontal erosion, overwash, saturation and accretion.

Wetlands, as one of the most relevant ecosystems for coastal vulnerability (Maltby, 1991; Kracauer *et al.,* 1997; EPA, 2009; Mitsch, 2009; Brown et al. 2016), are under much research to identify the main impacts due to climate change. In combination with the SLAMM model, these other impacts can be easily addressed. Global warming is expected to increase sea-level rise inundating of many low-lying coastal areas with implications on the biodiversity (i.e. shorebirds that rely on them for feeding). The most severe losses are likely to occur at sites where the coastline is unable to move inland because of steep topography or seawalls or other anthropogenic factors (Galbraith, 2002).

On the one hand, the advantages of the SLAMM model are that it can be applied from small to large scales providing information on the vulnerability of coastal habitats, flora, fauna and the shift of habitats due to changes in sea-level. All this information allows assessment of the conflicts between biodiversity and anthropogenic activities in coastal areas. On the other hand, SLAMM does not include feedbacks from hydrological and ecological systems nor socioeconomic information that could change due to sea-level rise (SLAMM, 2010).

Table 2. SLAMM model resume.

SLAMM	
Impacts considered	Wetland change (erosion, overwash, saturation, accretion, salinity)
Drivers	Relative Sea-Level rise
Appropriate scale	Local and regional, maximum 100.000km2
Spatial resolution	10-100 meters
Temporal scale	Based in the sea-level scenario used
Input parameters	DEM or LIDAR, Land cover, human infrastructures
Output products	Maps of flooding risk potential for ecosystems
Example of areas of application	Coastal areas, bays, estuaries, deltas, etc.
Technical information	SLAMM Model is open-source with a low or medium cost requiring medium expertise in order to use it. Technical documents and guidelines are available online.
Additional information	Status: Pre-Operational. Last version: SLAMM 6.0.1 and downloadable Purpose/Policy: To simulate the main processes affecting coastal land classes and mainly related with wetland conversions and shoreline modifications due to the sea-level rise. Test areas: Coastal areas in U.S (San Francisco, Delaware)

3.3.3 Barataria-Terrebonne Ecosystem Landscape Spatial Simulation (BTELSS)

BTELSS is a landscape model built to investigate and predict the environmental factors and pressures (subsidence, sea-level rise, changes in river discharge, etc) affecting wetland change over a long term period (30 years) within the Barataria and Terrebonne basins (U.S.A.).

The model is based on a hydrodynamic flooding module (using grid cells with possible different sizes) and an ecosystem module to control the habitat type (Table 3). To evaluate the accuracy of the model, validation and calibration are key steps. Calibration was carried out initializing the landscape of the model by the U.S. Fish and Wildlife Service (USFWS) habitat map 1978 and the results were compared with the habitat map 1988 (base case). In a second step, after calibration and validation, 30 year simulations are run in different scenarios (i.e. normal conditions, yearly mean sea-level and discharge conditions, and double rate of relative Sea-level Rise) to evaluate how the climate modified the landscape habitat and the patterns of the land loss (Martin et al., 2002).

The main outcomes reveal that land loss rates from interannual weather variability are responsible for the largest changes. Even when dry and wet years were repeated (extreme events), the model predicted lower land loss when compared to historical records (the normal conditions scenario) (Reyes et al., 2004).

Advantages of the BTLESS in reference to other models (i.e. Inundation model or SLAMM) is the possibility to include a large number of variables (data) such us hydrodynamics, vegetations, infrastructure, etc., that allow analysis of the natural habitats and the interaction among the factors.

Disadvantages are that the data needed for running the model is not easy to obtain (habitats maps at large scales to calibrate and validate the data) and that the expertise to run the model is very high (programming knowledge is essential). Both make the model complex and expensive to use.

BTLESS is used better approach understanding of plant communities and their adaptation to different environmental factors (i.e. sea-level rise, droughts, reduced river discharge, etc) in coastal areas (Reyes et al., 2000, McLeod et al., 2010).

Table 3. BTELSS model

BTELSS	
Impacts considered	Wetland change
Drivers	Relative sea-level rise, droughts, rivers discharge, Ecological and physical feedbacks
Appropriate scale	Local to regional. Maximum 100.000 km2
Spatial resolution	1 km2
Temporal scale	Defined by user (from 12 seconds to 100 years)
Input parameters	DEM (+Bathymetry), Climatic data, river discharges, sediment loads, land cover among other datasets.
Output products	Maps of land change, flooded and eroded areas. Including other maps of indexes such as salinity, sediment balances, etc.
Example of areas of application	River Basin Districts, Coastal and Transitional Waters, Coastal wetlands, Coastal areas, etc.
Technical information	BTLESS Model has a General Public Licence (GPL). The cost is relatively high, for academic use has no cost. High expertise is needed. There are no documentation or technical guidelines available. Programming knowledge required and expertise from the team developers.

Additional information	Status: Development - Pre-Operational. Last version: Unknown Purpose/Policy: To analyse and forecast the environmental factors affecting wetlands habitat change Test areas: Barataria and Terrabone basins, Lousiana and Mexican wetlands

3.3.4.SimCLIM

SimCLIM is a computer model system for examining the effects of climate variability and change over time and space. Its "open-framework" feature allows users to customize the model for their own geographical area and spatial resolution, as well as to append impact models.

SimCLIM is designed to support decision making and climate proofing in a wide range of situations. For example, risks can be assessed both in present times and in the future with the advantage that adaptation measures can be tested for present day and future conditions of climate change (Warrick *et al.,* 2005, Warrick *et al.,* 2007, Warrick, 2009, Nasim et al. 2018).

SimCLIM contain a set of tools for model developers such as a scenario generator, climate data browser, extreme values analyzer, image viewer as well as several models to evaluate, for instance, the coastal zone, human health and water (SimCLIM, 2010 and Warrick, 2009), although the user can incorporate their own models.

The model can be applied from local to global scales and it includes a sea-level scenario generator which allows the conclusion of regional and local parameters linked to the coastal areas and a simulation model of shoreline changes for beach and dune systems ((Table 4).

Data inputs for the Coastal Zone Model include shoreline response time in years, closure distance from the shoreline, depth of material exchange or closure depth in meters, dune height also in meters and residual shoreline movements by meter per year and climate data (long-term monthly mean and daily time series). The output is year-by-year change in relative shoreline position in meters to the year 2100 (McLeod, *et al.,* 2010).

The main advantages are the variety of geographic and temporal scales that can be used to run the model; it is flexible, user-friendly and relatively quick at generating scenarios and examining uncertainties.

The main disadvantage is related to the quality of the input data and the tools, for instance, the scenario generator is adaptable to the main General Circulation Models, GCM, but not to all (McLeod, et al., 2010). Focusing on the coastal erosion model, newer shoreline models, apart from the Bruun rule, might improve the outcomes of the model (Cowell *et al.,* 2006).

Table 4. SimCLIM model.

SimCLIM	
Impacts considered	Inundation (i.e. erosion)
Drivers	Relative sea-level rise, climate change
Appropriate scale	Local to global
Spatial resolution	Varies depending on inputs parameters
Temporal scale	Defined by user. Variable depending on impact model.
Input parameters	DEM, Climatic data, sea-level changes, impact models.
Output products	Maps of flooding potential in coastal areas and ecosystems.
Example of areas of application	Concrete coastal area, cities, River Basin Districts, regions, countries, regional seas, Europe and neighbouring countries.
Technical information	SimCLIM is commercial software with different license types depending on the users. The cost is lowmedium. The use of this model requires medium-high expertise. Documentation is available online and training is offered by the company.

Additional information	Status: Pre-Operational. Last version: SimCLIM 2.1.5.0 Purpose/Policy: To analyse the effects of climate variability and change over time and space. Assessment of the sea-level rise risk Test areas: Micronesia, Cook Islands and South East Australia

3.3.5. Dynamic Interactive Vulnerability Assessment (DIVA)

The DIVA model is an integrated, global model of coastal systems that assess natural, biophysical and socioeconomic developments due to sea-level rise and changes in socioeconomic patterns through the analysis of environmental factors; coastal erosion, flooding (coasts and rivers), wetlands change, salinity intrusion as well as adaptation in terms of rising dikes and sustaining beaches (Hinkel *et al.*, 2010).

As said by McLeod et al., 2010 and Hinkel, 2011: "DIVA downscales to relative sea-level rise by combining the sea-level rise scenarios with the vertical land movement resulting from glacial-isostatic adjustment and subsidence in deltas. The loss of dry-land is then assessed due to direct and indirect coastal erosion. Changes in wetland areas and type are assessed based on the rate of sea-level rise, the available accommodation space and the available sediment supply. The socio-economic damage of coastal flooding is assessed based on data of storm surge characteristics as well as the exposed people. The damage of salinity intrusion into the coastal systems is assessed in form of the area of agricultural land that is affected by salt water travelling up the lower reaches of rivers, taking into account coastal adaptation in terms of building-up dikes and nourishing beaches with a predefined adaptation strategy such as no protection, full protection or optimal protection" .

As an advantage, DIVA is designed for global, regional, and national level assessments, with an average coastal segment of 70 km, including available inputs parameters at European and Regional Sea scales. Disadvantages are that, due to the model resolution, DIVA is not appropriate for application at local scale. Due to the lack of reliable models, DIVA does not consider ecosystem-based adaptation measures (Table 5).

Table 5. DIVA model.

DIVA	
Impacts considered	Coastal and river flooding, coastal erosion, wetland change, salinity intrusion into rivers
Drivers	Global or regional sea-level rise, population growth, GDP growth, land use-change
Appropriate scale	National to global. Areas with a extent of 1.000.000 km2.
Spatial resolution	Coastline segments of 70km
Temporal scale	100 years (5 years time/step).
Input parameters	SRTM, coastal geomorphology, coastal population and GDP, land use and administrative boundaries.
Output products	Estimation of population under flood risk, wetland changes, damages and cost, amongst other outputs.
Example of areas of application	Countries, Regional Seas, Europe and neighbouring countries.
Technical information	DIVA Tool is currently not available for download due to a lack of resources for maintaining and supporting the software. It requires medium-high expertise. Technical documents or guidelines are not available online.

Additional information	Status: Pre-Operational. Last version: Unknown Purpose/Policy: To assess the bio-physical and socioeconomic consequences of sea-level rise. Test areas: Indonesia, Europe, Southeast Asia Type of software: Open-Source

3.3.6. Climate Framework for Uncertainty, Negotiation and Distribution (FUND)

The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) is an integrated assessment model of climate change. Although, FUND does not arise from a scientific basis in coastal impacts as previous models (SLAMM, SimCLIM or DIVA); it has capacity for providing information about climate change in a dynamic context, which makes it a useful and innovative tool (Anthoff and Tol, 2012).

The aim of FUND is to perform studies to link policy and climate change. It aggregates scenarios with a great variety of models (population, economics, greenhouse gas emissions, sea-level, etc.) developing time-steps of one year from 1950 to 2300, covering 16 major world regions (Table 6). Thus, cost benefit and cost assessment from reduction of greenhouse emissions (Tol, 2006a), efficiency of climate policy or equity and costs of climate change (Anthoff, 2009b) studies among others can be derived.

As every other model, FUND had advantages and disadvantages. On the one hand, the disadvantages are that the economic component is very simple to use i.e not including exchange rates and it has a non-user friendly interface (FUND, 2010 and Tol, 2006b). On the other hand, the flexibility of the model allows inclusion of already developed and new modules (i.e. climate change impacts module) after some user training to extend the studies to other topics (Narita *et al.*, 2009, Narita *et al.*, 2010, Anthoff *et al.*, 2009c, Nicholls *et al.*, 2009).

Table 6. DIVA model.

FUND	
Impacts considered	Wetland loss, dry land loss, water impact,
Drivers	Climate Change (and scenarios), Global Warming
Appropriate scale	Regional to Global
Spatial resolution	Defined by the user
Temporal scale	From 1950 to 2300 with time-steps of a year
Input parameters	Population and scenarios on emissions, climate, sealevel and other impacts.
Output products	Rates and statistics for decision making
Example of areas of application	Europe
Technical information	FUND model has different full and experimental versions available online for free download. Medium expertise is required to use the model, (not windows interface developed). The source code and technical documents are also available.
Additional information	Status: Development. Last version: FUND3.5 Purpose/Policy: To study the impacts of the climate change in a dynamic context. Test areas: Europe Type of software: Open-Source

3.3.7. Delft3D Modelling Suite

Deltares has developed a flexible integrated modelling suite called Delft3D for modelling both natural environments like coastal, river and estuarine areas and more artificial environments like harbours, locks and reservoirs. The Delft3D suite can simulate two (either in the horizontal or a vertical plane) and threedimensional flow, sediment transport and morphology, waves, water quality and ecology and is capable of handling the interactions between those processes.

The system is designed for use by domain experts and non-experts alike, which may range from consultants and engineers or contractors, to regulators and government officials, all of whom are active in one or more of the stages of the design, implementation and management cycle.

The Delft3D modelling suite has been applied in numerous applications all-over the world (currently about 2000 clients), e.g. for climate change studies, integrated coastal zone management, coastal engineering, environmental protection, flood risk management, flood forecasting, intake and outfall systems (Table 7). The Delft3D flow, morphology and wave modules are available in open source as per 1 January. 2011, and many research papers have been published since then, in which sea level rise impacts are evaluated (Best et al, 2017; Grossman et al. 2017, Shope et al 2017), including changes in wave heights (Grossman et al., 2017; Shope et al. 2017), or saltmarsh resilience (Hughes et al., 2017).

Table 7. Delft3D modelling suite

Delft3D modelling suite	
Impacts considered	Coastal and river flooding, drought, coastal erosion, environmental change (a.o. wetland loss), water quality change, salinity intrusion, damage and casualties
Drivers	Wind, waves, storm surge, tsunami, currents, sediments, global or regional sea-level rise
Appropriate scale	From local, regional, national to global.
Spatial resolution	Large-scale: ocean, continental shelf, coastal, estuarine, river; to: small-scale flow (e.g. laboratory scale)
Temporal scale	From minutes up to morphological time scale (1001000 years).
Input parameters	Bathymetry (depth values for all grid points), grid, DTM, roughness, vegetation, wind, pressure, time series (current, water level, etc.)
Output products	Maps, graphs and tables regarding water levels (incl. ground water), water depths, velocities, currents, sediments etc.
Example of areas of application	Climate change studies, vulnerability and risk assessments, integrated coastal zone management, coastal engineering, EIA, environmental protection, flood risk management, flood forecasting, intake and outfall systems
Technical information	Deltares provides consultancy firms, governmental organizations, universities and research institutes with maintenance and support services worldwide, including fully validated high quality Delft3D brand distributions. Installation guide, user manuals, technical reference manuals and tutorials including model data are available for download.
Additional information	Status: Operative Last version: 3.28.10 (for Windows) Purpose/Policy: To model natural environment Test areas: Netherlands, USA, Hong Kong, Singapore, Australia, Venice, etc Type of software: Open-Source

4. MODELS DISCUSSION

Coastal models are created to respond to the needs and requirements from a wide range of stakeholders. Hence, their aim is to provide the proper tools for different groups, from the scientific community to the policy makers; to evaluate coastal vulnerability at different scales. Therefore, the list of models explained here cover different spatial scales, spatial and temporal resolutions and a great variety of drivers of change and related impacts restricted by the availability and quality of data.

The Inundation model is considered (McLeod *et al, 2010)* an advantageous model if an easy and fast assessment of sea level rise is required for local to global scale. Besides this, the required financial and person resources are low and the outputs are readable and understandable for all relevant stakeholders (i.e. policy makers, environmentalist communities, etc). However, not taking biophysical and socioeconomic into account implies that results derived are not useful for high spatial resolution (national authorities or international negotiations) decision making in vulnerability or future adaptation management among others areas such as economic analysis, urban sprawl, etc.

To analyse the vulnerability in coastal areas (i.e. wetlands), more complete models are required. BTELSS and SLAMM are good options for assessing future coastal vulnerability and conflicts about land use between communities due to sea-level rise. Both models have the possibility to incorporate a great range of variables (i.e. BTLESS ecological and hydrological feedbacks). However, this requires high expertise to run the models which is cost intensive and time consuming. Hence, they are good options at local and regional level, but neither appropriate for higher scale nor adequate for international negotiations on vulnerability and/or adaptation.

When a full assessment of vulnerability in coastal areas is the objective, and socio-economical and environmental variables need to be included, SimCLIM, DIVA and Delft3D are the three main relevant approaches. They can inform stakeholders about the effect of sea-level rise in areas where resources and population are very much linked. Nevertheless, they are different: DIVA and Delft3D are developing; open-source models while SimCLIM is a fixed and commercial piece of software that requires specific training to be used. In analysing the impacts, SimCLIM includes a simple impact model for Coastal Assessment based on scenarios preloaded or customised in the scenario generator tool. DIVA and Delft3D incorporate a large set of impacts of climate change such us salinity intrusion and coastal erosion flooding, but external climate scenarios are required to run the model. SimCLIM and Delft3D are valid from local to global scales by different modules to incorporate the required data, whereas DIVA is well prepared to analyse regional to global level. Taking into consideration the previous characteristics, SimCLIM, Delft3D and DIVA appear very valuable tools to assess vulnerability, mitigation and adaptive capacity for national and international authorities.

If the assessment of coastal vulnerability is required from an economical point of view, the FUND model seems a good model option. FUND covers all scales from the local to global scale. FUND incorporates several modules to evaluate impacts such as climate change and requires defined ideas of the expected outcomes by decision makers. Additionally, high expertise is required to run the model to obtain useful outputs that are understandable by decision makers.

When assessing European coastal vulnerability evolvement due to the impact of sea level rise, or other drivers, it is necessary to clarify the purpose of the assessment, its spatial scale and to search for available data before selecting the appropriate model. The model users and the decision makers will need to understand the limitations of the models and of the existing knowledge about coastal vulnerability when analysing the model results.

These requirements will provide a full overview of the expected outcomes, enabling the decision makers to understand the knowledge required and which models fits their needs best. All the models summarised, except the inundation model, have common problems: the documentation of the model is weak and the expertise required to run the model is high. Thus, using such models will require including the scientific community from the outset to ensure the model produces useful outcomes for policy makers (McLeod *et al.,* 2010).

Projecting the future coastal evolution and vulnerability to climate change is difficult because many factors are involved. No standard method can be used by scientists to predict coastal changes in such a wide and diverse territory as the coastal zones in Europe.

For increasing the knowledge on the coastal areas in Europe there are many institutional and research initiatives developing and collecting data and information about the coastal risks and climate change impacts at the coast. These include the initiatives led by the European Commission (OurCoast and the Working Group on Indicators and Data) and national and regional initiatives developed by the Member States. There are many important datasets available on coastal impacts in Europe, despite the fact that these data are not always homogeneously produced for the all European Union Member States.

The successful use of one of the models for assessing coastal vulnerabilities, analysed in this paper, will depend on the users' need and expertise in each determined moment. Nevertheless, all of these models require accurate and well geographically distributed datasets. The result of the models depends on the quality of the input data, which will also ensure the comparability of different model outputs for coastal areas in Europe.

5. CONCLUSIONS

Coastal vulnerability assessments need to start by specifying a clear policy and/or research question. The IPCC definition of vulnerability to climate change can be a starting point for assessments but needs to be operationalized according to the specific policy question. Moreover, more transparency is needed across risk-hazard assessments and climate change assessments on concepts and definitions

Different tools are needed for assessments at different spatial and temporal scales, in different regions (e.g., Wadden Sea vs. Mediterranean), and for different policy purposes. Many models to assess coastal vulnerability are research models in "developmental" stage to be used by their developers and (possibly) other scientific experts. There are certaint experience regarding assessments of coastal vulnerability from local to continental scales. A multi-hazard approach is required to assess the vulnerability of coastal zones to climate change, considering changes in sea level together with sea temperature, storms, salinity, waves, and sedimentation, since coastal assessment requires a transdisciplinary approach.

Regarding the data, there is a need for analysis of adaptation policy measures (e.g., cost-benefit analysis) but this analysis requires different information than vulnerability assessments. Monitoring of key relevant parameters is essential (remote and in-situ). Globally available data (e.g., digital elevation models) need to be corrected for application at regional scales.

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