Methods for assessing current and future coastal vulnerability to climate change

ETC/ACC Technical Paper 2010/8
November 2010

Alejandro Iglesias-Campos, Alejandro Simon-Colina, Pablo Fraile-Jurado, Nikki Hodgson

European Topic Centre on Air and Climate Change

The European Topic Centre on Air and Climate Change (ETC/ACC)
is a consortium of European institutes under contract of the European Environment Agency
PBL UBA-D UBA-V NILU AEAT AUTh CHMI MET.NO ÖKO TNO REC

Front page picture:
Left: Flood barrier Oosterschelde Netherlands
Centre: Graphs and charts. Workplace
Right: Severe beach erosion

Author affiliation:
Alejandro Iglesias-Campos: Junta de Andalucía, Spain (ETC/LUSI)
Alejandro Simon-Colina: Universitat Autònoma de Barcelona, Spain, (ETC/LUSI)
Pablo Fraile-Jurado: Universidad de Sevilla, Spain
Nikki Hodgson: AEA, UK (project coordinator, ETC/ACC)

DISCLAIMER

ETC/ACC Technical paper 2010/8
European Topic Centre on Air and Climate Change
PO Box 303
3720 AH Bilthoven
The Netherlands
Phone +31 30 2743550
Fax +31 30 2744433
Email etcacc@mnp.nl
Website http://air-climate.eionet.europa.eu/

Contents

Acknowledgements to the reviewers:

European Environment Agency

André Jol
Stéphane Isoard
Hans-Martin Füssel
European Environment Agency

1. Introduction

This background paper identifies key aspects of methods, data and models for assessing current and future coastal vulnerability to climate change. The European Environment Agency (EEA), with the support of the European Topic Centre (ETC) on Air and Climate Change and the ETC on Land use and Spatial Information, has published various reports on climate change impacts and vulnerability in Europe. This background paper for the EEA on coastal vulnerability mapping was developed as input for an expert meeting that took place in Copenhagen on 27-28 October 2010. The paper was afterwards improved by including comments made at the meeting and also the conclusions from the meeting.

The objectives of the expert meeting were to assess coastal vulnerability mapping from the perspective of methodological options, observational evidence and future projections. Vulnerability of ecosystems as well as socio-economic systems are considered. Emphasis is placed on models available for the EU level and the more detailed national/regional/local levels, their methodological strengths and weaknesses, the spatial/temporal scales in which they operate, and their data input requirements and how the results are presented. Additional focus was on the identification of key factors determining coastal vulnerability and on indicators for vulnerability.

Currently, more than 80 million inhabitants live in the coastal areas of Europe, and these areas are expected to develop further in the coming decades thus increasing human pressures on ecosystems and natural resources. Increasing tourism will enhance such pressures. Coastal erosion has increased and may increase further. Thus the environmental and socio-economic aspects of the European coastal areas are important and there is a need to improve understanding of the different impacts, vulnerability and risks of climate change and their uncertainties.

Coastal zones are characterized by highly diverse ecosystems that are important as sources of food and habitats for many species. In many areas in Europe, population, economic activity, and arable land are concentrated in coastal zones. This has led to high artifitialization of coastal ecosystems, modification of coastal dynamics and a decrease in resilience and adaptive capacity.

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, T *et al.,* 2005).

This background paper looks at definitions of coastal vulnerability in the context of global and local relative sea-level (section 2) and focuses on the data, methods and models available for assessing vulnerability (section 3) followed by a discussion (section 4) of a selection of models and finally it provides a summary of the key outcomes of the expert meeting (section 5).

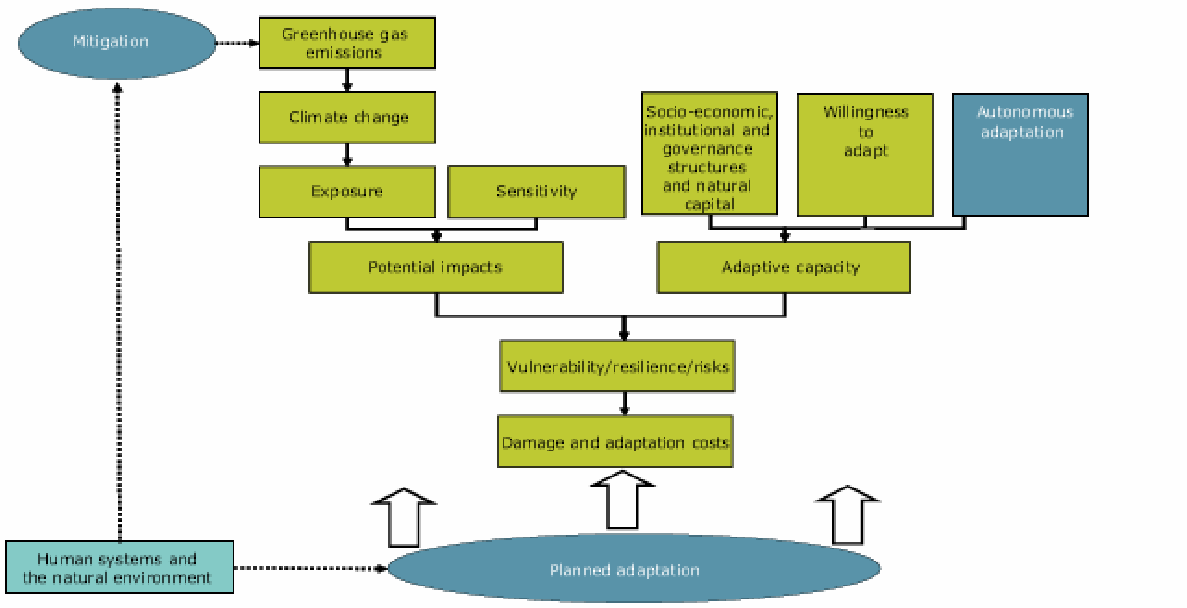
2. Coastal vulnerability to sea-level rise

2.1. What is vulnerability to climate change and how can we assess it?

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).

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, B *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, 2010). The most challenging aspect of the vulnerability definition provided by the IPCC is the concept of adaptive capacity. This is because to make adjustments or changes to current action (adaptation) many social, political, economic, technological and other factors need to be considered (Figure 2.1).

Figure 2.1. Conceptual framework for climate change impacts, vulnerability, disaster risks and adaptation options (EEA, 2010b)



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

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.

It is important to understand policy needs and processes and at which scale (EU, national, local) these are relevant, to select the most appropriate vulnerability assessment method. Adaptation is now recognised as a necessary strategy to complement ongoing climate change mitigation efforts. The White Paper on Climate Change Adaptation (European Commission, 2009) recognises the need to mainstream climate change adaptation in key EU policy areas. The Commission is preparing for an EU wide strategy on climate change adaptation by 2013. Other EU policies and instruments relevant for coastal areas include Integrated Maritime Policy (and action plan), Marine Framework Directive, Maritime Spatial Planning, Marine Knowledge, Integrated Coastal Zone Management (ICZM) (including the Protocol on Integrated Management of Coastal Areas for the Mediterranean), Floods Directive, and Strategic Environmental impact Assessment (SEA) and Environmental Impact Assessment (EIA). At the national level a number of EU Member States have published national adaptation strategies.

2.2. Vulnerability at Europe's Coasts

Coastal wetlands, including salt marshes or other marshes subject to tidal flooding and normal wind tides, provide breeding grounds and habitats for many marine organisms as well as for waterfowl, shorebirds, and other wildlife. They also protect against flooding and help maintain water quality. Furthermore, these coastal environments are important economically, generating employment in the tourism and commercial fishery industries. Coastal wetlands already experience non-climate change pressures from residential and commercial development, agricultural and urban run-off, shoreline modification, municipal waste disposal, oil spills, and over-harvesting of resources (Wetlands International Organization, 1993).

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. 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.

Increases in sea-level are projected to increase intensity and frequency of storm surges and coastal flooding, and to increase salinity intrusion in European rivers, bays and coastal aquifers. In general terms, without adaptation, a rise in sea-level will inundate and displace wetlands and lowlands, erode shorelines, exacerbate coastal storm flooding, and impact water quality.

The uncertainty of climate projections and vulnerabilities require novel adaptation measures and policy approaches. There are already examples, among them robust adaptation planning with the so called adaptation tipping points, adopted for the Thames Estuary in UK (which includes designing and implementing decisions in a flexible way, and which can change if new knowledge becomes available). Another example is the 'building with nature' approach in the Netherlands, that moves away from "hard" engineered coastal protection to "soft" ones as beach nourishment and growth.

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 socio-economic conditions and coastal environmental dynamics is a prerequisite that will lead to more sustainable management of the coastal zone.

Coastal vulnerability differs very much across Europe because of differences in e.g. coastal morphology, existing coastal protection measures and socio-economic and cultural aspects.

2.3. Relative sea-level rise

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 a 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.

2.4. Global mean sea-level rise

Eustatic rise of global sea-level cannot be measured directly, due to a high spatial variability (Pugh, 2004). There are three major types of eustasy; geoidal eustasy, climate eustasy, and tectonic eustasy. In this paper we will only consider the one related to climate change because it is the only one relevant for the time-scales considered in this context. 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.

According to the IPCC, thermal expansion has been the main contributor to observed sea-level change in the 20th century (IPCC 2001, 2007a). It is quite a complex process, related to the physical properties of water which has its maximum density at 4ºC. Increasing seawater temperatures over 4ºC results in a decrease of the density of seawaters. Due to this non-linear behaviour, the heating of the oceans leads to regional differences, because water will expand more in the tropics than in colder oceans. It is not easy to measure this driver of sea-level rise due to the existence of very few long-term ocean temperature series.

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.

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).

In the past, the main cause of sea-level fluctuations during the Quaternary period has been the melting of glaciers, small ice caps and the ice sheets of Antarctica and Greenland (Lowe, 1997).

In the middle of the last 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 sea-level 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.

2.5. Local sea-level change

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 areas.

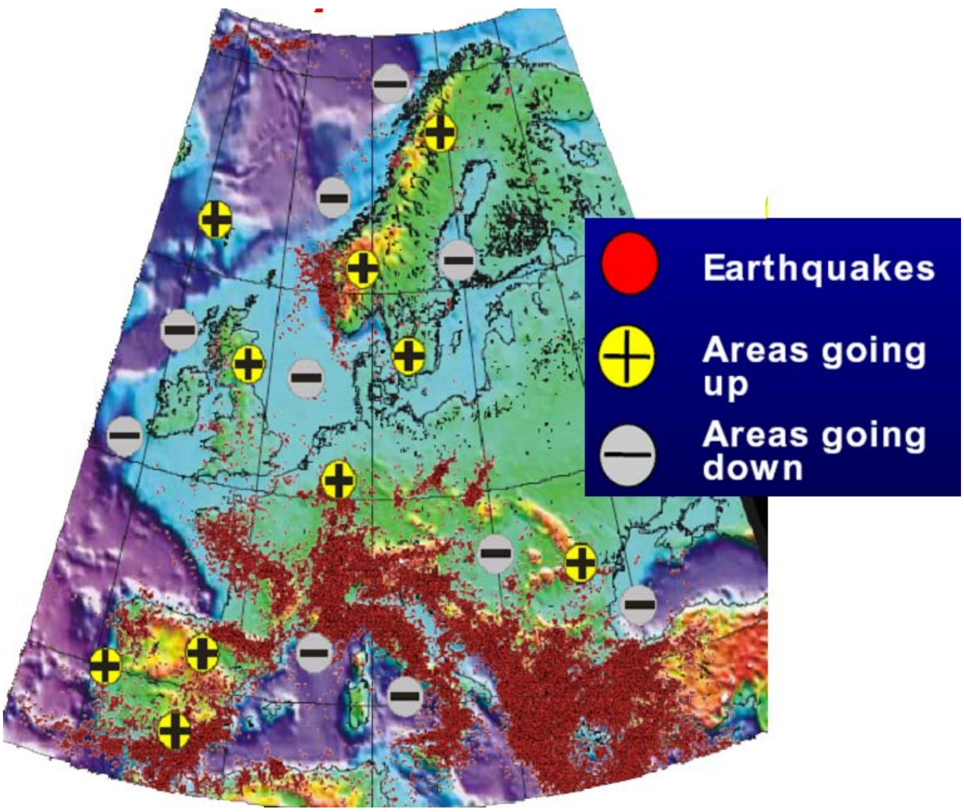
It is important to mention that the measurements taken from remote sensors have shown a high spatial variability in the local sea-level rise, ranging from slight negative trends to positive trend exceeding 10 mm / year in some areas (CSIRO, 2010). Due to the characteristics of this type of sensor, these measures are not relative, so they can be understood as absolute trends.

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 y 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 y García, 2003, Pugh 2004).

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 2.2).

Figure 2.2. Lowland in Coastal Countries



Source: Topo-Europe – PICASSO Workshop

However, it is usually very difficult to identify the limits of the uplifting or subsidence zones in a coastal area, and even more difficult to quantify them. Only studies made by GPS measurements have proved to be an accurate source of information (Rutigliano *et al.*, 2000).

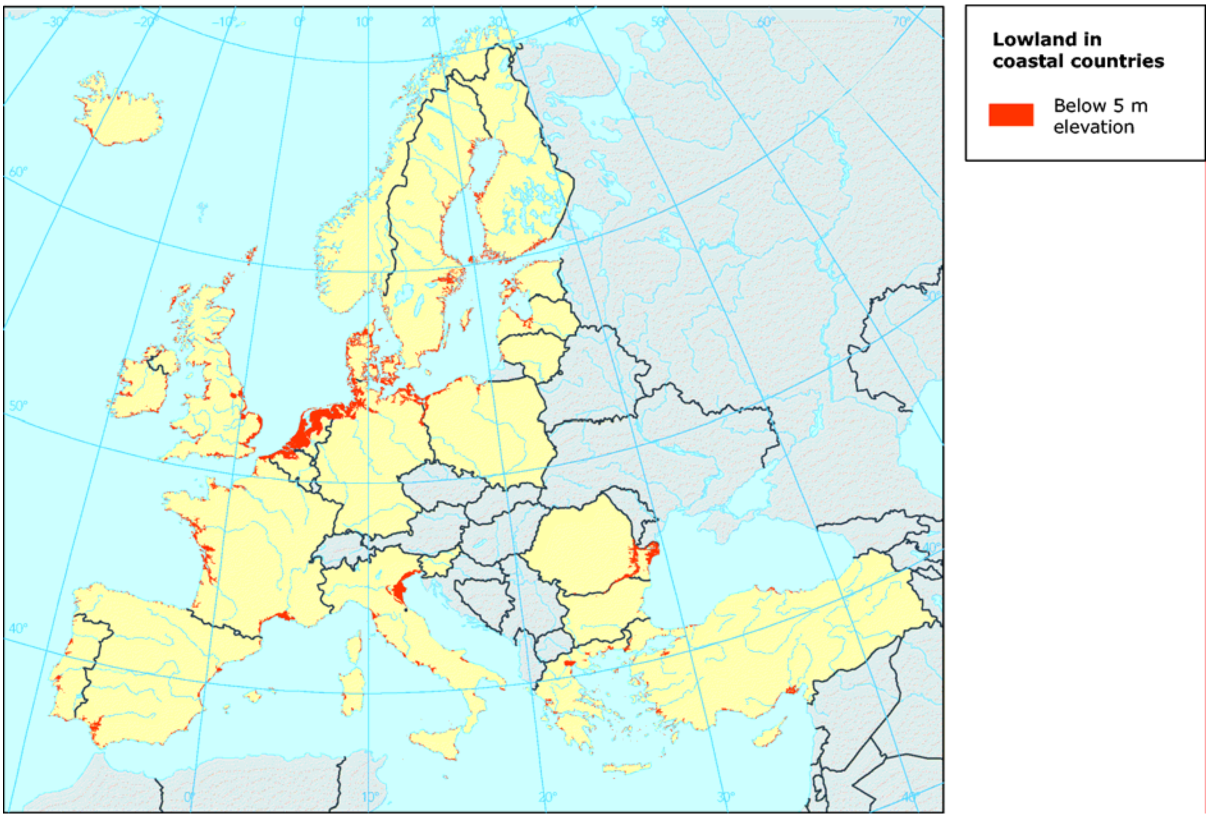
In Europe, the projected regional mean sea level rise can be up to 50% higher than the global due to regional influences, including the enhanced melting of the Greenland ice. Other climatic phenomena, such as the sea surface temperature coupled ocean-atmosphere phenomenon El Niño and La Niña, also are 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 2.3).

Figure 2.3. 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 sea-level 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) for Europe is the **SRTM90**. 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 3 arc second (approximately a 90m resolution). A 1 arc second data product was also produced, but is not available for all countries. The vertical error of the SRTM90 is reported to be less than 16m. The data currently being distributed by NASA/USGS (the finished product) contains "no-data" holes where water or heavy shadow prevented the quantification of elevation. These are generally small holes, which nevertheless render the data less useful, especially in fields of hydrological modelling. The SRTM 90m DEM has a resolution of 90m at the equator, and is provided in mosaiced 5 degrees x 5 degrees tiles for easy download and use. All data is produced from a seamless dataset to allow easy mosaicing. The data is available in both ArcInfo ASCII and GeoTiff format to facilitate its ease of use in image processing and GIS applications.

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 Syro-African depression and some areas from the Netherlands, all under sea-level were corrected. The DEM was hillshaded using ArcMap and Spatial Analyst using following parameters: Azimuth: 315, Altitude: 45, Model shadows: Yes, Z factor: 10, Cell size (accuracy): 1000 m.

The **ETOPO5** global relief model was generated from a digital data base of land and sea-floor elevations on a 5-minute latitude/longitude grid. The resolution of the gridded data varies from true 5-minute grid for the ocean floors for the USA, Europe, Japan, and Australia to 1 degree in data-deficient parts of Asia, South America, northern Canada, and Africa. The original data from different Oceanographic Institutes around the world were assembled in 1988 into the worldwide 5-minute grid by Washington University.

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.

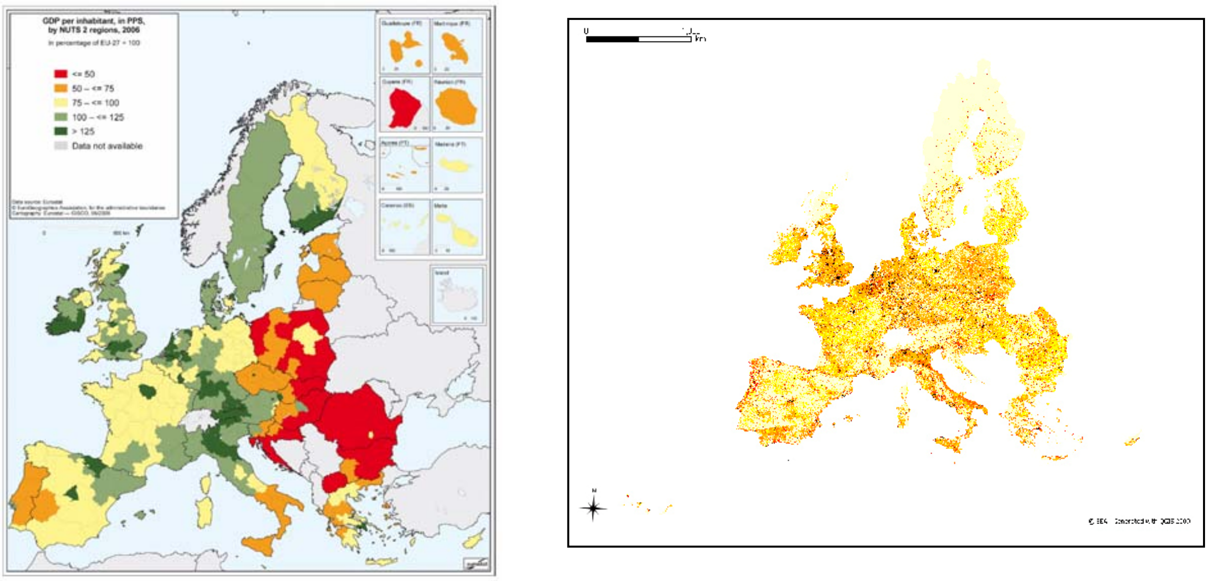
With regards to relevant **socio-economic data,** demographic tables were compiled from data provided directly by the national statistical offices to Eurostat, especially total population living in coastal regions, population type classes and population projections. The data are collected each year through 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.

For the calculation of the Gross Domestic Product in Europe, Eurostat has different statistics related to general indexes and GDP linked with other parameters at national level, which can be accessed via the official Eurostat website.

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 3.1). 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 km2. Each pixel has a size of 100 m x 100 m including the data in integer values (Gallego, FJ, 2010).

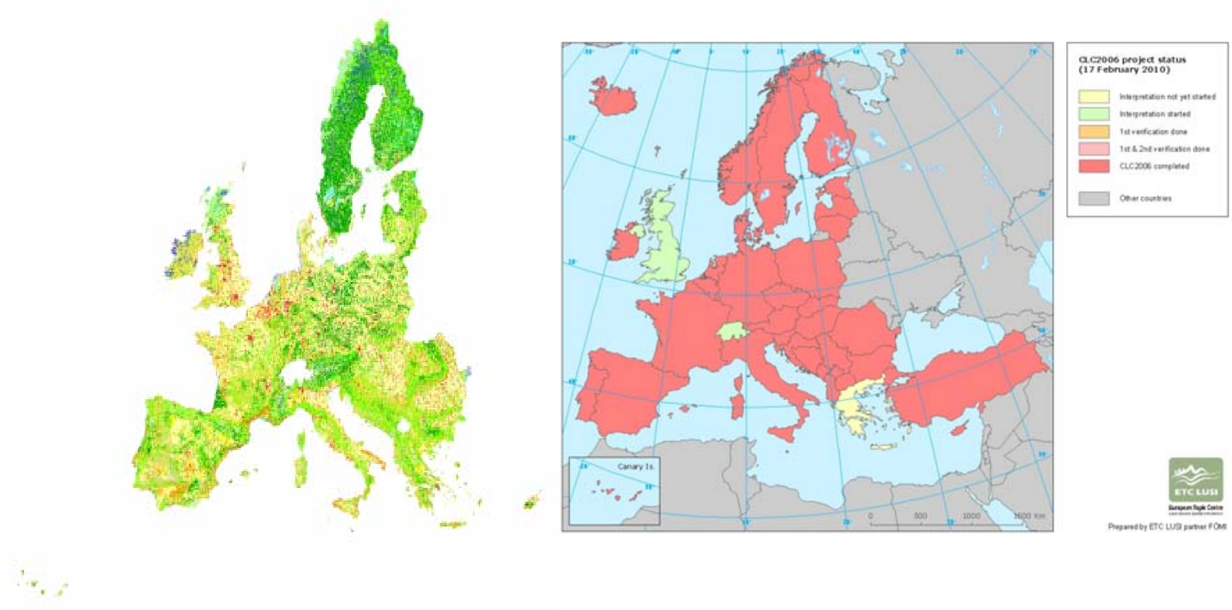
Figure 3.1. GDP Indexes and Population Density GRID disaggregated with Corine



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 3.2). The standard CLC nomenclature includes 44 land cover classes. These are grouped in a three-level hierarchy. The five first-level categories are: 1) artificial surfaces, 2) agricultural areas, 3) forests and semi-natural areas, 4) wetlands, and 5) water bodies. All national teams responsible for developing Corine Land Cover adopted this standard nomenclature. Although the 44 categories have not changed since the implementation of the first CLC inventory (1986–1998), the definitions of most of the nomenclature elements have been improved.

Figure 3.2. Corine Land Cover 2000 and Corine Land Cover 2006 Implementation



Source: EEA – ETCLUSI, 2010

3.2. Climate change vulnerability indicators

The purpose of this background paper is to identify methods on coastal vulnerability, to improve the understanding of the dynamics of the coastal systems, to identify hotspots and to raise awareness of the problem causing vulnerability in the coastal areas. 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.

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, 2010).

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. In addressing these limitations, the modified framework (Driving Force-State-

Response model) incorporating social, economic, institutional and natural system pressures into the PSR model was developed by the United Nations Commission on Sustainable Development (UNCSD).

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.

During 2010, the ETC/ACC and the German Environmental Agency have led a study on vulnerability indicators affecting city areas in Europe, with special attention to the coastal cities. Three examples on coastal indicators and indexes have been integrated in this chapter.

Components influencing the vulnerability of urban coastal areas to storm surge-driven flooding[1]	
Source:	Harvey *et al.*, 2009
Maps:	No
Purpose (thematic, policy):	Demonstration of the vulnerability of coastal areas across Europe to the impacts of rising sea levels and in particular storm surge events for raising awareness of the potential increase in flooding events based on current levels of protection.
Audience, political level:	Depends on specific purpose
Scale (spatial, temporal):	Spatial: European to city level Temporal: mainly past data, except sea level rise and people flooded (2080, A2)
Components:	Exposure: 1. Sea level rise projection (mm/yr) 2. Storm surge: change in height of 50 year return extreme water level event
	Sensitivity: 3. Current and projected number of people flooded across Europe's coastal areas (thousand/year) 4. Current population density 5. Elevation and slope 6. Coverage of sea defences in Europe
	Adaptive Capacity: 7. Gross domestic product in Euros/inhabitant 8. Education level: ISCED6 Second stage of tertiary education leading to an advanced research qualification - level 6 (ISCED 1997)
Data availability	1. EEA (in progress: NW Europe, 100 km spaced points, ?, annual increases)

[1] This is not an actual indicator – in other words only developed to demonstrate a process rather than to be used for policy. However, the data sources are relevant.

Components influencing the vulnerability of urban coastal areas to storm surge-driven flooding[1]	
(spatial extent, resolution, past time series, future projections)	2. Lowe and Gregory, 2005 (unknown) 3. JRC (in progress: unknown, unknown, 1961-1990, 2080 (A2)) 4. Eurographics (EU27, NUTS3, unknown, unknown) 5. USGS (EU27, 0.0833 DECIMAL DEGREES, unknown, unknown) 6. EEA (unknown) 7. Eurostat (EU 27, NUTS2, 2002-2006, no future projections) 8. Eurostat (EU 27, NUTS2 and 1, 2004-2006, no future projections)
Methods (scaling, standardization, combination):	Not suggested
Interpretation Clear purpose: Reproducibility: Simplicity: Data reliability: Knowledge based:	 Yes, but not the audience No, no aggregation method is given No, no aggregation method is given Unknown Yes
Limits:	No aggregation methodology, only data availability to form an indicator was analysed.

Indicators for coastal vulnerability assessment at the regional scale	
Source:	Torresan *et al.*, 2008
Maps:	Yes, Veneto area maps for different components
Purpose (thematic, policy):	Set of coastal vulnerability indicators at the regional scale to understand and manage the complexities of a specific study area, to cope with a range of climate-change related issues in the medium and long term.
Audience, political level:	Decision makers at the local and regional scale
Scale (spatial, temporal):	Spatial: regional scale Temporal: past data
Components:	Exposure: none
	Sensitivity: 1. Administrative units 2. Location of Primary Italian rivers 3. Geomorphological characteristics/coastal typologies (open coast sandy shores, open muddy shores, open clayey-gravel shores, open slump-prone shores, sandy barriers and spits, open/exposed hard-rock cliffed shores) 4. Wetland migratory potential WMP (morphological response of coastal landforms and ecosystems to seal-level rise) 5. Coastal population density
	Adaptive capacity: none
Data availability (European, Cities)	Topograhic, geomorphological and geological maps and data sets of Italian authorities, and Image and Corine land Cover dataset (2000), Italian census data
Methods (scaling, standardization, combination):	The coastline was classified in reasonably homogeneous segments (such as in the DIVA approach) characterized by the same attributes for each components in each unit. The procedure was map intersection and overlay using GIS.
Interpretation Clear purpose: Reproducibility: Simplicity: Data reliability: Knowledge based:	 No Yes The GIS procedure is rather simple, but the data provision difficult High Based on the DIVA approach, but simplified due to data constrains
Limits:	The results of the procedure are “spatial homogeneous sensitivity units”, which do not

Indicators for coastal vulnerability assessment at the regional scale	
	allow a comparative assessment of the different units. Exposure and adaptive capacity components are not considered.

Coastal sensitivity index (CSI)	
Source:	Abuodha & Woodroffe 2010
Maps:	Yes, for the Illawarra coast (Australia): maps of specific components and the indices
Purpose (thematic, policy):	A coastal sensitivity index to characterise susceptibility was assessed.
Audience, political level:	Unknown
Scale (spatial, temporal):	Spatial: 155 km coastline, with raster cells of 1.5 km by 1.5 km Temporal: Past data on exposure components, current data for sensitivity components
Components:	Exposure 1. Relative sea level rise 2. Mean wave height 3. Mean tidal range
	Sensitivity: 4. Rock type 5. Coastal slope 6. Geomorphology 7. Barrier type 8. Shoreline exposure 9. Shoreline change (historical trend of shoreline movement)
	Adaptive Capacity: none
Data availability (European, Cities)	Tide gauge records for exposure data, Orthorectified aerial photography, GPS data, fieldwork for sensitivity data,
Methods (scaling, standardization, combination):	The variables were classified and semi-qualitatively ranked in 5 groups according to their assumed sensitivity (very low to very high). An index is derived by determining the square root of the products of the ranked variables divided by the total number of variables. The variables were not weighted. Four indices were calculated with different combinations of variables.
Interpretation Clear purpose: Reproducibility: Simplicity: Data reliability: Knowledge based:	 No Yes Yes, except data provision Unknown Yes, mainly conventional variables used based on literature review, ranking based on expert knowledge
Limits:	No relation to urban areas, only physical sensitivity components are included. The ranking enables a comparison of different regions. The reasons for the ranking were discussed

3.2.1. The Coastal Vulnerability Index

Due to the difficulties in collecting detailed data at local and regional scale, an index which integrates different datasets that are already available at European scale with high resolution, might be useful.

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).

For a better understanding of the results, it is essential to emphasize that the CVI is a relative index on vulnerability to potential sea-level changes. (Ojeda-Zújar, J *et al.*, 2009).

The CVI integrates quantitative variables through a relatively easy application.

- Geology/Geomorphology variables: These variables are considered depending on the erosion resistance (geomorphology), the tendencies of long term changes in the coastline (erosion taxes) and the sensitivity to processes of marine inundations (coastal slope).
- Physical/Hydrodynamic variables: The three additional variables contribute to erosion processes and inundation in the coastal zones. The swell average level, the relative sea-level change taxes and the average tidal range.

The Coastal Vulnerability Index (CVI) (Ojeda-Zújar, J *et al.*, 2009) integrates six variables as follows.

$$\sqrt[2]{\frac{a \cdot b \cdot c \cdot d \cdot e \cdot f}{6}}$$

Notes: a) geology resistance, b) erosion tax, c) coastal slope, d) average swell, e) relative sea-level change tax, f) average tidal range

The CVI is divided into four different classes using three percentages as a limit (25%, 50% and 75%). The use of these percentages is a way to organise the vulnerability values, in this way it is possible to identify the different coastal stretches taking into account its relative vulnerability. This result should not be associated to specific changes in the coastline. For the coast of Andalusia (Spain), the CVI provides values in between 2, 23 and 35, 35 (Figure 3.2, Table 3.1) (Ojeda-Zújar, J *et al.*, 2009).

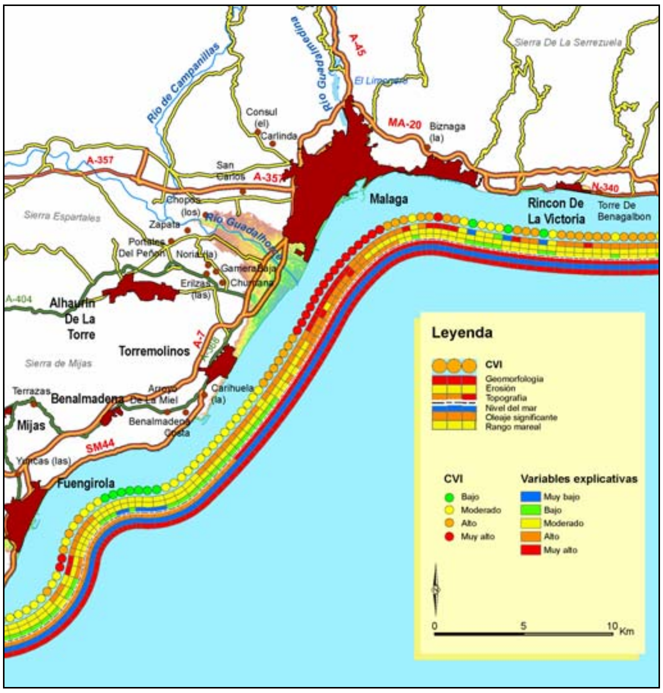
Table 3.1 CVI classification ranges

Variables	Low	Medium	High	Very high
Classified vulnerability	1	2	3	4
CVI Value	(2.23, 6,32)	(6.32, 10.00)	(10.00, 14.14)	(14.14, 35.35)

Source: Ojeda-Zújar, J *et al.*, (2009)

In the case study of Andalusia (Spain), the variables are geomorphology, erosion potential, topography, sea level, wave systems and tidal range. Each variable is classified by a risk level (very low, low, moderate, high and very high), resulting in the CVI as low, moderate, high and very high. The final result can be associated with coastal cities, deltas and low coastal plains (Figure 3.2)

Figure 3.2 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).

In previous and related studies (Gornitz, 1990; Shaw *et al.*, 1998), large tidal range (macrotidal; tide range > 4m) coastlines were assigned a high risk classification, and microtidal coasts (tide range <2.0 m) received a low risk rating. This approach was based on the concept that large tide range is associated with strong tidal currents that influence coastal behaviour. Junta de Andalucía has chosen to invert this ranking such that a macrotidal coastline is at a low risk in Spain. Their reasoning is based primarily on the potential influence of storms on coastal evolution, and their impact relative to the tide range. For example, on a tidal coastline, there is only a 50 percent chance of a storm occurring at high tide. Thus, for a region with a 4 m tide range, a storm having a 3 m surge height is still up to 1 m below the elevation of high tide for half a tidal cycle. A microtidal coastline, on the other hand, is essentially always "near" high tide and therefore always at the greatest risk of inundation from storms.

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 waves situations (National Meteorological Institutes) are available.

3.3. 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 models discussed in this background paper have been selected by EU experts and the EEA. 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. 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).

There are three main advantages of using inundation models. 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).

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)

"Wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres. They may incorporate riparian and coastal zones adjacent to the wetlands, and islands for bodies of marine water deeper than six metres at low tide lying within the wetlands" (RAMSAR, 1971).

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 *et al.*, 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.

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:** The aim is to analyse the sea-level rise (based on the minimum elevation and slope by cell) being the Mean Tide Level constant.
- **Horizontal Erosion:** The estimation or rate is based on a threshold of maximum fetch and specific parameters for each site (i.e. proximity of the marsh to estuarine water or open ocean)
- **Overwash:** It is the flow of water and sediments over the crest of the beach and deposition into the nearby wetlands (i.e. and not coming back to the water bodies). SLAMM only assesses barrier islands below 500 meters where the beach migration and sediments movement are computed.
- **Saturation:** Being the water table level at which the ground water is equal to atmospheric pressure; coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the water table to rising sea-level close to the coast.
- **Accretion:** This process fosters sea-level rise by sedimentation.

Wetlands, as one of the most relevant ecosystems for coastal vulnerability (Maltby, 1991; Kracauer *et al.*, 1997; Winter *et al.*, 2000; EPA, 2009; Mitsch, 2009), 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).

SLAMM can provide useful information besides its disadvantages from local to global level with a medium cost of the service and the expertise.

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. 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). For validation, the model was adjusted to the USFWS habitat map 1956. Results from the model, 32 year simulations with the data parameters of 1978 - 1988, were compared against USFWS habitat map 1988 revealing accuracy above 75%. Thus, the results of the model are reasonable at regional scale although small-scale processes were not included such as plant and soil process at less than 1 km2 or hydrologic process at less than 100 km2 (Reyes et al., 2000).

In a second step, after calibration and validation, 30 year simulations (1988 – 2018) 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 in the scientific community to 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).

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

3.3.3. 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).

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.

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).

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 low-medium. 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

3.3.4. 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 raising dikes and sustaining beaches (Hinkel *et al.*, 2010).

The first version of the DIVA model was developed as a tool for integrated assessment of coastal areas by the EC-funded project DINAS-COAST, Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise, (DINAS-COAST Consortium, 2006; Hinkel and Klein, 2009).

As said by McLeod et al., 2010 and Hinkel, 2010: "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.

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

3.3.5. 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 (FUND, 2010 and Anthoff, 2009a).

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. 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).

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, sea-level 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

3.3.6. 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 three-dimensional 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. The Delft3D flow, morphology and wave modules are available in open source as per 1 January. 2011.

Delft3D offers in combination with other open source products, such as XBeach, SWAN, OpenEarth, OpenDA and OpenMI, and products, such as SOBEK, HABITAT, WFD Explorer, DAMAGE, a powerful modelling suite for integral solutions to climate change.

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 (100-1000 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 (see Table 4.1).

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.

Table 4.1. Summary of the relevant coastal models

Model	Scale and Spatial Resolution	Temporal Resolution	Input	Output	Impact of drivers	Drivers of change	Examples executed & possible applications	Costs of model use
Inundation Model	- Local – Global - Define by the user and the inputs	Defined by the user	DEM, Sea-level Rise, Scenarios, Socioeconomic data	Maps of potential Flooding	Inundation	Relative sea-level rise	- Global and U.S. Coastal Areas - Coastal areas, RBD in Europe and Neighbouring countries	Low
SLAMM	- Local and Regional (Mx. 100.000 km2) - 1 – 100m	Time-steps of 5-25 years can be used based on the sea-level rise scenario	DEM (i.e. SRTM or LIDAR), land cover, human infrastructures	Map of flooding risk potential for ecosystem	Wetlands change (Erosion, Overwash, Saturation, Salinity)	Sea-level Rise	- US Coast, San Francisco Delaware, Galveston Bay -Coastal areas, bays, estuaries, deltas	Low – Medium
BTELSS	-Local and Regional (Mx. 100.000 km2) - 1km2	Variable time-steps (12s to daily), simulation time up to 100yrs	DEM (+Bathymetry), Climatic data, river discharges, sediment loads, land cover among other datasets. Map habitats	Maps of land change, flooded and eroded areas. Including other maps of indexes such as salinity, sediment balances, etc.	Wetland change	Relative sea-level rise, droughts, rivers discharge	-Barataria and Terrebonne basins, Louisiana, Mexican wetlands -River Basin Districts, Coastal and Transitional Waters, Coastal wetlands, Coastal areas, etc.	High
SimCLIM	Local to global	Varies depending on inputs parameters	DEM, Climate data, sea-level changes, scenarios, impact models.	Maps of flooding potential in coastal areas and ecosystems.	Inundation (i.e. erosion)	Relative sea-level rise, climate change	- Micronesia, Cook Islands, South East Australia - Concrete coastal area, cities, RBDs, regions, countries, regional seas, Europe and neighbouring countries.	Low – High (depending on expertise required)
DIVA	- National to global. Coastline segments.	100 years (5 years time/step).	DEM (SRTM), coastal geomorphology, coastal population and GDP, land use and administrative boundaries.	Estimation of population under flood risk, wetland changes, damages and cost, amongst other outputs.	Coastal and river flooding, coastal erosion, wetland change, salinity intrusion into rivers	Global or regional sea-level rise, population growth, GDP growth, land use-change	- Indonesia, Europe, Southeast Asia - Countries, Regional Seas, Europe and neighbouring countries.	Medium (depending on expertise required)
FUND	- Regional to Global - Defined by the user	From 1950 to 2.300 with time-steps of a year	Population and scenarios on emissions, climate, sea-level and other impacts.	Rates and statistics for decision making	Wetland loss, dry land loss, water impact	Climate Change (and scenarios), Global Warming	Europe	Medium
DELFT3D MODELLING SUITE	- From local to global -Defined by the user	From 1000 to 1000 years	Bathymetry (depth values for all grid points), grid, DTM, roughness, vegetation, wind, pressure, time series (current, water level, etc.)	Maps, graphs and tables regarding water levels, including ground water, water depths, velocities, currents, sediments, etc	Coastal and river flooding, drought, coastal erosion, environmental change, etc.	Wind, waves, storm surges, tsunami, currents, sediments.	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	Medium

Source: Adapted from McLeod *et al.,* 2010

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).

The integration of the terrestrial and marine environment into the coastal zone context requires multiple efforts in order to take into account all the processes that have an impact in this busy zone between the land and the sea.

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. In this sense, the EEA has drafted this background paper on existing methods for assessing and mapping current and future coastal vulnerability to climate change.

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 background 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. Key outcomes of the expert meeting

On 27-28 October an expert meeting was held at EEA (Copenhagen) on ‘Coastal vulnerability assessment methods’. About 25 experts attended from seven countries (Denmark, Germany, Ireland, Italy, Netherlands, Spain, and United Kingdom) and from the European Commission (DG MARE, JRC-IES), EEA, ETC ACC and ETC LUSI.

The objectives of this expert meeting were to consider coastal vulnerability mapping from the perspective of observational evidence and future projections (e.g. key factors of coastal vulnerability and related indicators). Vulnerability of ecosystems as well as socio-economic systems (e.g. infrastructure) was considered. The meeting discussed available EU level and more detailed national/regional/local models, their methodological strengths and weaknesses, the spatial/temporal scales in which they operate, and their data input requirements (current availability/gaps), and how the results are presented (e.g. maps, at different scales). The meeting also discussed the usefulness of coastal vulnerability assessments at the European level for improving coastal management strategies that address climate change and socio-economic pressures. Finally also the content and planning of a forthcoming EEA coastal assessment report was discussed.

The European Commission (DG MARE) was invited to make a presentation on the policy perspectives of DG MARE on climate change adaptation, as well as on the EU policy developments and future requirements. In order to guide future activities and scientific researches DG MARE mentioned the following policy needs and requirements:

- On knowledge base:
    - Strengthening efforts for producing data, indicators and maps on socio-economic impacts of climate change in coastal areas and the sea, including impacts on maritime sectors.
    - Reducing uncertainties on the impacts of climate change at regional and local level.
    - Producing a stocktaking of the existing databases and observation programmes on climate change risks, vulnerabilities and impacts will be useful. What does already exist and how can this knowledge be used.
- On projections and assessments:
    - Working towards more realistic socio-economic scenarios which also include adaptation measures and producing data at more detailed scales.
    - Using cost-benefit analysis on climate change adaptation measures.
    - Integrating information on the economic value of ecosystems providing goods and services in the models for assessing the vulnerability of the coast to climate change. Towards ecosystem-based adaptation strategies to increase resilience of ecosystems and communities.
- On Governance: better coherence between science and policy:
    - Improving current models to assess the vulnerability to climate change of the coast and the policy requirements and priorities.
    - Strengthening feed back and flows of information between researchers and policymakers.
    - Reaching coherence with/between on-going research projects (EU funds).
    - Foster synergies between data produced by research projects and current and future initiatives on data sharing and making data easily available and public such

as the EU adaptation clearinghouse mechanism, EEA products/services, EMODNET, etc

The meeting agreed on the following conclusions.

General:

- (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
- More transparency is needed across risk-hazard assessments and climate change assessments on concepts and definitions
- Some existing EC directives (Water Framework; Floods) already have guidance on how to integrate adaptation into the directive (and vulnerability) assessments (e.g. flood risk maps)
- Relevant EU policies and instruments include the White Paper on Climate Change Adaptation, Integrated Maritime Policy (and action plan), Marine Framework Directive, Maritime Spatial Planning, Marine Knowledge, Integrated Coastal Zone Management (ICZM) (including the Protocol on Integrated Management of Coastal Areas for the Mediterranean), Floods Directive, Strategic Environmental impact Assessment (SEA) and Environmental Impact Assessment (EIA) but also sectoral policies (e.g. energy, transport)
- 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
- Model-based decision-support tools are being used for policy support
- Experience exists 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.
- Coastal assessment requires a transdisciplinary approach
- There is a need for analysis of adaptation policy measures (e.g., cost-benefit analysis) but this analysis requires different information than vulnerability assessments
- Estimates of economic costs of climate change vary by at least one order of magnitude depending on assumptions
- Coarse-scale coastal vulnerability maps and indices have yet to be applied to assess policy effectiveness / efficiency

Conclusions regarding data:

- 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

- The coastal vulnerability index (CVI) has been calculated (with some modifications) to assess the biophysical vulnerability of coastal zones in different regions
- The CVI has been applied to identify regions where further studies are needed, confirming prior expert knowledge
- Other indicators have been used to address different policy purposes, which have different data needs

Conclusions regarding the planned 2012 EEA coastal assessment report:
The outline was generally accepted (Introduction – setting the scene; Trends in state of coastal zones; Living by the sea: pressures and impacts; Current trends in policy responses; Building the conceptual framework for the coast). Proposals to include more on the following aspects: Spatial planning, Insurance aspects, Examples of flexible approaches over long-term time line, Link to National Adaption Strategies

6. References

Abuodha, P.A.O. and Woodroffe, C.D. 2010. Assessing vulnerability to sea-level rise using a coastal sensitivity index: a case study from southeast Australia. Journal *of Coastal Conservation*, pp. 1-17

Allison, I.; Bindoff, N.L.; Bindschadler, R.A.; Cox, P.M.; de Noblet, N.; England, M.H.; Francis, J.E.; Gruber, N.; Haywood, A.M.; Karoly, D.J.; Kaser, G.; Le Quéré, C.; Lenton, T.M.; Mann, M.E.; McNeil, B.I.; Pitman, A.J.; Rahmstorf, S.; Rignot, E.; Schellnhuber, H.J.; Schneider, S.H.; Sherwood, S.C.; Somerville, R.C.J.; Steffen, K.; Steig, E.J.; Visbeck, M.; Weaver, A.J., 2009. *The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science*. The University of New South Wales Climate Change Research Centre (CCRC), Sydney.

Anthoff, D., Tol, R.S.J., Yohe, G.W., 2009a. *Discounting for climate change*. Economic and Social Research Institute. ESRI Working Paper No. 276.

Anthoff, D., Hepburn C., Tol, R. S. J. 2009b. Equity weighting and the marginal damage costs of climate change. *Ecological Economics*, 68 (3), 836 – 849.

Anthoff, D., Tol, R.S.J., Yohe, G.W. 2009c. Risk aversion, time preference, and the social cost of carbon. *Environmental Research Letters*, 4 (2), 024002.

Bates, P.D., Dawson, R., Hall, J., Horritt, M., Nicholls, R., Wicks, J., Mohamed-Hassan, M. 2005. Simplified two-dimensional numerical modelling of coastal flooding and example applications. *Coastal engineering*, 52 (9), 793 - 810.

Bates, P.D., De Roo, A.P.J. 2000. A simple raster-based model for flood inundation simulation. *Journal of Hydrology*, 236 (1-2), 54 - 77

Bowen, R.E, and Riley, C. 2003. Socio-economic indicators and integrated coastal zone management. *Ocean and Coastal Management*, 46: 299-312.

Cooper, J.A.G., McLaughlin, S. 1998. Contemporary multidisciplinary approaches to coastal classification and environmental risk analysis. *Journal of Coastal Research*, 14 (2), 512 - 524.

Cowell, P.J., Thom, B.G., Jones, R.A., Everts, C.H., Simanovic, D. 2006. Management of Uncertainty in Predicting Climate-Change Impacts on Beaches. *Journal of Coastal Research* 22 (1), 232 - 245.

CSIRO, 2010. *Historical Sea-level* Changes, available at: http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html [10th September 2010]

DINA-COAST Consortium, 2006. *DIVA 1.5.5.* Postdam Institute for Climate Impact Research, Postdam, Germany.

Downing, T., Patwardhan, A., Klein R., Mukhala, E., Stephen, L., Winograd, M., Ziervogel, G. 2005. Assessing Vulnerability for Climate Adaptation. Adaptation Policy Framework Report, Chapter 3. In: Lim, B.; *Spanger-Siegfried,E*. (eds). Adaptation Policy Framework for

Climate Adaptation: Developing Strategies, Policies and Measures. UNDP, Cambridge University Press, Cambridge, UK, pp 61 -90.

EEA, 2006. *The changing faces of Europe's coastal areas*, EEA report no. 6/2006, European Environment Agency, Copenhagen.

EEA, 2010a. 2010 *State of the Environment and Outlook Report – Thematic assessment: Understanding Climate Change*, European Environment Agency, Copenhagen.

EEA, 2010b. 2010 *State of the Environment and Outlook Report – Thematic assessment: Adapting to climate change*, European Environment Agency, Copenhagen.

EPA, 2009. Environmental Protection Agency of the United States. *Wetlands.* http://water.epa.gov/type/wetlands/index.cfm [10th September 2010]

Eurosion, 2004. Living with *coastal erosion in Europe: Sediment and Space for Sustainability. Coastal erosion-Evaluation of the need for action.* DG-Environment. European Commission.

FUND, 2010. *Climate Framework for Uncertainty, Negotiation and Distribution (FUND).* http://www.mi.uni-hamburg.de/FUND.5679.0.html [13th September 2010]

Füssel, H.M. and Klein R. 2006. Climate Change Vulnerability Assessments: An Evolution Of Conceptual Thinking. *Climatic Change*, 75: 301–329.

Galbraith, L., Jones, R., Park, R., Clough, J., Herrod-Julius S., Harrington B., Page G. 2002. Global Climate Change and Sea-level Rise: Potential Losses of Intertidal Habitat for Shorebirds. *Waterbirds,* 25 (2), 173 - 183.

Gallego F.J. 2010. A population density grid of the European Union, *Population and Environment,* 31 (6), 460 – 473.

German Advisory Council on Global Change, 2006. *The Future Oceans – Warming Up, Rising High, Turning Sour*. [Schubert R., Schellnhuber H.J., Buchmann N., Epiney A., Greießhammer R., Kulessa M., Messner D., Rahmstorf S., Schmid J.] WBGU, Berlin.

Gornitz, V., White T.W., Cushman R.M. 1991. Vulnerability of the U.S. to future sea-level rise. In *Proceedings of Seventh Symposium on Coastal and Ocean Management*. Long Beach, CA (USA), 1991, pp 2354 – 2368.

Gornitz, V., Daniels, R.C., White, T.W., Birdwell, K.R. 1993. *The development of a coastal risk assessment database: vulnerability to sea-level rise in the U.S. Southeast*. U.S. Government Report, Oak Ridge National Laboratory Tennessee. DE-AC05-84OR21400.

Harvey, A. , J. Hinkel, L. Horrocks, R. Klein, R. Lasage, N. Hodgson, T. Sajwaj and M. Benzie (2009). *Preliminary assessment and roadmap for the elaboration of Climate Change Vulnerability Indicators at regional level*. Not published yet, but available at DG ENV. Reference: ENV.G.1/ETU/2008/0092r. Final Report to the European Commission.

Hinkel, J. and Klein, R.J.T. 2009. The DINAS-COAST project: developing a tool for the dynamic and interactive assessment of coastal vulnerability. *Global Environmental Change*, 19 (3), 384 - 395.

Hinkel, J., 2010. Measuring vulnerability and adaptive capacity: Towards a clarification of the science policy interface. *Global Environmental Change*, in press.

Horritt, M.S., Bates P.D. 2001. Effects of spatial resolution on a raster based model of flood flow. *Journal of Hydrology*, 253 (1-4), 239 - 249.

IPCC, 2001, Summary for Policymakers. In: *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Burkett, V, Condignotto, JO, Forbes, DL, Mimura, N, Beamish, RJ, Ittekkot, V.] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007a, Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller]. Cambridge University Press, Cambridge, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007b. *Climate change 2007: impacts, adaptation and vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Isoard, S., 2010. Perspectives on adaptation to climate change in Europe; in Ford, J.D. and Berrang Ford, L. (eds) *Climate Change Adaptation in developed nations*. Springer.

Junta de Andalucía – Regional Ministry of Environment, 2009. *Coastal Information System of Andalusia – Environmental Information Network of Andalusia, Spain (REDIAM).* www.juntadeandalucia.es/medioambiente/rediam [2nd September 2010]

Kracauer Hartig, E., Grozev, O., Rosenzweig, C. 1997. Climate change, agriculture and wetlands in Eastern Europe: vulnerability, adaptation and policy. *Climatic Change*, 36 (1), 107 - 121.

Levrel, H., Kerbirious, C., Couvet, D., Weber, J. 2008. OECD pressure-state-response indicators for managing realistic perspective for a French biosphere reserve. *Biodiversity and conservation*, Volume 18, Number 7, 1719-1732.

Lowe, J.J. and Walker, M.J. 1997. Reconstructing Quaternary environments, Prentice Hall.

Martin, J.F., Reyes E., Kemp, G.P., Mashriqui, H., Day, J.W. 2002. Landscape Modeling of the Mississippi Delta. *BioScience*, 52 (4), 357 – 365.

Maltby, E., 1991. Wetland management goals: wise use and conservation. *Landscape and Urban Planning*, 20 (4), 9-18.

McLeod, E., Poulter, B., Hinkel, J., Reyes, E., Salm, R., 2010. Sea-level rise impact models and environmental conservation: A review of models and their applications. *Ocean and Coastal Management* – OCMA2738. In Press, Corrected Proof.

Meehl, G.A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., & Zhao, Z.-C. 2007 Global climate projections. In *Climate change 2007: The physical science basis*. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [ed. Solomon, S, Qin, D, Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L.], pp. 433-497. Cambridge University Press, Cambridge, UK.

Mitrovica, J.X. and Mile G.A. 2002. On the origin of Late Holocene highstands within equatorial ocean basins. *Quaternary Science Review*, 21, 2179-2190

Mitsch, W.J., Gosselink, J.G., Zhang, L. & Anderson, C.J. 2009. *Wetland ecosystems*. John Wiley and Sons

Narita, D., Tol, R.S.J., Anthoff, D. 2009. Damage costs of climate change through intensification of tropical cyclone activities: an application of FUND. *Climate Research*, 39 (2), 87 – 97.

Narita, D., Tol, R.S.J., Anthoff, D. 2010. Economic costs of extratropical storms under climate change: an application of FUND. *Journal of Environmental Planning and Management*, 53 (3), 371 – 384.

Nicholls, R., Wong, P., Burkett, V., Codignotto, J., Hay, J., McLean, R., Ragoonaden, S., Woodroffe, C. 2007. Coastal systems and low-lying areas. [In: Parry, M., O. Canziani, J. Palutikof, P. van der Linden and C. Hanson (eds.)], *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 315 – 356.

Nicholls, R.J., Tol, R.S.J., Vafeidis, A.T. 2009. Global estimates of the impact of a collapse of the West Antarctic ice sheet: an application of FUND. *Climatic Change* 91 (1-2), 171 - 191

NOAA, 2010. http://www.csc.noaa.gov/digitalcoast/inundation/glossary.html [25th August 2010)]

Ojeda-Zújar, J, Álvarez-Francosi, JI, Martín-Cajaraville, D, Fraile-Jurado, P. 2009. El uso de las TIG para el cálculo del índice de Vulnerabilidad costera (CVI) ante una potencial subida del nivel del mar en la costa andaluza (España). *GeoFocus*, 9, p-83-100. ISSN – 1578-5157.

Park,R.A., Clough J.S., Jones, R., Galbraith, H. 2003. Modeling the Impacts of Sea-level Rise. *NOAA Proceedings of the XIII Biennial Coastal Zone Conference*. Baltimore, USA, July 2003.

Park, R. A., Trehan, M.S., Mausel, P.W., Howe, R.C. 1989. *The Effects of Sea-level Rise on U.S. Coastal Wetlands and Lowlands.* Holcomb Research Institute, Butler University, Indianapolis, Indiana. pp. 48 + 789.

Priestnall, G., Jaafar, J., Duncan, A. 2000. Extracting urban features from LiDAR digital surface models. *Computers, Environment and Urban Systems*, 24 (2), 65-78.

Pugh, D, 2004. *Changing Sea-levels. Effects of Tides, Weather and Climate*. Cambridge University Press, Cambridge, Cambridge, United Kingdom

Rahmstorf, S. 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. *Science* 315 (5810), 368 – 370

RAMSAR, 1971. Convention on Wetlands of International Importance especially as Waterfowl Habitat. Ramsar (Iran), 2 February 1971. UN Treaty Series No. 14583. As amended by the Paris Protocol, 3 December 1982, and Regina Amendments, 28 May 1987.

Reyes, E., White, M.L., Martin, J.F., Kemp, G.P., Day, J.W., Aravamuthan, V. 2000. Landscape Modeling of Coastal Habitat Change in the Mississippi Delta. *Ecology*, 81 (8), 2331- 2349

Reyes, E., Martin, J.F, White, M.L, Kemp, G.P. 2004. Habitat Changes in the Mississippi Delta: Future Scenarios and Alternatives. In: *Landscape Simulation Modeling* (Modelling Dynamics Systems), Springer New York. pp. 119 – 142

Rutigliano, P, VLBI Network Team, 2000, *Vertical motions in the western Mediterranean area from geodeticand geological data*. X General Assembly of the WEGENER Project (WEGENER 2000). Royal Institute and Observatory of the Army. Ministry of Defence of Spain. Sept. 18-20, 2000.

SLAMM 6.0.1, 2010. *Technical documentation*. http://warrenpinnacle.com/prof/SLAMM6/SLAMM6_Technical_Documentation.pdf [13th September 2010]

Shaw, J., Taylor, R.B., Forbes, D.L., Ruz, M.-H., and Solomon, S. 1998. Sensitivity of the Canadian Coast to Sea-Level Rise, *Geological Survey of Canada Bulletin* 505, 114 p

Scientific Committee on Antarctic Research, 2009. *Antarctic Climate Change and the Environment*. Scott Polar Research Institute, Cambridge.

SimCLIM, 2010. SimClim Online Help. http://simclim.climsystems.com/docs/topic.php?name=contents [13th September 2010]

Smith, B. and Wandel, J. 2006. Adaptation, Adaptive Capacity and Vulnerability. *Global Environmental Change*, 16 (3), 282 – 292

Tel, E, García M.J. 2003. El nivel del mar en las costas españolas y su relación con el clima. *Asociación Española de Climatología*. Serie 3, pp-101-110.

Titus, J.G., Park R.A., Leatherman S.P., Weggel, J.R., Greene, M.S., Mausel, P.W., Brown, S., Gaunt, C., Trehan, M., Yohe, G.W. 1991. Greenhouse Effect and Sea-level Rise: Loss of Land and the Cost of Holding Back the Sea. *Coastal Management*, 19 (2), 171 - 204

Tol, R. 2006a. Exchange rates and climate change: An application of FUND. *Climate Change*, 75 (1-2), 59 - 80.

Tol, R.S.J. 2006b. Multi-Gas Emission Reduction for Climate Change Policy: An Application of FUND. *The Energy Journal*. Multi-Greenhouse Gas Mitigation and Climate Change Policy Special Issue, 235 - 250.

Topo-Europe PICASSO Workshop http://www.topo-europe.eu/

Torresan, S., Critto, A., Dalla Valle, M., Harvey, N., Marcomini, A. 2008. Assessing coastal vulnerability to climate change: Comparing segmentation at global and regional scales. *Sustainability Science* 3 (1), pp. 45-65.

United Nations Economic Commission for Europe. 2003. *Environmental Monitoring and Reporting.* http://www.unece.org/env/europe/monitoring/EnvMonRep/index.html [10th September 2010]

Vaze, J., Teng, J., Spencer, G. *2010.* Impact of DEM accuracy and resolution on topographic indices. *Environmental Modelling and Software.* Volume: 25 Issue: 10 Pages: 1086-1098.

Veermer, M. and Rahmstorf, S. 2009. Global sea-level linked to global temperature. http://www.pnas.org/content/early/2009/12/04/0907765106.full.pdf [10th September 2010]

Warrick, R.A., Ye, W., Kouwenhoven, P., Hay, J.E., Cheatham, C. 2005. New Developments of the SimCLIM Model for Simulating Adaptation to Risks Arising from Climate Variability and Change. *International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand. Melbourne, December 2005, pp. 170 - 176.

Warrick, R.A., Cox, G. 2007. New developments of SimCLIM software tools for risk-based assessments of climate change impacts and adaptation in the water resource sector. *Proceedings of the Third International Conference on Climate and Water*. Helsinki, Finland, September 2007, pp. 551 - 558

Warrick, R.A. 2009. Using SimCLIM for modelling the impacts of climate extremes in a changing climate: a preliminary case study of household water harvesting in Southeast Queensland. *18th World IMACS / MODSIM Congress*. Cairns, Australia, July 2009, pp. 2583 – 2589

Wetlands International Organization, 1993. *Wetlands benefits* http://www.wetlands.org/WatchRead/tabid/56/mod/1570/articleType/ArticleView/articleId/2466/Wetland-benefits.aspx [5th September 2010]

Wetlands International Organization, 2010. www.wetlands.org [4th September 2010]

Winter, T.C. 2000. The vulnerability of wetlands to climate change: a hydrologic landscape perspective. *Journal of the American Water Resources Association*, 36 (2), 305 - 311.

Yanagi, A. 1994. Sea Level Variation in the Eastern Asia. *Journal of Oceanography*. Vol 50, pp 643-651.

Zheng, N., Tachikawa, Y., Takara, K. 2008. A distributed flood inundation model integrating with rainfall-runoff processes using GIS and Remote Sensing Data. *ISPRS Congress*, Beijing, China, July 2008, pp. 1513 – 1518

Web link references

EEA
Population density
http://www.eea.europa.eu/data-and-maps/data/population-density-disaggregated-with-corine-land-cover-2000-1
Corine 1990:
http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-1990-raster
Corine 2000:
http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-raster
Corine 2006:
http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster

Corine seamless vector data is also available for each of these products.

Additionally to the Corine datasets, there are many other products such as the Corine land cover changes 1990-2000 and 2000-2006, including the land and ecosystem accounts.
http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-1990-2000
http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-2006
Specific work done on coastal land cover mapping, extracting the coastal information from the general database applying a coastal buffer of a range in between 1 and 10 kilometres from the shoreline.

EUROSTAT
Data Regional statistics available:
http://epp.eurostat.ec.europa.eu/portal/page/portal/region_cities/regional_statistics/data/main_tables

The degree of urbanisation
http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco/popups/references/Population%20Distribution%20-%20Demography

NOAA
Vulnerability Assessment Techniques and Applications (VATA)
http://www.csc.noaa.gov/vata/case_pdf.html
http://www.csc.noaa.gov/rvat/environ.html

MODELS' Websites:
Slamm
http://www.slammview.org/
Btelss
http://ecobas.org/www-server/rem/mdb/btelss.html
Simclim
http://www.climsystems.com/simclim/
DIVA
http://www.diva-model.net

FUND
http://www.fnu.zmaw.de/fileadmin/fnu-files/models-data/fund/technical.pdf
http://www.fnu.zmaw.de/FUND.5679.0.html
Delft3D
www.deltares.nl/en/software-alg

Further acknowledgements

Jochen Hinkel
Potsdam Institute for Climate Change Impact Research (PIK), Germany

Inke Schauser
Federal Environmental Agency, Germany

Comments were provided by the following experts

Tom Bucx
Deltares, The Netherlands

Natasha Marinova
Wageningen University, The Netherlands

David Prandle
Proudman Oceanographic Laboratory and Bangor University, UK

Authors

Alejandro Iglesias-Campos: ETC LUSI / Junta de Andalucía, Spain
Alejandro Simon-Colina: ETC LUSI / Universitat Autònoma de Barcelona, Spain,
Pablo Fraile-Jurado: Universidad de Sevilla, Spain

Project coordinator

Nikki Hodgson
AEA Technology group