Methods for assessing coastal vulnerability to climate change

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1 Introduction

A significant and increasing share of the EU population lives in coastal areas. Approximately half the EU population lives 50 km or less from the coast (ESTAT, 2009), with 19% of the EU population (86 million people) living within a 10 km coastal strip (EEA, 2006). It is likely that such numbers will increase in the future. Collectively, this is both placing growing demands on coastal resources as well as increasing people's exposure to coastal hazards (Sterr *et al*., 2003).

Coastal areas are dynamic and complex multi-function systems. A wide number of often conflicting human socio-economic activities occur in these areas. These include urbanisation, tourism and recreational activities, industrial production, energy production and delivering, port activities, shipping, and agriculture. Coastal systems are also characterised by important ecological and natural values; their high habitat and biological diversity is fundamental to sustain coastal processes and provide ecosystem services which are essential also for human well-being (MEA, 2005). Human activities often conflict with the need to preserve natural coastal systems and their ecological processes. In the context of climate change, highly urbanised and infrastructured coastal areas are of particular concern since they can drastically limit and even impede natural adaptive processes, such as inland migration or vertical accretion of wetland systems.

Climate change adds additional pressure on European coastal systems (Richards and Nicholls, 2009) by increasing vulnerability on already highly vulnerable areas. This can include the development of new impacts, intensification of already occurring impacts, and synergic and cascading effects. The main impacts of climate change in the coastal zone are expected to be related to sea-level rise and other key meteorological changes. These include changes in the frequency and intensity of extreme whether events such as storms and associated surges (EEA, 2008), although uncertainty on storm surge projections is rather high (see section 2.1). Indeed, approximately 140,000 km^2 of EU land is currently within 1 m of mean sea level. In some countries, such as Denmark, the Netherlands, Italy, Germany and England, these low-lying coastal areas are densely inhabited (EEA, 2010a). This makes coastal human systems particularly vulnerable to sea-level rise and changes in intensity and frequency of flooding. Besides permanent inundation of low-lying coastal areas due to sea level rise and increased flooding, other expected climate change impacts include increased erosion of beaches and cliffs, degradation of coastal ecosystems (in particular wetland and deltas), and saltwater intrusion in freshwater systems (EEA, 2010a; ETC/ACC, 2010a, ETC/ACC, 2010b). Other less studied impacts may significantly contribute to increase coastal vulnerability in particular at the local or regional level, such as changes in hydrodynamic regimes, impacts on water trophic conditions, changes in biological communities and impacts on commercially important marine species.

The assessment of coastal vulnerability to climate change is therefore a key issue at the European level. EEA has addressed the issue in many of its reports, the most recent and relevant being: "The changing faces of Europe's coastal areas" (EEA, 2006; see in particular chapters 2.7 Coastal dynamics and risk, 3. Living by the sea, and 4.3 Climate change, coastal risks and ICZM), "Impacts of Europe's changing climate – 2008 indicator-based assessment" (EEA, 2008; see in particular chapter 7.4 Coastal areas), and "The Europe Environment: State and Outlook 2010. Adapting to climate change" (EEA, 2010a; see in particular chapter 2.2 Coastal zones). Within this context, EEA has used results from the DIVA model to assess coastal vulnerability to climate change in terms of population affected and economic damages (see an example in Figure 4-13).

In order to improve its capacity and expertise in this area, EEA has also analysed methodological aspects of coastal vulnerability assessments. In particular in October 2010, EEA organised a first expert workshop on methods (and data) for assessing current and future coastal vulnerability to climate change to consider complementary or alternative assessment approaches. Results of the workshop were used to finalise a technical paper on existing "Methods for assessing current and future coastal vulnerability to climate change" drafted by ETC/ACC (2010b). The technical paper "European coastal climate change impacts, vulnerability and adaptation: a review of evidence", drafted by ETC/ACC (2010a), complements the conclusions of the workshop. The main conclusions of the October 2010 EEA workshop that are relevant for the key issues and questions to be addressed in this paper can be summarised as follows:

- Coastal vulnerability assessment initially needs the clear definition of policy and decision making objectives and related questions;
- Some existing EU Directives and policies provide a good policy framework to define coastal vulnerability objectives and more in general to support coastal adaptation to climate change. These include among others: White Paper on Climate Change Adaptation, Integrated Maritime Policy and related Maritime Spatial Planning, Marine Strategy Framework Directive, Water Framework Directive, Floods Directive and Integrated Coastal Zone Management Policy
- Different tools may be indicated to approach coastal vulnerability assessment at different spatial and temporal scales, in different regions and for different policy purposes;
- A multi-hazard approach is required in assessing vulnerability of coastal zones to climate changes, thus implying the evaluation of impacts induced by various drivers, such as changes in sea-level, storms, salinity, waves, temperature and sedimentation patterns;
- Vulnerability assessment should possibly consider also the analysis of current and future adaptation strategies and measures, significantly influencing coastal vulnerability. Specific data are needed to address this component;
- Data availability is still a key issue; monitoring of key relevant parameters is essential and globally available data (e.g. sea level rise projections or digital elevation models) need to be corrected or detailed to address regional specificities;
- The coastal Vulnerability Index, and other indices and indicators, can be useful in addressing different policy purposes related to coastal vulnerability and in particular to highlight most "critical" regions.

Based on the previous work done, there is the need to understand what available methods (indicators, index, GIS and model based methods) can be operatively and concretely applied for assessing coastal vulnerability to climate change for the European and Regional Sea context. This technical paper represents a step forward compared to the work previously done and focuses on an operational perspective; thus it does not aim to illustrate a comprehensive literature review on the topic (see on this issue ETC/ACC, 2010b and Mcleod *et al*., 2010), rather to point out those approaches and methods that may be concretely applied to derive coastal vulnerability maps or other summary information for the European and Regional Sea contexts.

A draft version of the technical paper was used as background information for the second EEA's expert workshop on "Methods and tools for assessing coastal vulnerability to climate change at the European scale" that was held on 8-9 June 2011 in Copenhagen. This workshop discussed and evaluated options for improving assessment of the social, economic and/or ecological risks of climate change for coastal regions throughout Europe to support policy-making at European and/or regional sea scales. Discussion topics included:

- Availability of computer models, vulnerability/risk indices, and other approaches for assessing important aspects of coastal vulnerability to climate change, their respective data needs and availability, and their applicability in different regions and/or to different coastal types.
- Usefulness of European-wide datasets that are available, or are expected to become available, for improving coastal vulnerability/risk assessments in Europe.

The specific goals of the workshop were:

- Identify one or more methods to be operatively applied for the assessment of coastal vulnerability to climate change and sea level rise for the European and/or Regional Sea context;
- Provide recommendations for an appropriate and efficient use of existing methods for mapping and analysing vulnerability and risks of coastal systems to climate change and sea level rise at the European and Regional Sea context;
- Provide recommendations for the further improvement of available approaches and methods.

The discussion was structured on the basis of the following main open questions:

- Are there any other relevant methods (indicators, indices, GIS and/or model-based ones) to be considered in the technical paper analysis?
- Is it possible to select a sub-set of “proper” methods to be used for the assessment of coastal vulnerability to climate change at the European and Regional Sea contexts?
- Shall a multi-scale/multi-context approach, i.e. different methods for different contexts (from European to sub-regional), be considered as a feasible and concretely applicable approach?
- What specific recommendations for the appropriate and efficient use of existing methods are most relevant?
- What recommendations for further improvement of available data and methods/models are most relevant?

The feedback received during the workshop was very useful to support the ETC-CCA work on the analysis and evaluation of the applicability of existing methods for coastal vulnerability assessment at the European and Regional Sea levels. The main points of discussion and the conclusions have therefore been integrated in this technical paper.

Besides this introduction, the technical paper includes the following further chapters dealing with: key definitions and elements to be considered when addressing the practicalities of coastal vulnerability assessment at the European and Regional Sea level (chapter 2); identification of those methodological characteristics that are considered particularly relevant for assessing coastal vulnerability at the European and Regional Sea contexts (chapter 3); description of selected methods (chapter 4); description of visualisation tools that may be particularly useful in providing scientific-based summary information to coastal practitioners and decision makers as well as being powerful communication tools (chapter 5); data availability and data needs at the European and possibly Regional Sea level (chapter 6); and a final chapter on conclusive remarks (7).

2 Coastal vulnerability to climate change in Europe

2.1 Coastal Vulnerability to climate and non-climate drivers

Sea level rise is currently one of the most important climate change pressures on the European coasts. It is expected to continue rising and possibly accelerate during this century due to the increase in the average global surface temperature, and contributions from changes in ice sheet dynamics. According to the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) sea level is projected to rise between the present (1980 to 1999) and the end of the 21st century (2090 to 2099) under the six SRES scenarios[1] by between 18 and 59 centimetres. The global mean sea-level rise scenarios are based on thermal expansion and ice melt, excluding possible rapid changes in ice flow and melting from Greenland and Antarctica (Nicholls *et al*., 2007). However, recently observed accelerated ice flow and melting in some Greenland outlet glaciers and West Antarctic ice streams suggested that contribution from the ice sheets to rates of global sea-level rise could substantially increase (Rahmstorf, 2007; Anderson *et al*., 2009; Vermeer and Rahmstorf, 2009; Rahmstorf, 2010). Knowledge of these processes is still a developing area of science and while there is limited consensus on the upper bound of global sea-level rise, one prominent study of ice flow rates suggests that the maximum physically plausible limit of sea level rise by 2100 is 2 m (Pfeffer *et al*, 2008). More plausible, but still accelerated glaciological conditions, could lead to a sea level rise of 0.8 metres by 2100 (Pfeffer *et al*., 2008). Other recent studies suggest a rise of several meters within the next few centuries (Anderson *et al*., 2009; Rahmstorf, 2007)[2].

What matters most is not the global-mean sea level rise but the locally observed, relative sea level change, which takes into account regional sea level variations and vertical movements of the land (see also chapter 6). Hence a major source of uncertainty is how sea level rise will manifest itself at regional scales (Nicholls and Klein, 2005). There are other climate-related effects in coastal zones besides sea-level rise such as the change in the frequency, intensity and spatial patterns of coastal storms, changes in wave climate both regarding the average direction and intensity of the transported energy and changes in precipitation. This will be especially relevant for low-lying coastal areas prone to coastal, river and/or pluvial flooding, but confidence in model projections of future scenarios of climate variables other than sea-level rise is rather low and is only beginning to improve. Other climatic changes that could have significant consequences for coastal zones, such as changes in wind direction and intensity, remain highly uncertain.

The coastline is constantly changing through the action of several factors such as wave height and direction, wind speed, water depth, sediment supply, removal and transport along the coast, strength of tides, rates of relative sea level change, as well as rainfall and the frequency and intensity of extreme meteorological and climate events, including storm surges. Furthermore, coastal ecosystems are also particularly sensitive to the increase in sea surface temperature, ocean acidification, salt water intrusion, rising water tables and to altered runoff patterns (ETC-ACC, 2010a). Climate change has an influence over all these drivers and therefore introduces further vulnerability to coastal zone systems, as expressed by the following examples concerning the Baltic and the Black Seas.

In cold-temperate seas like the Baltic Sea, increasing seawater temperature can be especially important as this could affect the period of sea ice coverage, reducing coasts' ability to withstand wave impacts and

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[1] According to the IPCC AR4, in the considered period (1980-1999 ; 2090-2099) sea level is projected to rise by 0.18 - 0.38 m for the SRES B1 scenario, by 0.20 - 0.43 m for the SRES B2 scenario, by 0.21 - 0.48 m for the SRES A1B scenario, by 0.20 - 0.45 m for the SRES A1T scenario, by 0.23 - 0.51 m for the SERS A2 scenario, and by 0.26 - 0.59 m for the SRES A1FI scenario.

[2] It should be also considered that available sea level rise projections can be derived through different approaches, including: physical models (e.g. the IPCC AR4 approach), semi-empirical models (e.g. Rahmstorf, 2007; Vermeer and Rahmstorf, 2009), or analysis of past large-scale events and/or physical constraints (e.g. Rohling *et al*., 2008; 2009).

erosion processes (Sterr *et al*., 2003). Due to the salinity stratification of the Baltic Sea the rise of the sea level and possible changes in weather patterns can have many different types of effects, including changes in the fisheries (Hagen and Feistel, 2005). Thus sea level rise in the Baltic Sea is not just about higher water levels on the coast; it is a complex phenomenon with many possible effects. The Black Sea is a highly anoxic body (lacking in oxygen) and restricted flushing makes it vulnerable to land-based disturbances such as agricultural runoff, urbanization, and pollution (McCracken *et al*., 2008; Stanev, 2011). Changes in sea-level, sea water pH and the extent of oxygen deficiency, together with other factors, can create negative synergistic effects to which Black Sea ecosystems may have little resistance (ETC-ACC, 2010a).

Coastal vulnerability assessments to climate change are mainly centred on absolute or preferably relative sea-level rise and less focused on other climate change dimensions (in particular because of the significant uncertainty) and even less on non-climatic environmental and socio-economic changes (Nicholls *et al*., 2008). Indeed, coastal systems suffer great pressures from direct and indirect effects resulting from several human-induced drivers linked to population, economic growth, and related land-use changes. Thus, in general, coastal vulnerability assessments should adopt an integrated approach considering climate and non-climate induced environmental changes, socio-economic developments and the mutual interaction among these factors. However, the separated analysis of effects induced by each driver typology (i.e. climate change, other environmental and socio-economic drivers) is also important, since it enables the understanding of their relative importance for the coastal system. Indeed, the approach to be used (totally or partially integrated or specifically focusing on climate change drivers) strictly depends on the policy purpose of the coastal vulnerability assessment as well as on the stage of the policy development. For example, in an initial stage it could be more important to clearly understand what are the areas most vulnerable to sea level rise and other climate change drivers independently of the expected socio-economic evolution; thus enabling the identification of the more critical zones and in a second step also to consider the effects of changes of other drivers in these specific zones.

Climate change impacts result from the interaction between climate and non-climate drivers and have significant regional variations (Nicholls *et al*., 2008). Nicholls and Klein (2005) summarised the most significant bio-geophysical effects of sea level rise (see Table 2-1).

Natural coastal ecosystems (such as beaches, barrier islands, wetlands, estuaries, deltas, etc.) may be able to totally or partially cope with and adjust to relative sea level rise by growing vertically, migrating inland or expanding laterally. However, natural adaptive capacity strictly depends on sea level rise rates; if these will be more rapid than natural process rates (e.g. wetland vertical accretion rates) natural ecosystems will not be able to counteract the negative effects induced by sea level rise. Vulnerability to severe and accelerating sea-level rise can be compounded by high population density along the coast, presence of sea defences and infrastructure, susceptibility of coastal regions to storms and environmental stressors (such as extreme precipitation events, drought or invasive species) and in general other effects induced by climate change drivers (Anderson *et al*., 2009).

The effects summarised in Table 2-1 may induce a wide variety of socio-economic impacts such as, increased loss of property and coastal habitats, increased flood risk and potential loss of life, damage to coastal protection works and other infrastructure, loss of renewable and subsistence resources, loss of tourism, recreation, and transportation functions, loss of non-monetary cultural resources and values and impacts on agriculture and aquaculture through decline in soil and water quality.

Table 2-1 Most significant bio-geophysical effects of sea level rise including relevant interacting climate and non-climate stresses (source: modified from Nicholls and Klein, 2005)

Bio-geophysical effect		Other relevant factors	
		Climate	**Non-climate**
Permanent inundation		Sea level rise	Vertical land movement (uplift and subsidence), land use and land planning
Flooding and storm damage	Surge (open coast)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
	Backwater effect (river)	Run-off	Catchment management and land use
Wetland loss (and change)		CO_2 fertilisation, sediment supply	Sediment supply, migration space, direct destruction
Erosion	Direct effect (open coast)	Sediment supply, wave and storm climate	Sediment supply
	Indirect effect (near inlets)		
Saltwater Intrusion	Surface waters	Run-off	Catchment management and land use
	Groundwater	Rainfall	Land use, aquifer use
Rising water tables/impeded drainage		Rainfall	Land use, aquifer use

The EU's Marine Strategy Framework Directive (2008/56/EC) established European Marine Regions and their sub-regions (see Figure 2-1) taking into account hydrological, oceanographic and bio-geographical features. ETC-ACC (2010a) used the Marine Regions and sub-regions defined in the Directive - with the exception of the Adriatic (which was combined with the Ionian and Central Mediterranean Sea) - to define key messages on climate change vulnerabilities and adaptation at the regional and sub-regional level. The IPPC Fourth Assessment Report identifies six main climate drivers (hazards) for coastal systems (Nicholls *et al*., 2007): change in storm frequency and intensity, change in wave patterns, sea level rise, sea water temperature increase, CO_2 concentration increase and related ocean acidification, and increase in run-off. Table 2-2 summarises the main vulnerabilities for each European marine sub-region taking into account the above mentioned main climate drivers for coastal systems.

Number	European marine regions and sub-regions
1	Baltic Sea
2	North-east Atlantic Ocean: Greater North Sea
3	North-east Atlantic Ocean: Celtic Seas
4	North-east Atlantic Ocean: Bay of Biscay and Iberian Coast
5	North-east Atlantic Ocean: Macaronesian biogeographic region
6	Mediterranean Sea: Western Mediterranean Sea
7	Mediterranean Sea: Adriatic Sea, Ionian Sea and Central Mediterranean Sea
8	Mediterranean: Aegean-Levantine Sea (Eastern Mediterranean)
9	Black Sea

Figure 2-1 Location of European Marine Regions and sub-regions as defined by the Marine Strategy Framework Directive 2008/56/EC (source: ETC-ACC, 2010a).

Table 2-2 Main climate change hazards and vulnerabilities in different European Marine Regions and sub-regions (source: modified from ETC-ACC, 2010a).

European marine sub-regions	Main hazards and vulnerabilities
Baltic Sea (1)	Storms surges River flooding Salt water intrusion Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (fisheries, tourism)
North-east Atlantic Ocean Greater North Sea (2)	Storm surges Coastal flooding Coastal erosion Altered salinity Salt water intrusion Loss of marine habitats, ecosystems and biodiversity Loss of property and infrastructure
North-east Atlantic Ocean Celtic Seas (3)	Coastal flooding Coastal erosion Loss of marine habitats, ecosystems and biodiversity Decrease of salmon production Loss of property and infrastructure
North-east Atlantic Ocean Bay of Biscay and Iberian Coast (4)	Coastal flooding Coastal erosion Loss of marine habitats, ecosystems and biodiversity
North-east Atlantic Ocean: Macaronesian bio-geographic region (5)	Salt water intrusion Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (fisheries, aquaculture, tourism, health)
Mediterranean Sea: Western Mediterranean Sea (6)	Coastal flooding Coastal erosion Altered salinity Salt water intrusion Freshwater scarcity Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (fisheries, tourism, health)
Mediterranean Sea: Adriatic Sea, Ionian Sea and Central Mediterranean Sea (7)	Coastal flooding Coastal erosion Salt water intrusion Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (heritage, tourism, health)

European marine sub-regions	Main hazards and vulnerabilities
Mediterranean Sea: Aegean - Levantine Sea (8)	Coastal erosion Coastal flooding Salt water intrusion Introduction of alien species Socio-economic vulnerabilities (agriculture, tourism)
Black Sea (9)	Coastal flooding Coastal erosion Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (fisheries)

2.2 Conceptual definition of vulnerability to climate change and related concepts

The assessment of coastal vulnerability to climate change involves several concepts that must be clearly defined. The concept of vulnerability is defined differently in the various scientific areas in which it is used (Füssel, 2007) and is closely related to other concepts, such as hazard, risk and resilience.

Hazards can be of a technological origin or associated with natural extreme events (like storm surges and tsunamis), some of them specifically influenced by climate change and sea level rise, leading to threats and damages to the population, the environment and/or material assets (Schmidt-Thomé and Kallio, 2006). The concept of risk combines the probability of occurrence of an event with the likely impacts or consequences associated the event (ETC-ACC, 2008). Risk therefore is strictly related to the quantitative (whenever possible, for example through the analysis of historical datasets) or qualitative estimation of probability of possible events. Resilience can be described as the amount of disturbance that a system can absorb while still remaining in the same state or maintaining its functions. In other words it is the degree to which a system is capable of reorganisation and renewal or the degree to which a system can build and increase its adaptive capacity (ETC-ACC, 2008). Given the close relation between resilience and natural adaptive capacity, some authors use them synonymous (Nicholls *et al*., 2007).

The glossaries of the IPCC Third and Fourth Assessment Reports define vulnerability to climate change as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. According to the IPCC vulnerability is a function of the character, magnitude, and rate of climate change to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, 2001; 2007). This definition implies three important concepts: *exposure, sensitivity* and *adaptive capacity*. Exposure defines the nature and amount to which the system is exposed to climate change phenomena, sensitivity reflects the system’s potential to be affected (adversely or beneficially) by such changes, while adaptive capacity describes the system's ability to evolve (autonomously or according to planned measures) in such a way as to maintain (totally or at least partially) its key functions in the face of external changes. The vulnerability of coastal systems to sea-level rise and to other drivers of change is determined by their sensitivity, exposure and adaptive capacity (Nicholls and Klein, 2005). The relationships between all the above concepts can be integrated in the conceptual framework for climate change impacts, vulnerability, disaster risks and adaptation options shown in Figure 2-2.

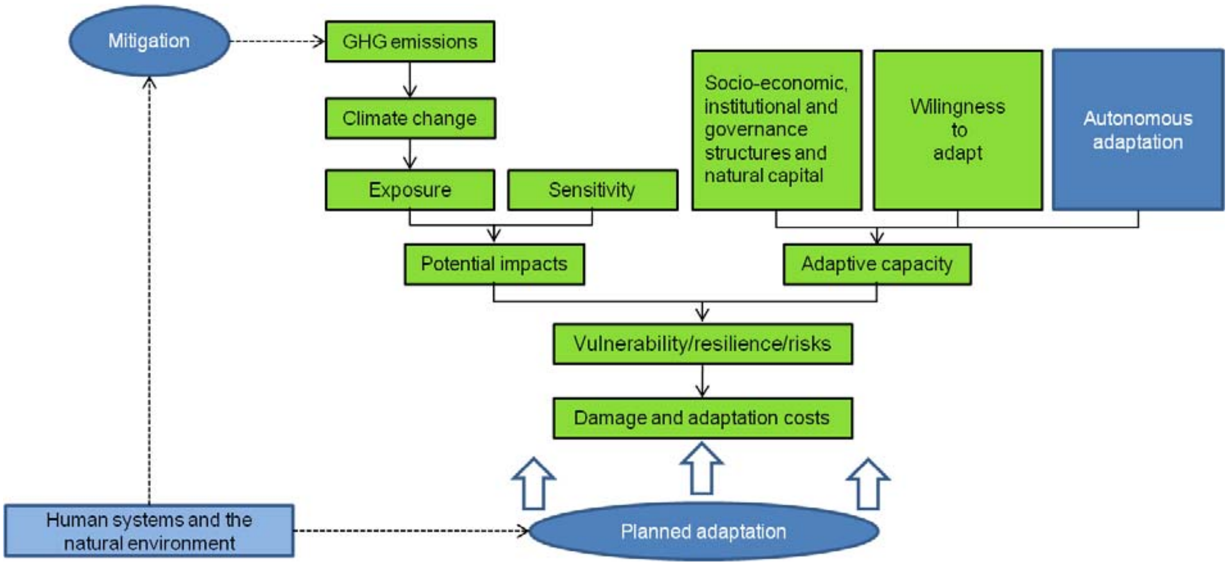

Figure 2-2 Conceptual framework for climate change impacts, vulnerability, disaster risks and adaptation options (source: EEA, 2010a; ETC-ACC, 2010b).

The IPCC definitions of vulnerability to climate change, and its related components (exposure, sensitivity, and adaptive capacity) provide a suitable starting position to explore possibilities for vulnerability assessment but they are not operational. Therefore, a vulnerability assessment should start by defining the policy or scientific objective as clearly as possible, and to choose the scope and methods accordingly. Key questions in the scoping phase include: What is vulnerable or what specific parts of the system are most vulnerable? Which impacts are relevant? Vulnerable to what climate change effects? What is the timeframe (time scenario) involved in the vulnerability assessment?

Indeed the operational definition of the vulnerability concept is related to the specific issue and/or context (e.g. the coastal area) addressed by the analysis, also implying that spatial and temporal variations of vulnerability in general and coastal vulnerability in particular are taken into consideration, as described in the following section.

2.3 Coastal management and adaptation

Vulnerability (and related concepts) is specific to a given location, sector or group and depends on its ecological and socio-economic characteristics (Hinkel and Klein, 2007). Furthermore it is dynamic because exposure, sensitivity and adaptive capacity vary by time, by stimulus and depend on several ecological, social, economic, political and technological aspects (ETC-ACC, 2010b).In this perspective, vulnerability assessments require different tools at different spatial and temporal scales, in different regions and for different policy purposes (ETC-ACC, 2010b). Considering the complex nature of coastal zone dynamics and the long-term implications of climate change, coastal policy and management requires new broad-scale integrated assessment and management tools across a range of scales: local, sub national (or regional), national and European. Assessments at each of these scales provides useful information to coastal zone management and if the studies are consistent across the scales, they can allow nesting of the results, maximizing their use for policy purposes (Nicholls and Klein, 2005). A more detailed approach at the local and regional scale is essential to understand and manage the complexities of a specific study area and allows the identification of more specific vulnerable areas and sectors that could support policy decision making in the design of appropriate adaptation strategies (Torresan *et al.,* 2008). Coastal vulnerability assessments at the regional scale require that coastal systems and dynamics are described in great detail and that more complex and data-intensive models, more site-specific metrics and indicators are used (Torresan *et al*., 2008). Another important aspect to be considered is the time scale involved in coastal zone processes and dynamics, which for example can range from hours to days for storm surges, from days to years for tidal ranges and from decades to millennia in the case of regional vertical land movements.

The sustainable management of costal zones in Europe depends heavily on the success of an integrated adaptation to climate and other changes that takes into consideration and promotes the system's adaptive capacity. Realistic assessment of adaptation options requires detailed analysis to capture the potential variation in responses within a region for a certain time frame, rather than assuming a uniform adaptation response (Nicholls and Klein, 2005). The need for adaptation to climate change is evident and in coastal areas this need is greatest and will continue for centuries considering long-term coastal challenges such as sea level rise. Nicholls *et al*. (2007) show that when efforts to reduce climate-related risks to coastal systems are reactive and standalone they are less effective than when they are part of integrated coastal zone management. Integrated coastal zone management is recognised as the most appropriate process to deal with climate change, sea-level rise and other current and long-term coastal challenges (Nicholls *et al*., 2007; Nicholls and Klein, 2005).

Proactive adaptation to climate change aims to reduce a system's vulnerability by minimising risk and/or enhancing the system's resilience. Nicholls and Klein (2005) identified five objectives of proactive adaptation for coastal zones: increasing robustness of infrastructural designs and long-term investments; increasing flexibility of vulnerable managed systems; enhancing adaptability of vulnerable natural systems; reversing maladaptive trends; and improving societal awareness and preparedness. Coastal adaptation is a complex and iterative process and for coastal zones there is another classification of three basic adaptation strategies that is often used:

- Protect - to reduce the risk of the event by decreasing the probability of its occurrence;
- Accommodate - to increase society's ability to cope with the effects of the event; and
- Retreat - to reduce the risk of the event by limiting its potential effects (Smit *et al*., 2001; Nicholls and Klein, 2005).

Nicholls *et al*. (2007) presented a scheme where the linkages between these approaches and the evolution of thinking with respect to planned adaptation practices in the coastal zone are illustrated (Figure 2-3).

The EC White Paper on Adaptation to Climate Change (COM (2009) 147 final) focuses on four pillars of action; one of these pillars deals with mainstreaming adaptation into EU key policy areas. The EU has a set of instruments and policies relevant for coastal areas, which can facilitate marine and coastal adaptation to climate change, including: Marine Strategy Framework Directive, Water Framework Directive, Floods Directive, Integrated Coastal Zone Management Policy for the European Union, Birds and Habitats Directives, Integrated Maritime Policy for the European Union, Maritime Spatial Planning, and Marine Knowledge policy. Furthermore, EU Member States are developing and implementing national adaptation strategies. The implementation of these strategies have generated hard and soft measures and actions, such as improvements to or installation of coastal defences/flood barriers/drainage dikes, adaptation of conservation management of ecosystems and their services, adaptation of agriculture and water management, integration of climate change into spatial and urban planning, implementation of beach nourishment schemes and institutional and legal measures (ETC-ACC, 2010a).

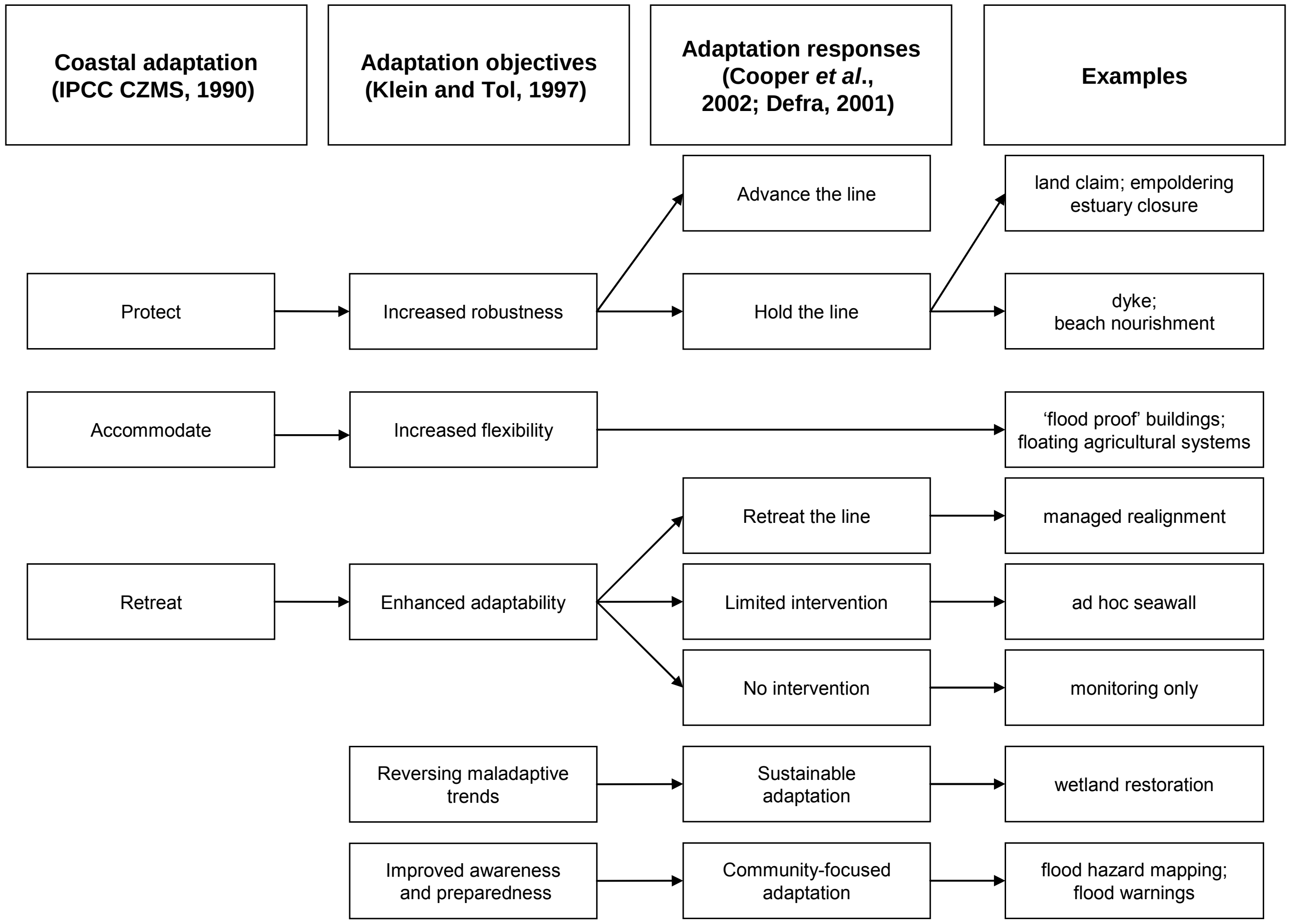

Figure 2-3 Evolution of planned adaptation practices in coastal zones (source: Nicholls *et al*., 2007).

3 Criteria for evaluating methods for coastal vulnerability assessment

Work of the former ETC/ACC and the results of the first expert workshop held in October 2010 (see chapter 5 of the ETC/ACC technical paper, 2010b) have identified several criteria for selecting and evaluating methods for assessing coastal vulnerability to climate change. Some characteristics related to spatial scale and resolution are minimum requirements for further consideration in this paper whereas others describe desirable features of vulnerability assessments. Some of these criteria are in conflict with each other (e.g. simplicity and comprehensibility), which requires careful balancing of their importance in light of the assessment purpose. These criteria help to understand what issues are already addressed and covered by existing methods and what other relevant issues are either partially considered or not considered at all.

Key requirements are:

- **Applicability at the European or Regional Sea scale.** The method must be applicable either to large parts of European coastal region or to one or more European regional seas, thus integrating relevant information from several countries. According to the Marine Strategy Framework Directive (2008/56/EC) Europe's sea is divided in four marine regions: Baltic Sea, North-east Atlantic Ocean, Mediterranean Sea and Black Sea[3] (Figure 2-1). The methods shall be able to properly take into consideration the Regional Sea specificities related to coastal vulnerability to climate change.
- **Spatial resolution at least as detailed as the DIVA model (coastal segment of about 70 km).** The spatial resolution of the DIVA model is considered a benchmark since this model has been used previously by the EEA, enabling the generation of coastal vulnerability maps at the NUTS 2 level. It is important to stress that a too detailed scale could make the application of the method too complex or even impossible at the European scale. This may be due to unavailability of data for the whole Europe, excessive computational time, or confusing visualisation of the results.

Further evaluation criteria might be:

- **Possibility to address different temporal scenarios**. The 2050 and 2100 time horizons are of particular concern because they are already considered by EEA in previous reporting activities (see for example EEA, 2010a).
- **Relevance for assessing vulnerability related to one or more key climate change impacts.** Permanent inundation due to sea level rise and change in the frequency and intensity of costal flooding are recognised as the most relevant impacts for coastal zones, in particular due to their direct implication for human settlements, infrastructures and socio-economic characteristics. Other regionally important impacts include coastal erosion, saltwater intrusion in rivers and groundwater, and impacts on wetlands.
- **Applicability to different typologies of coastal systems**. Examples include wetlands, beaches, rocky coasts, and estuaries.
- **Possibility to assess social, economic and ecological risks of climate change in coastal regions.** Systems at risk include population, built infrastructure, and economic activities but also natural ecosystems.

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[3] Some of the regions are divided in sub-regions, such as in the case of the North-east Atlantic Ocean, including North Sea, Celtic Seas, Bay of Biscay and Iberian coast, Macaronesian biogeography region; and the Mediterranean Sea sub-divided in the following sub-regions: Western Mediterranean Sea, Adriatic Sea, Ionian Sea and Central Mediterranean Sea, Aegean-Levantine Sea.

- **Consideration of adaptation measures.** The assessment may include already implemented measures as well as scenarios of future adaptation. This may be possible for some adaptation measures, such as in the case of coastal defences and beach nourishment that are for example already considered by the DIVA model (Hinkel and Klein, 2010), while it can be very difficult, in particular at the European scale, for other adaptation measures (such as soft technological interventions, governance re-structuring, planning and zoning).
- **Possibility to vary assumptions and scenarios.** Ideally, maps and/or indicators showing how the vulnerability of European coastal systems varies in relation to: climate change and sea level rise scenarios, time horizons, socio-economic dynamic scenarios, adaptation/no adaptation options.
- **Consideration of regional climate change scenarios.** Climate hazards, in particular sea level rise, vary substantial across Europe. For this reason, assessment methods should consider regional information about sea level rise, subsidence rates, etc., rather than global or European averages.
- **Assessment of uncertainties.** Uncertainties in the assessment of coastal vulnerability to climate change are related, for example, to: climate change scenarios, current environmental and socio-economic conditions (including coastal protection), process modelling, non-climatic scenarios (for example related to evolution of the socio-economic system or of the adaptation capacity). Information on the uncertainty range is important if the results of vulnerability assessments are to be used directly for policy and decision making.
- **Availability of underlying data and/or models.** The relevance of various assessment methods for EEA largely depends on the availability of required data across Europe. Furthermore, in the case of computer models these should be publicly available or available at a reasonable cost.

Obviously, there is a trade-off between completeness and complexity/simplicity in the use of the method. Very advance methods can be robust and reliable, but may also require a lot of input data, time and expertise as well as generating complex output that may not be ideal in supporting their actual use in policy and decision making or communication to EU citizens.

4 Assessment methods

This chapter describes the methods most commonly used to assess coastal vulnerability to climate change. Their description is structured in four main categories:

- Index-based methods (section 4.1);
- Indicator-based approach (section 4.2), also including related GIS applications;
- GIS-based decision support systems (DSS; section 4.3);
- Methods based on dynamic computer models (section 4.4).

Index and indicator-based approaches are described in two different sections of this technical paper since they are characterised by methodological differences, although a sharp distinction is not always evident. Index-based approaches express coastal vulnerability by a one-dimensional, and generally unitless, risk/vulnerability index. This index is calculated through the quantitative or semi-quantitative evaluation and combination of different variables. These approaches are not immediately transparent since the final index does not enable the understanding of assumptions and aggregations that led to its calculation. A clear explanation of the adopted methodology is therefore essential to support the proper use of index-based approaches. Indicator-based approaches, in contrast, express the vulnerability of the coast by a set of independent elements (i.e. the indicators) that characterise key coastal issues such as coastal drivers, pressures, state, impacts, responses, exposure, sensitivity, risk and damage. These indicators are in some cases combined into a final summary indicator. This approach allows the evaluation of different aspects related to coastal vulnerability within a consistent assessment context.

At the end of the chapter, Table 4-7 summarises the main characteristics of the described methods according to the criteria presented in the previous chapter[4]. This assessment builds on the analysis in ETC/ACC (2010b) and in McLeod *et al.* (2010), considering further scientific literature where appropriate, as well as suggestions and feedbacks expressed by the EEA's expert workshop held in June 2011.

4.1 Index-based methods

The present section of the paper describes assessment methods based on several variants of the coastal vulnerability index (CVI). Sub-section 4.1.1 briefly illustrates the original formulation of the CVI index, including some slight modifications to adapt the index to local specificities. As widely recognised (ETC-ACC, 2010b), the greatest limitation of this formulation is the incapacity to address socio-economic aspects (such as for example number of people affected, infrastructure potentially damaged and economic costs) in the assessment of coastal vulnerability (Gornitz *et al*., 1993; Cooper and McLaughlin, 1998). To deal with this main limitation, two main possible approaches are available: (i) use of the original CVI index in association with other indicators and integrated indices able to more properly represent the complexity of the coastal system; (ii) modify/extend the original formulation of the CVI also taking into account socio-economic systems. Illustrative examples of modifications of the CVI, which are potentially useful to assess coastal vulnerability at the European level, are described in sub-sections 4.1.2 and 4.1.3. Other examples of indices are available in the literature; however these are generally more difficult to apply to the geographical areas

[4] Table 4-7 in particular summarises main characteristics of the following methods: all index-based methods described in section 4.1, the Eurosion approach (described in section 4.2), DESYCO GIS-based Decision Support System (see section 4.3), all methods based on computer modelling addressed in section 4.4. Table 4-7 criteria cannot be fully applied to other indicators described in section 4.2, which are therefore not included in this table. Finally, the GIS-based DSS section also includes a brief description of the DITTY-DSS experience. DITTY-DSS represents an approach rather than a specific method to be used in coastal vulnerability assessment. Its main characteristic could not be therefore summarised in the overview table.

and scales of interest to the EEA. For example, Mendoza and Jimènez (2008, 2009; Mendoza, 2008) developed a methodology to assess coastal vulnerability at regional and local scales, focusing on the impacts of storms. More precisely, flooding and erosion were taken into account separately and then integrated into a single CVI to storms. This methodology was applied to the 42 Catalan beaches, which cover about 260 km of the 700 km of the entire Catalan coastline.

GIS tools may fully support the spatial application of CVI indices. GIS can be used to process spatial data related to CVI variables and produce maps highlighting their spatial distribution. GIS also enables the overlap of CVI results with other spatial information (such as layers representing coastal defence measures, population density, urbanisation indices, and ecological and/or biodiversity values). Thus, GIS supports the integrated analysis which is crucial in coastal vulnerability assessment. In the coastal zone, GIS tools are particularly useful, given the fine spatial resolution required to characterise areas of high risk, and the large geographical areas that need to be covered. Modern GIS software allows for this multi-scale and multi-criteria analysis to be carried out both interactively, in order to test a model, and subsequently programmatically, via a scripting interface.

4.1.1 Coastal Vulnerability Index – CVI

The Coastal Vulnerability Index (CVI) is one of the most commonly used and simple methods to assess coastal vulnerability to sea level rise, in particular due to erosion and/or inundation (Gornitz *et al*., 1991). The CVI provides a simple numerical basis for ranking sections of coastline in terms of their potential for change that can be used by managers to identify regions where risks may be relatively high. The CVI results can be displayed on maps to highlight regions where the factors that contribute to shoreline changes may have the greatest potential to contribute to changes to shoreline retreat (Gutierrez *et al.,* 2009).

The first methodological step deals with the identification of key variables representing significant driving processes influencing the coastal vulnerability and the coastal evolution in general (Gornitz *et al*., 1991). As successively described, the number and typology of key variables can be slightly modified according to specific needs; in general CVI formulation includes 6 or 7 variables. The second step deals with the quantification of key variables. Although various methodologies may be available for this step, quantification is generally based on the definition of semi-quantitative scores according to a 1-5 scale (Gornitz, 1990; Hammer-Klose and Thieler, 2001); 1 indicates a low contribution to coastal vulnerability of a specific key variable for the studied area or sub-areas, while 5 indicates a high contribution. Afterwards (third step), key variables are integrated in a single index. Gornitz and White (1992) and Gornitz *et al*. (1997) proposed and tested (in terms of sensitivity analysis) different formulas (considering 7 key variables) for the derivation of the final CVI (see Figure 4-1).

Product mean: $CVI_1 = \frac{(x_1 * x_2 * x_3 * x_4 * \ldots x_n)}{n}$,

Modified product mean: $CVI_2 = \frac{[x_1 * x_2 * ½(x_3 + x_4) * x_5 * ½(x_6 + x_7)]}{n - 2}$,

Average sum of squares: $CVI_3 = \frac{(x_1^2 + x_2^2 + x_3^2 + x_4^2 + \ldots x_n^2)}{n}$,

Modified product mean (2): $CVI_4 = \frac{(x_1 * x_2 * x_3 * x_4 * \ldots x_n)}{5^{(n-4)}}$,

Square root of product mean: $CVI_5 = [\, CVI_1 \,]^{½}$, and

Sum of products: $CVI_6 = 4x_1 + 4x_2 + 2(x_3 + x_4) + 4x_5 + 2(x_6 + x_7)$.

Where: n =variables present; x_1=mean elevation; x_2=local subsidence trend; x_3=geology; x_4=geomorphology; x_5=mean shoreline displacement; x_6=maximum wave height; x_7=mean tidal range.

Figure 4-1 Different formulas tested by Gornitz *et al*. (1992; 1997) to derive the final CVI index[5]

CVI_5 was generally used (for example in Gornitz *et al*., 1991, Gornitz, 1990; 1991a); Gornitz and White (1992) and Gornitz *et al*. (1997) also suggested that CVI_6 may be preferable to CVI_5 (CVI_6 was used in Gornitz *et al*., 1994). Actually, the product has the advantage of expanding the range of value. On the other hand, it may be quite sensitive to small changes in individual factors; the square root of the geometric mean has been introduced to dampen the extreme range (Gornitz, 1991b). Finally as a fourth step CVI values are then classified in *n* different groups (usually 3 (e.g. Gornitz et al., 1997) or 4 (e.g. Gornitz et al., 1991; Thieler and Hammar-Klose, 1999; Ojeda-Zujar et al., 2009) groups are considered) using n-1 percentiles as limits (e.g. 25%, 50%, 75% in Thieler and Hammar-Klose, 1999 or Ojeda-Zujar et al., 2009). This classification enables the evaluation of the relative coastal vulnerability of the different studied coastal parcels (such as sub-areas included in a wider coastal system).

The CVI formulation based on the square root of product mean (CVI_5) has been widely used in other applications at the local, regional and supra-regional level. The U.S. Geological Survey (USGS) used this formulation to evaluate the potential vulnerability of the U.S. coastline at the national scale (Thieler and Hammar-Klose, 1999) and on a more detailed scale for the U.S. National Park Service (Thieler *et al*., 2002). In particular USGS considered six variables, combined through the following equation:

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

where: a = geomorphology; b = shoreline change rates; c = coastal slope; d = relative sea level rate; e = mean significant wave height; f = mean tidal range.

[5] The choice and naming of the various formulas presented above (CVI_1 to CVI_6) raises a number of questions. For example, the use of multiplicative factors and denominators in the various so-called “product means” is not clear. Specifically, CVI_1 and CVI_4 are distinguished by a constant factor only, and CVI_5 is simply the square root of CVI_1. As a result, these three index variants produce exactly the same ranking of coastal segments and thus exactly the same classification of coastal segments by percentile groups. Furthermore, neither the term “product mean” nor the term “sum of products” appears to be an accurate description of the actual formula.

Ojeda-Zújar *et al*. (2009) basically applied the same CVI formulation to the Andalusia coastline (about 800 km in length). Resulting absolute CVI values range between 2.23 and 35.35; these were standardised in to the following four classes: Low – 1 (2.23 < CVI < 6.32); Medium – 2 (6.32 < CVI < 10.00); High – 3 (10.00 < CVI < 14.14); Very high – 4 (14.14 < 35.35). Results of the analysis have been mapped through a GIS system, thus enabling the identification of the most vulnerable areas at fine spatial scales (see for example coastal vulnerability map for Andalusia in Figure 4-2). More recently, some changes to the methodology were considered in the Andalusia application. In particular the coastal slope parameter (variable *c* in the above formula) was replaced by a "topographic index" expressing the average value of the following three variables (after normalization): mean height, mean slope and inland penetration area (Fraile Jurado, 2011).

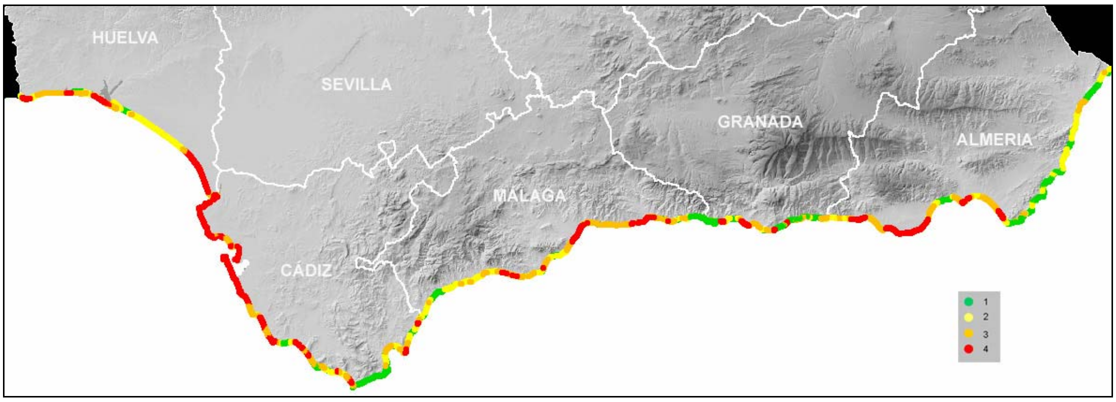


Figure 4-2 Vulnerability map for Andalusia: CVI value were calculated for coastal parcels of 200 m length (source: Ojeda-Zújar *et al*., 2009).

Other authors slightly adapted the CVI to a particular coastal zone or region, modifying not only the number but also the typology of key variables. Abuodha and Woodroffe (2006) for example applied the CVI to seven beaches of the Illawarra Coast in Australia. The CVI was customised to this purpose; in particular the formulation considered different key variables (but again the CVI_5 formulation), i.e.:

$$CVI = \sqrt[2]{\frac{a1 \cdot a2 \cdot a3 \cdot a4 \cdot a5 \cdot a6 \cdot a7}{7}}$$

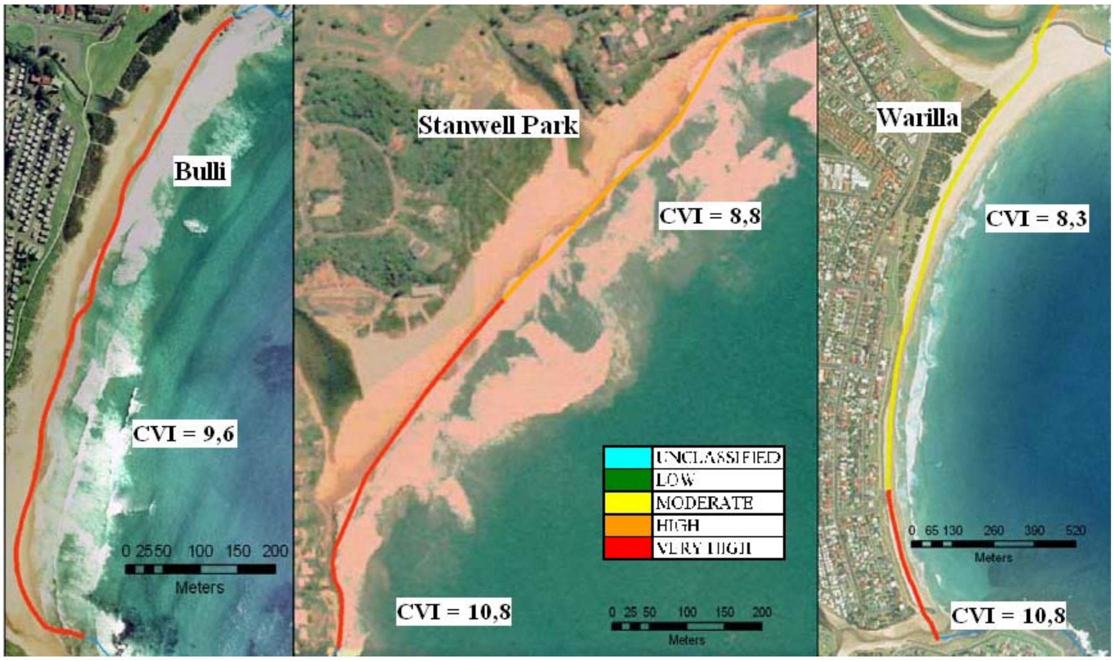
where: a1 = dune height; a2 = barrier type; a3 = beach type; a4 = relative sea-level change; a5 = shoreline erosion or accretion; a6 = mean tidal range; a7 = mean wave height. The first three variables (a1, a2, a3) replace the "a" and "c" variables (geomorphology and coastal slope, respectively) identified by Thieler and Hammar-Klose (1999); indeed the authors considered "dune height", "barrier type" and "beach type" more representative for the Australian coast and the analysed local scale (Abuodha and Woodroffe, 2006).

Table **4-1** and Figure 4-3 respectively illustrates the ranking scores of key variables considered for the Illawarra coast and vulnerability maps for three example beaches (Bulli, Stanwell Park, Warilla).

Table 4-1 Ranking scores of key variables for the Australian beach case (source: Abuodha and Woodroffe, 2006).

	Very Low	Low	Moderate	High	Very high
Variable	**1**	**2**	**3**	**4**	**5**
Dune height (m)	> 30.1	20.1 - 30.0	10.1 - 20.0	5.1 - 10.0	0 - 5.0
Barrier types	Transgressive	Prograded	Stationary	Receded	Mainland beach
Beach types	Dissipative (D) Longshore bar trough (LBT)	Rhythmic bar beach (RBB)	Transverse bar rip (TBR)	Low tide terrace (LTT)	Reflective (R)
Relative sea-level change (mm/yr)	≤ -1.1 Land rising	-1.0 - 0.99	1.0 - 2.0 Eustatic rise	2.1 - 4.0	≥ 4.1 Land sinking
Shoreline erosion accretion (m/yr)	≥ +2.1 Accretion	1.0 – 2.0 Stable	-1.0 - +1.0 Erosion	-1.1 - -2.0 Erosion	≤ -2.1 Erosion
Mean tidal range (m)	≤ 0.99 Microtidal	1.0 – 1.9 Microtidal	2.0 – 4.0 Mesotidal	4.1 – 6.0 Mesotidal	≥ 6.1 Macrotidal
Mean wave height (m)	0 – 2.9	3.0 – 4.9	5.0 – 5.9	6.0 – 6.9	≥ 7.0

Figure 4-3 Coastal vulnerability map for 3 beaches of Illawarra coast in Australia (source: Abuodha and Woodroffe, 2006).



4.1.2 Coastal vulnerability index for sea level rise – CVI (SLR)

Özyurt (2007) and Özyurt *et al.* (2008) developed a CVI to specifically assess impacts induced by sea level rise. The index is determined through the integration of 5 sub-indices, each one corresponding to a specific sea level rise related impact. The author applied this methodology to the Göksu Delta in Turkey, where the five considered SLR impacts were: coastal erosion, flooding due to storm surges, permanent inundation, salt water intrusion to groundwater resources and salt water intrusion to rivers/estuaries. Each sub-index is determined by the semi-quantitative assessment of both physical and human influence parameters (in the case of the Göksu Delta analysis, 12 physical and 7 human influence parameters were considered – Table 4-4); each parameter may contribute to the definition of more than one sub-index.

A value ranging between 1 and 5 is assigned to each parameter, in relation to its severity and contribution to the vulnerability of the analysed coastal system. Table 4-2 and Table 4-3 summarises the criteria used to determine parameter values in the case of the Göksu Delta analysis. Each sub-index (related to a specific SLR impact) is calculated by the following formula:

$$CVI_{impact} = \frac{(0{,}5 \times \sum_{1}^{n} PP_n) + (0{,}5 \times \sum_{1}^{m} HP_m)}{CVI_{least\ vulnerable}}$$

where: PP = Physical Parameters; HP = Human Influence Parameters; n and m = the number of physical and human influence parameters, respectively, considered for a particular impact; $CVI_{least\ vulnerable}$ = the value of the sub-index for the least vulnerable theoretical case, meaning all parameters equal to 1. Fine-tuning of the method can include weighting of individual parameters and of groups of parameters (physical PP and human influence HP groups). In the above formula no weight definition is considered; meaning that parameters contribute equally to the definition of the sub-indices.

CVI index values vary between 1 and 5, and can be integrated in an overall final index CVI (SLR), according to the following formula:

$$\text{CVI(SLR)} = \frac{\sum_{i=1}^{5} \text{Total Impact}_i}{\sum_{i=1}^{5} \text{Least Vulnerable Case}_i}$$

The above formula integrates all the five sub-indexes (see Table 4-4 for the numerator and denominator meanings). However the CVI (SLR) index may be also determined by integrating only a subset of the five considered impacts, those playing a more relevant role in the vulnerability of the studied coastal system. Özyurt (2007) stresses the importance to include at least the following impacts in the definition of the final index: coastal erosion, flooding and permanent inundation. Results of the analysis can be described through a matrix, such as the one developed for the Göksu Delta (Table 4-4), also illustrating the contribution of each specific parameter and sub-index to the overall coastal vulnerability.

Table 4-2 Parameters of human influence and the corresponding ranges (source: Özyurt, 2007)

Range					
	Very low	**Low**	**Moderate**	**High**	**Very high**
Human Parameters	**1**	**2**	**3**	**4**	**5**
Reduction of sediment supply	>80%	60-80%	40-60%	20-40%	<20%
River flow regulation	Not affected		Moderate affected		Strongly affected
Engineered frontage	<5%	5-20%	20-30%	30-50%	>50%
Groundwater consumption	>20%	20-30%	30-40%	40-40%	>50%
Land use pattern	Protected area	Unclaimed	Settlement	Industrial	Agricultural
Natural protection degradation	>80%	60-80%	40-60%	20-40%	<20%
Coastal protection structures	>50%	30-50%	20-30%	5-20%	<5%

Table 4-3 Physical parameters and corresponding ranges (source: Özyurt, 2007)

	Range					
		Very low	**Low**	**Moderate**	**High**	**Very high**
Physical Parameters		**1**	**2**	**3**	**4**	**5**
Rate of SLR	mm/yr	<1	1-2	2-5	5-7	7-9 and over
Geomorphology		Rocky cliff coasts, fiords	Medium cliffs, indented coasts	Low cliffs, glacial drift, alluvial plains	Cobble beaches, estuary, lagoon	Barrier beach, sand beach, salt marsh, mudflats, deltas, mangrove, coral reefs
Coastal slope		>1/10	1/10-1/20	1/20-1/30	1/30-1/50	1/50-1/100
Significant wave high	m	<0.5	0.5-3.0	3.0-6.0	6.0-8.0	>8.0
Sediment budget		More than 50% of the shoreline is in accretion	Between 10-30% of the shoreline is in accretion	Less than 10% of the shoreline is in erosion or in accretion	Between 10-30% of the shoreline is in erosion	More than 50% of the shoreline is in erosion

	Range					
		Very low	**Low**	**Moderate**	**High**	**Very high**
Physical Parameters		**1**	**2**	**3**	**4**	**5**
Tidal range	m	>6.0	4.0-6.0	2.0-4.0	0.5-2.0	<0.5
Proximity to coast	m	>1000	700-1000	400-700	100-400	<100
Type of aquifer		Leaky confined		Confined		Unconfined
Hydraulic conductivity	m/day	0-12	12-28	28-41	41-81	>81
Depth to groundwater level above sea	m	>2.00	1.25-2.00	0.75-1.25	0.00-0.75	<0,00
River discharge	m^3/s	>500	250-500	150-250	50-150	0-50
Water depth at downstream	m	≤1	2	3	4-5	>5

Table 4-4 Coastal Vulnerability Index – CVI (SLR) matrix for Goksu Delta (source: Özyurt 2007)

Impact	Physical Parameters							Human Influence Parameters							Total impact	Least Vulnerable Theoretical Case	CVI Impact
	Parameter	1	2	3	4	5	**Total**	**Parameter**	1	2	3	4	5	**Total**			
Coastal Erosion	P1.1 Rate of Sea Level Rise		1				2	H1.1 Reduction of Sediment Supply			1			3			
	P1.2 Geomorphology					1	5	H1.2 River Flow Regulation			1			3			
	P1.3 Coastal Slope					1	5	H1.3 Engineered Frontage		1				2			
	P1.4 H⅓				1		4	H1.4 Natural Protection Degradation					1	5			
	P1.5 Sediment Budget				1		4	H1.5 Coastal Protection Structures					1	5			
	P1.6 Tidal Range					1	5										
	TOTAL	0	1	0	2	3	**25**	**TOTAL**	0	1	2	0	2	**18**	21,5	5,5	**3,90909**
Flooding due to Storm Surge	P2.1 Rate of Sea Level Rise		1				2	H2.1 Engineered Frontage		1				2			
	P2.2 Coastal Slope					1	5	H2.2 Natural Protection Degradation					1	5			
	P2.3 H⅓				1		4	H2.3 Coastal Protection Structures					1	5			
	P2.4 Tidal Range					1	5										
	TOTAL	0	1	0	1	2	**16**	**TOTAL**	0	1	0	0	2	**12**	14	3,5	**4**
Inundation	P3.1 Rate of Sea Level Rise		1				2	H3.1 Natural Protection Degradation					1	5			
	P3.2 Coastal Slope					1	5	H3.2 Coastal Protection Structures					1	5			
	P3.3 Tidal Range					1	5										
	TOTAL	0	1	0	0	2	**12**	**TOTAL**	0	0	0	0	2	**10**	11	2,5	**4,4**

Impact	Physical Parameters							Human Influence Parameters							Total impact	Least Vulnerable Theoretical Case	CVI Impact
	Parameter	1	2	3	4	5	**Total**	**Parameter**	1	2	3	4	5	**Total**			
Salt Water Intrusion to Groundwater Resources	P4.1 Rate of Sea Level Rise		1				2	H4.1 Groundwater Consumption				1		4			
	P4.2 Proximity to Coast				1		4	H4.2 Land Use Pattern					1	5			
	P4.3 Type of Aquifer			1			3										
	P4.4 Hydraulic Conductivity	1					1										
	P4.5 Depth to Groundwater Level Above Sea		1				2										
	TOTAL	1	2	1	1	0	**12**	**TOTAL**	0	0	0	1	1	**9**	10,5	3,5	**3**
Salt Water Intrusion to River/Estuary	P5.1 Rate of Sea Level Rise		1				2	H5.1 River Flow Regulation			1			3			
	P5.2 Tidal Range					1	5	H5.2 Engineered Frontage		1				2			
	P5.3 Water Depth at Downstream		1				2	H5.3 Land Use Pattern					1	5			
	P5.4 Discharge				1		4										
	TOTAL	0	2	0	1	1	**13**	**TOTAL**	0	1	1	0	1	**10**	11,5	3,5	**3,28571**

4.1.3 Composite Vulnerability Index

Szlafsztein and Sterr (2007) formulated an index combining a number of separate variables that reflect natural and socio-economic characteristics that contribute to coastal vulnerability due to natural hazards. Selected indicators can differ in number, typology and scales of evaluation according to the study area. Once selected, indicators are aggregated according to an appropriate set of weights.

First of all, with respect to the two existent vulnerability dimensions, the parameters that characterize them can also be classified as natural and socioeconomic variables. Then data for each variable are placed into classes, assigning a rank between 1 and 5 according to their relative vulnerability: very low (1), low (2), moderate (3), high (4), and very high (5). The classification method used is the so-called Jenks's natural breaks algorithm. Therefore, each of these variables is weighted according to its importance in determining the vulnerability of coastal areas to natural hazards.

The classification of all the coastal information has been greatly aided by the development of GIS applications as well as integrated remote sensing applications. Separated GIS-layers are overlaid and the variable scores combined into natural and socio-economic vulnerability indices, which when combined represent the total vulnerability index. Szlafsztein and Sterr (2007) first applied this index of composite vulnerability to a coastal area in Brazil, considering the following 'natural' parameters: coastline length and sinuosity, continentality in terms of coastline density into municipal areas, coastal feature (estuarine, beach etc.), coastal protection measures, fluvial drainage, flooding areas. Socio-economic parameters considered were: total population and total population affected by floods (both divided into age classes), density of population, non-local population (i.e. born elsewhere but living in considered areas), poverty, municipal wealth. Figure 4-4 (a, b and c) shows the spatial patterns of natural, socio-economic and total vulnerability classes.

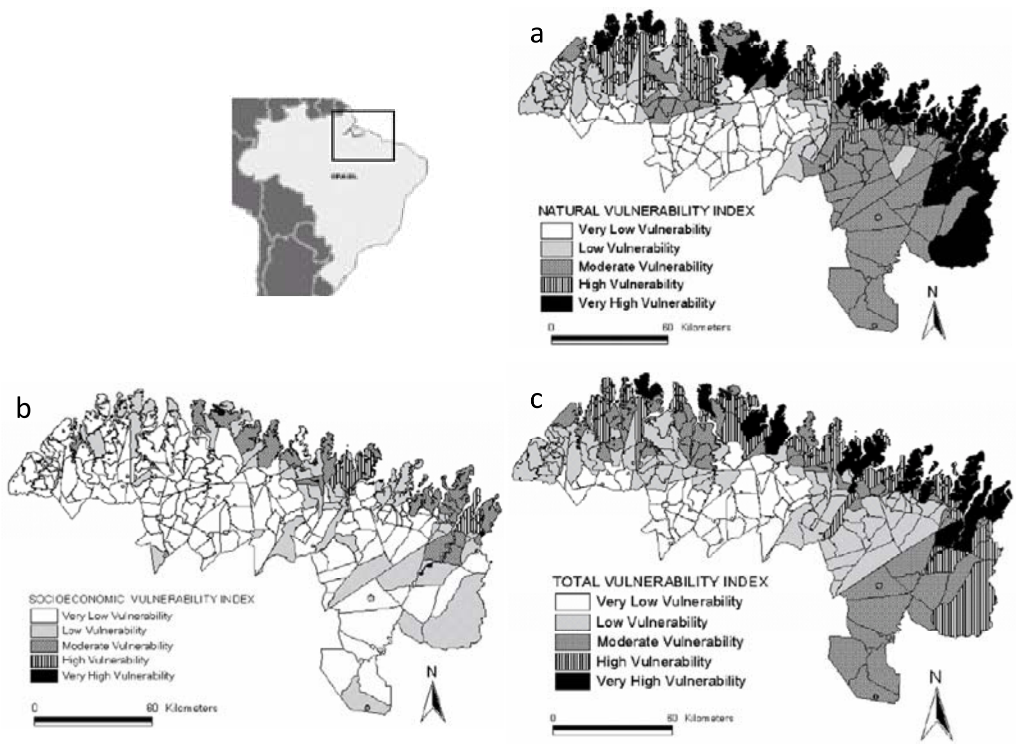


Figure 4-4 Coastal zone in Brazil: spatial distribution of the natural (a), socio-economic (b) and total vulnerability (c) index (Source: Szlafsztein and Sterr, 2007)

4.1.4 Multi-scale coastal vulnerability index

McLaughlin and Cooper (2010) developed a multi-scale CVI, specifically integrating erosion impacts, which can be applied to other climate change induced impacts, too. The index integrates three sub-indices: (i) a coastal characteristic sub-index, describing the resilience and coastal susceptibility to erosion, (ii) a coastal forcing sub-index, characterising the forcing variables contributing to wave-induced erosion, (iii) and a socio-economic sub-index, describing targets potentially at risk. The computation of each sub-index is determined on the basis of various variables, whose specific identification (number and typology) depends on the considered application scale. Figure 4-5 illustrates the variables used to derive the three sub-indexes in Northern Ireland (at the national scale) (McLaughlin *et al*., 2002, McLaughlin and Cooper, 2010). The same authors applied the CVI index (and the sub-indices) to the regional and the local scale, too; in these cases a selection of the national scale variables was used.

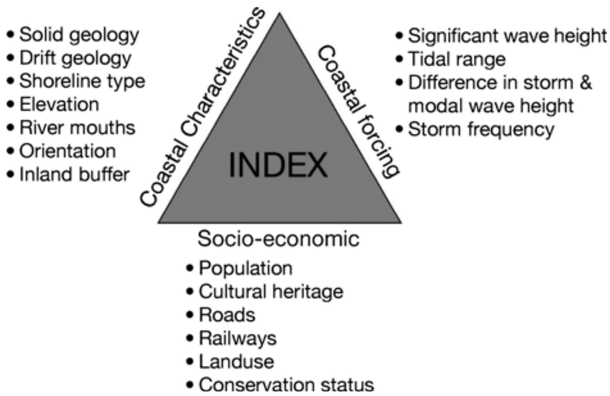


Figure 4-5 Variables used for the national scale application in Northern Ireland (source: McLaughlin and Cooper, 2010).

The identified variables (a set for each analysed spatial scale) are then ranked according to a 1-5 scale (according to Gornitz, 1990) in order to express their contribution to the coastal system vulnerability; with 5 being the highest value and 1 the lowest. Table 4-5 illustrates the matrix used to rank the three sub-index variables for the national scale application in Northern Ireland (McLaughlin and Cooper, 2010). The 1-5 scale allows the mathematical combination of different variables. Sub-indices are calculated by the sum of the values of the relative variables; the obtained number is then standardised to the range 0-100. In the case of the Northern Ireland application (national scale) considered in Figure 4-5 and in Table 4-5, the sub-indices are calculated through the following formulas:

$$\text{Coastal Characterization (CC) sub-index} = \{[(\text{sum of CC var.}) - 7]/28\} \times 100$$

$$\text{Coastal Forcing (CF) sub-index} = \{[(\text{sum of CF var.}) - 4]/16\} \cdot \times 100$$

$$\text{Socio-Economic (SE) sub-index} = \{[(\text{sum of SE var.}) - 6]/24\} \cdot \times 100$$

The final CVI index is computed through the average of the three sub-index values, as shown in the formula below:

$$\text{CVI} = (\text{CC sub-index} + \text{CF sub-index} + \text{SE sub-index}) / 3$$

Finally, CVI values can be visualised as a colour-coded vulnerability map, such as in the case of Figure 4-6 (McLaughlin *et al*., 2010).

This CVI index is rather easy to calculate and can be applied to various spatial scales, thus supporting multi-scale analysis that is important for costal planning and management (McLaughlin *et al*., 2010). Besides the characterisation of physical elements, the CVI also integrates socio-economic elements. This component however does not always significantly influence the overall index score, probably because the socio-economic sub-index depends on variables that in some or even many cases are dichotomous variables (McLaughlin *et al*., 2002).

Table 4-5 Evaluation matrix for the variable ranking and calculation of the three sub-indexes for the national scale application in Northern Ireland (source: McLaughlin and Cooper, 2010).

Sub-index	Variable	1	2	3	4	5
CC	Shoreline type	High cliff (>40 m)	Medium cliff (20-40 m)	Low cliff (10-20 m)	Shingle ridge/bar	Sand beach/dune
	Rivers	Absent				Present
	Solid geology	Plutonic, volcanic, high–medium grade metamorphics	Low-grade metamorphics, sandstone and conglomerate well cemented	Most sedimentary rocks	Coarse and/or poorly sorted unconsolidated sediments	Fine unconsolidated sediment, volcanic ash
	Drift Geology	Bedrock, urban	Till/boulder, clay		Raised beach, deposits	Alluvium, blown sand, peat, glacial sands and gravels, glacial outwash sands, recent marine
	Elevation	>30	20-30	10-20	5-10	<5
	Orientation	Not relevant, e.g. sea loughs		Easterly		Northerly
	Inland buffer	500-1000 m inland				0-500 m inland
CF	Significant wave height (m)	0-0.74 N 0-0.24 E	0.74-1.49 N 0.24-0.48 E	1.49-2.23 N 0.48-0.72 E	2.23-2.98 N 0.72-0.96 E	>2.98 N > 0.96 E
	Tidal range (m)	>5	3,5-5	2-3,5	1-2	<1
	Difference in modal and storm waves (m)	<0.10 N <0.10 S	0.10-1.70 N 0.10-0.25 S	1.70-3.30 N 0.25-0.40 S	3.30-4.90 N 0.40-0.55 S	>4.9 N >0.55 S
	Frequency of onshore storms (%)	0-2.8	2.8-5.6	5.6-8.4	8.4-11.2	>11.2
SE	Settlement	No settlement	Village	Small town	Large town	City
	Cultural heritage	Absent				Present

Sub-index	Variable	1	2	3	4	5
	Roads	Absent		A-class		Motorway, dual, carriageway
	Railways	Absent				Present
	Land use	Water bodies, marsh/bog and moor, sparsely vegetated areas, bare rocks	Natural grasslands, coastal areas	Forest	Agriculture	Urban and industrial Infrastructure
	Conservation designation	Absent		International		National

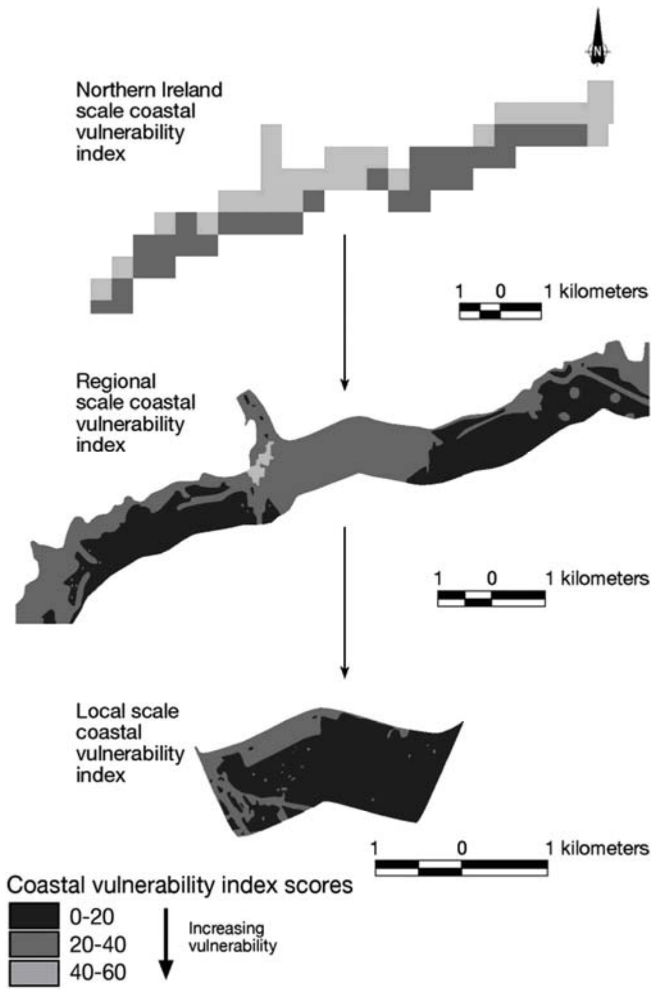


Figure 4-6 Vulnerability maps showing the CVI index for Northern Ireland (national scale), Coleraine Borough Council (Regional scale) and Portrush east Strand (Local scale) (source: McLaughlin and Cooper, 2010).

4.2 Indicator-based approach

Relevant examples of indicator-based approach at the European level include the Eurosion and Deduce projects, which are briefly described below. On the basis of the DPSIR approach (EEA, 1995) the Eurosion project identified thirteen indicators to support the assessment of coastal erosion risk throughout Europe[6]. The indicator set included nine sensitivity indicators[7]:

1) Relative sea level rise (best estimate for the next 100 years);
2) Shoreline evolution trend status;
3) Shoreline changes from stability to erosion or accretion;

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[6] http://www.eurosion.org/index.html (last access: 10.08.2011)

[7] The Eurosion project defines the following indicators as "sensitivity indicators", including within the sensitivity category also pressure and state indicators. It is therefore more coherent with the study to simply call them sensitivity indicators.

4) Highest water level;

5) Coastal urbanisation (in the 10 km land strip);

6) Reduction of river sediment supply;

7) Geological coastal type;

8) Elevation;

9) Engineered frontage (including protection structure).

For example, Figure 4-7 shows the erosion trend along the coasts in Europe (note that some EU regions were not included in the analysis).

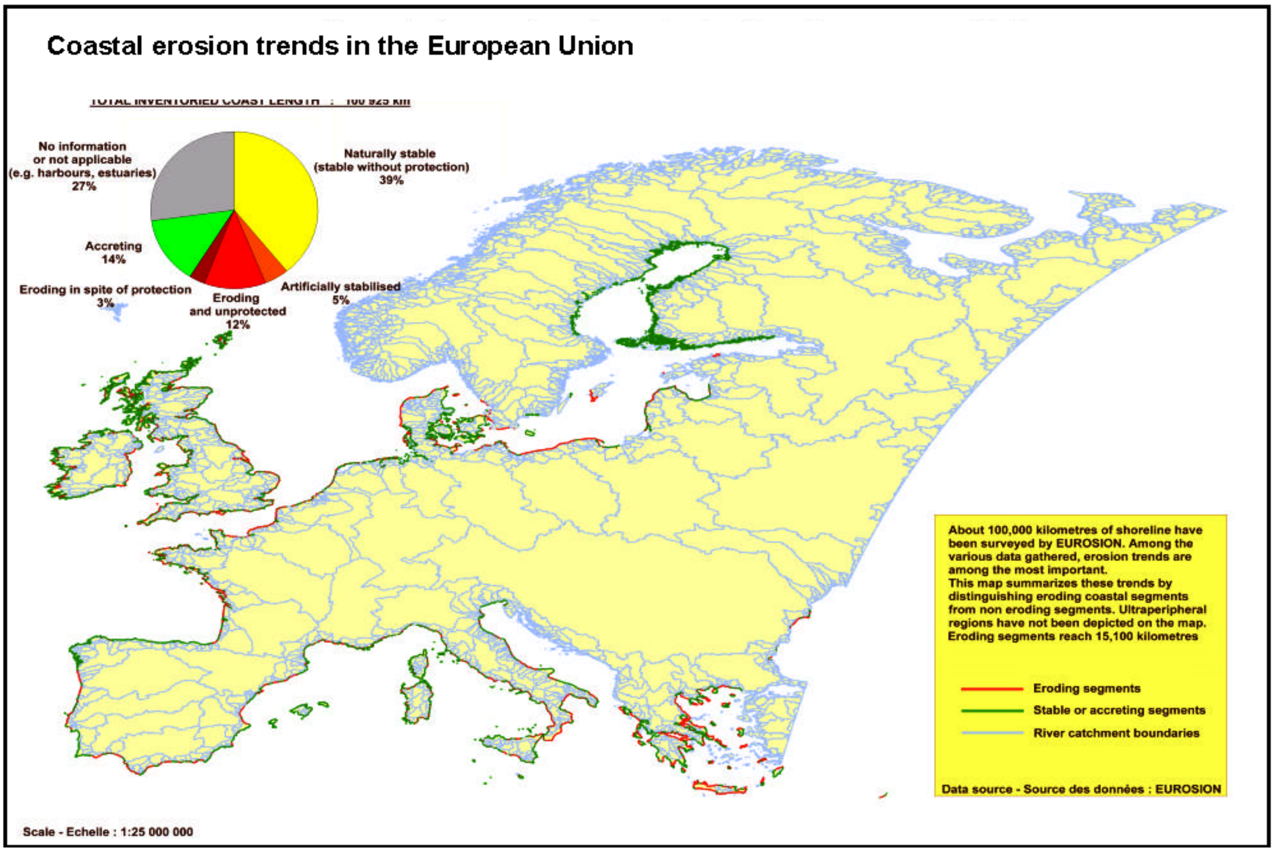

Figure 4-7 Coastal erosion trends in the European Union
(source: http://www.eurosion.org/reports-online/part2.pdf - last access: 05.09.2011)

Furthermore, four impact indicators were identified:

10) Population living within the RICE (Radius of influence of coastal erosion and flooding);

11) Coastal urbanisation (in the 10 km land strip);

12) Urbanised and industrial areas within the RICE;

13) Areas of high ecological value within the RICE.

Each indicator was evaluated according to a semi-quantitative score that represents low, medium and high level of concern about the expected future risk or impact erosion (Eurosion, 2004). The evaluation of the identified indicators was supported by the Eurosion database, structured in various spatial data layers covering the European scale[8]. Finally, sensitivity and impact indicators were aggregated to respectively derive a sensitivity score and an impact score whose product defines the “risk of coastal erosion” subdivided in four classes: very high, high, moderate and lower exposure (Figure 4-8). It should be noted that the interpretation of the terms “impact” and “exposure” in Eurosion differs significantly from their predominant interpretation in the climate change context, as defined in the IPCC Fourth Assessment Report (2007).

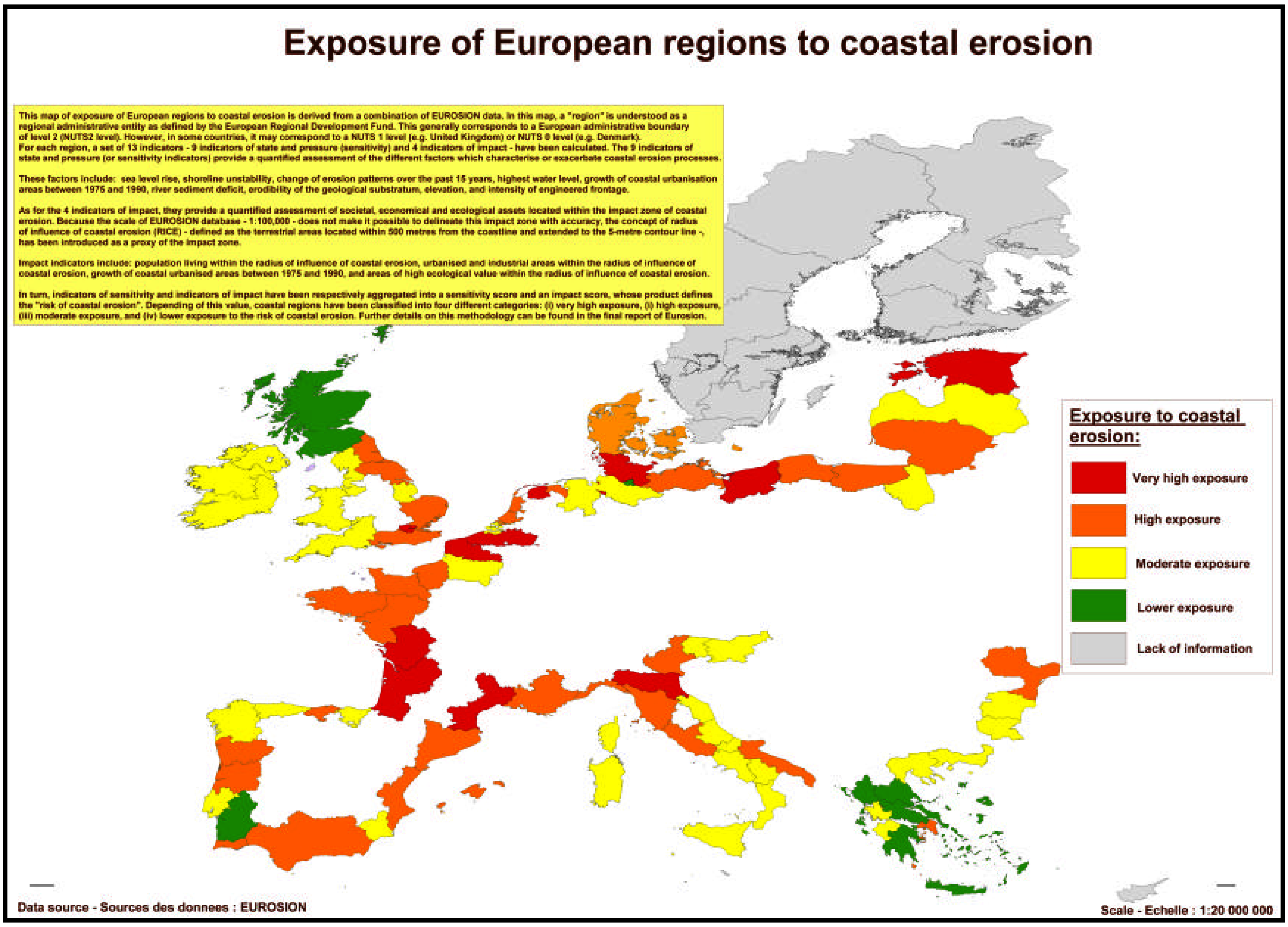

Figure 4-8 Exposure of European regions to coastal erosion.
(source: http://www.eurosion.org/reports-online/part2.pdf - last access: 05.09.2011)

The Deduce Interreg project (2004-2007) defined a core set of 27 indicators (Table 4-6), composed of 46 measurements, (Deduce Consortium, 2007) to monitor the sustainable development of the coastal zone at different scales (European, national, regional and local). The 27 indicators are specifically oriented to monitor the progress towards the achievement of seven key goals. The Deduce indicator set does not specifically assess coastal vulnerability and adaptation to climate change but it represents a useful tool to contextualise these issues within the wider ICZM framework. The Deduce project also defined a core set of progress indicators to measure the progress of the implementation of ICZM. Vulnerability to climate change is addressed in the following three indicators:

- Sea level rise and extreme weather conditions; including three measures: (25.1) number of “stormy days”, (25.2) rise in sea level relative to land, (25.3) length of protected and defended coastline;

[8] http://www.eurosion.org/database/quickstart.html (last access: 10.08.2011).

- Coastal erosion and accretion; including three measures: (26.1) length of dynamic coastline, (26.2) area and volume of sand nourishment, (26.3) number of people living within an “at risk” zone;
- Natural, human and economic assets at risk; including two measures: (27.1) area of protected sites within an “at risk” zone; (27.2) value of economic within an “at risk” zone.

Indicators can be also useful to assess coastal vulnerability at more detailed scales (local to regional) or for specific coastal ecological systems. For example, the recent Delta Alliance project “Comparative assessment of the vulnerability and resilience of 10 deltas” used DPSIR indicators and Spatial Layer approach to support decision making related to the current and future state of ten major deltas in the world, including the Rhine-Meuse and Danube deltas in Europe (Bucx, 2010).

Table 4-6 Deduce sustainable development indicators (source: Deduce Consortium, 2007)

Goals	Indicators
1. To control further development of the undeveloped coast as appropriate	1) Demand for property on the coast
	2) Area of built-up land
	3) Rate of development of previously undeveloped land
	4) Demand for road travel on the coast
	5) Pressure for coastal and marine recreation
	6) Land taken up by intensive agriculture
2. To protect, enhance and celebrate natural and cultural diversity	7) Amount of semi-natural habitat
	8) Area of land and sea protected by statutory designations
	9) Effective management of designated sites
	10) Change in significance coastal and marine habitats and species
3. To promote and support a dynamic and sustainable coastal economy	11) Loss of cultural distinctiveness
	12) Patterns of sectoral employment
	13) Volume of port traffic
	14) Intensity of tourism
	15) Sustainable tourism
4. To ensure that beaches are clean and that coastal waters are unpolluted	16) Quality of bathing water
	17) Amount of coastal, estuarine and marine litter
	18) Concentration of nutrients in coastal waters
	19) Amount of oil pollution
5. To reduce social exclusion and promote social cohesion in coastal communities	20) Degree of social cohesion
	21) Relative household prosperity
	22) Second and holiday homes
6. To use natural resources wisely	23) Fish stocks and fish landings
	24) Water consumption
7. To recognise the threat to coastal zones posed by climate change and to ensure appropriate and ecologically responsible coastal protection	25) Sea level rise and extreme weather conditions
	26) Coastal erosion and accretion
	27) Natural, human and economic assets at risk

4.3 GIS-based Decision Support Systems

The vulnerability-to-risk assessment is a key component of Decision Support Systems (DSSs) for coastal areas. For example, DPSIR or multi-model based risk analyses are the core of DSSs described and analysed in the book edited by Marcomini *et al*. (2009) (see in particular section 3) and focusing on coastal areas, although limited to water management purposes (e.g. MODELKEY, CADDIS).

To take a step forward, an integrated Regional Risk Assessment (RRA) methodology was developed and included into the GIS-based DEcision support SYstem for Coastal climate change impact assessment (DESYCO; Torresan *et al.,* 2010).

4.3.1 DESYCO

DESYCO was formulated as a DSS for the assessment and management of multiple climate change impacts on coastal areas and related ecosystems (e.g. beaches, wetlands, forests, protected areas, groundwater, urban and agricultural areas). It adopts an ecosystem approach and implements a Regional Risk Assessment (RRA) methodology, based on Multi-Criteria Decision Analysis (MCDA), in order to identify and prioritize areas and targets at risk in the considered region.

DESYCO requires the analysis of different climate change related stressors (e.g. sea level rise, storm surges, waves, water temperature and salinity) and affected resources (e.g. water, soil, biodiversity) in order to assist coastal communities in planning adaptation measures. The DESYCO overall implementation is composed of three main phases:

- the scenarios construction, aimed at the definition of future climate scenarios for the examined case study area at the regional scale;
- the integrated impact-risk assessment, aimed at the prioritization of impacts, targets and affected areas at the regional scale;
- the impact-risk management, devoted to support adaptation strategies for the reduction of the risks and impacts in the coastal zone, according to ICZM principles.

Particularly in the early stages of its development, DESYCO consisted in the identification of vulnerability indicators and indices for the evaluation of climate change impacts in coastal zones. Indeed, before analysing the risk, the first step of RRA in DESYCO considers a series of impacted systems and/or resources for which a matrix of vulnerability indicators can be built. Alternatively, combined indices (representing the sensitivity of the coast to the damaging effects of climate change hazards) can be built accounting for different systems or sectors (termed "receptors"). Such indicators or indices can be selected from datasets related to fields such as geomorphology, ecology, biology and socio-economics.

According to the RRA, vulnerability indicators or indices are classified in three main categories of factors:

- Susceptibility Factors (SFs), describing the degree to which a receptor is affected, either adversely or beneficially, by climate related stimuli;
- Value Factors (VFs), identifying relevant environmental and socio-economic values of the receptors that need to be preserved for the interest of the community (e.g. land use, human activities);
- Pathway Factors (PFs), being physical characteristics of the receptors determining their exposure to climate change hazards (e.g. elevation, distance from coastline).

According to the selected indicators, and in order to represent potentially significant hazard scenarios at the regional scale and build climate change exposure maps to be used in the risk assessment, a chain of models was set up for two study areas: the Northern Adriatic Sea (Italy) and the Gulf of Gabès (Tunisia). This chain includes different types and spatial scales of numerical models simulating relevant circulation and morphodynamic processes recognized as influencing climate change impacts on coastal areas, ranging from models reproducing atmosphere and ocean dynamics to models simulating relevant circulation and biogeochemical processes in coastal waters. The single outputs from the multi-model chain are called hazard metrics (HMs), to be included in the quantitative RRA model.

Until now, DESYCO was developed and tested for the coastal areas of the Northern Adriatic Sea and of the Gulf of Gabès. Its applicability to other contexts is under evaluation at the Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC) through other on-going projects (e.g. TRUST and SALT Life+ projects, aiming to assess and manage climate change impacts on two Italian groundwater systems). The results are expected to be published by December 2011. DESYCO can in principle be up-scaled to the European level; according to relevant experts participating in the June 2011 EEA experts' workshop (Torresan et al., 2011), such an up-scaling will need a few months' effort.

Consequently, in order to identify site-specific (i.e. North Adriatic Sea) targets and areas vulnerable to potential climate change impacts, a subset of vulnerability indicators was considered. The subset refers to different coastal receptors (e.g. beaches and dunes, wetlands, hydrological systems, protected areas, fisheries and aquaculture), and to different climate change impacts (e.g. erosion, inundation, water quality variations). Moreover, such a subset also encompasses a wide range of bio-geophysical and socio-economic factors representing the coastal vulnerability to climate change at the regional scale. Last but not least, it was selected taking into account the data availability and reliability for the study area.

In the RRA, vulnerability indicators and HMs are combined for estimating risks and damages related to each receptor, according to the following equations:

$$R_{j,k,s} = f_1\left\lfloor E_{(k,s)}, S_{(j,k)} \right\rfloor$$

$E_{k,s}$ = exposure related to the impact k and the scenario s

$S_{j,k}$ = susceptibility of the receptor j to the impact k

$R_{j,k,s}$ = risk related to the impact k, an exposure $E_{k,s}$ and a susceptibility $S_{j,k}$

$$\mathrm{D}_{\mathrm{j,k,s}} = \mathrm{f}_2\left\lfloor \mathrm{R}_{(\mathrm{j,k,s})}, \mathrm{Va}_{(\mathrm{j,k})} \right\rfloor$$

$D_{j,k,s}$ = damage related to an impact k, a risk $R_{j,k,s}$ and a value $Va_{j,k}$

The exposure function $E_{(k,s)}$ is an impact specific function aggregating $HM_{(k,s)}$ for the scenario *s* and the impact *k* with $PF_{(j,k)}$ associated to the receptor *j* and the impact *k*. For impacts affecting the terrestrial environment (e.g., sea level rise inundation, storm surge flooding) the exposure function is used to project the information provided by sea water models inland. The susceptibility and the value functions ($S_{(j,k)}$ and $Va_{(j,k)}$) aggregate $SF_{(j,k)}$ and $VF_{(j,k)}$ related to the receptor *j* and the impact *k* using specific MCDA (Multi Criteria Decision Analysis) functions made available by the model. Furthermore, vulnerability thresholds to be applied to the selected indicators, as well as methods for aggregating and weighting the indicators have been identified.

DESYCO is integrated within a GIS and implements GIS functionalities based on open source libraries. As a result, both indicators and vulnerability maps will allow a quick visualisation and comparison of the assessment for different segments of the region, supporting the prioritisation of those coastal areas and receptors for planning urgent intervention or adaptation by decision planners. Figure 4-9 shows the flow of information leading to the production of maps during the different stages of the RRA.

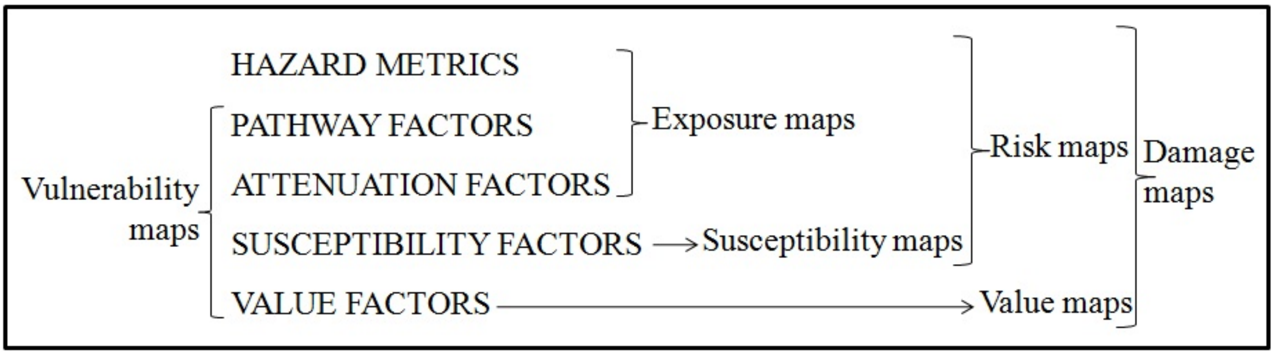

Figure 4-9 Integration of factors and metrics to produce the cascade of maps from the DESYCO-RRA system

Within DESYCO and the related RRA approach, numerical model simulations used for the construction of climate change scenarios and exposure maps have been validated through the comparison with observed data for a control period. Moreover, the feasibility of the system structure and the usability of its interface for end users were tested through stakeholder analysis and user questionnaires. These confirmed the validity of the methodology choices (such as the validity of the set of receptors investigated by DESYCO) and provided useful recommendations for further improving the DSS framework.

The evaluation of the results provided by the RRA and DESYCO for the case studies can benefit from a sensitivity analysis that allows the assessment of how much uncertainty in the system output is influenced by uncertainty in its input parameters (i.e. scores and weights). This information could be useful for the DSS end users because it explains synthetically how much the assessment of an RRA study is biased by expert judgments.

The main issues and gaps related to the vulnerability-risk assessment procedure offered by DESYCO through the construction maps are: i) the diversity of data sources, formats, and spatial scales that introduced geographical errors; and ii) for now, the limited availability of well differentiated test areas. Building a multi-model chain requires great initial efforts in terms of time and resources, especially in order to make the tool applicable beyond the actual study area. However, once set up, the model chain can be improved with other models and used to perform other scenario simulations. Moreover, as for other integrated GIS-model risk assessments the use of alternative models could be possible when the risk-related processes are assessed in other coastal areas or under different spatial scales or when the available input datasets for the selected modelling scheme are limited.

Indeed, DESYCO's RRA structure is not limited to a fixed suite of models and/or scenarios. In particular, scaling up the approach requires including less sophisticated schemes in the integrated framework, more simplified parameterisation and fewer detailed input data. Dealing with numerous and heterogeneous data for small extents increases the complexity of simulated impact processes, as well as the analysis of the results. Finally, the tool can be further improved by supplying the models with a more complete dataset or adding additional indicators/simulated processes following the increased production and availability of thematic maps.

In any case, it is important to keep in mind two key-points: i) the uncertainty from either input data quality-quantity or model formulation contributes to the final estimation of risk and has to be, as much as possible, quantified; ii) the vulnerability-risk classification should not attempt to provide absolute predictions about the impacts of climate change, rather, it is a relative index providing information about the areas within a region that are affected more severely than others.

4.3.2 DITTY-DSS

As highlighted previously, flexibility is a key factor in vulnerability assessment tools. The risk analysis system embedded in the DITTY-DSS approach (Mocenni *et al.,* 2009) attempts to address this need. The core of such DSS is indeed represented by the mathematical and analytical models (e.g., biogeochemical, hydrodynamic, ecological, socio-economic models) developed for each study site during the course of the DITTY project[9]. These are used to simulate alternative scenarios, and to provide corresponding system performance indicators related to the decision criteria. Multi-Criteria Data Analysis (MCDA) is finally applied to evaluate and rank the alternatives on the basis of both the values of the indicators and the interaction with the decision maker.

According to the DITTY scheme in Figure 4-10, models play a key role between the control option generation, and the MCDA comparison. The block “control options'' provides the alternative control options by assigning different values to the controllable variables. The block “external factors” describes the uncontrollable variables that cannot be manipulated by the decision makers but do affect the system performance (e.g., the climate conditions and water balance for the lagoon models; the prices and the market data for the economic models), affecting the uncertainty of the decision process. The “models” block represents a suitable interconnection of the models used to describe the system behaviour and its vulnerability, making simulations and predictions of, e.g., the physical, chemical and biological, as well as the economic and social variables of the system. Successive blocks are related more specifically to the DSS phase.

Although the DSS development was initially targeted to Mediterranean lagoons, in a wider European perspective the proposed DSS structure is in principle applicable to all types of coastal lagoons, and even more generally to transition water systems as defined by the Water Framework Directive.

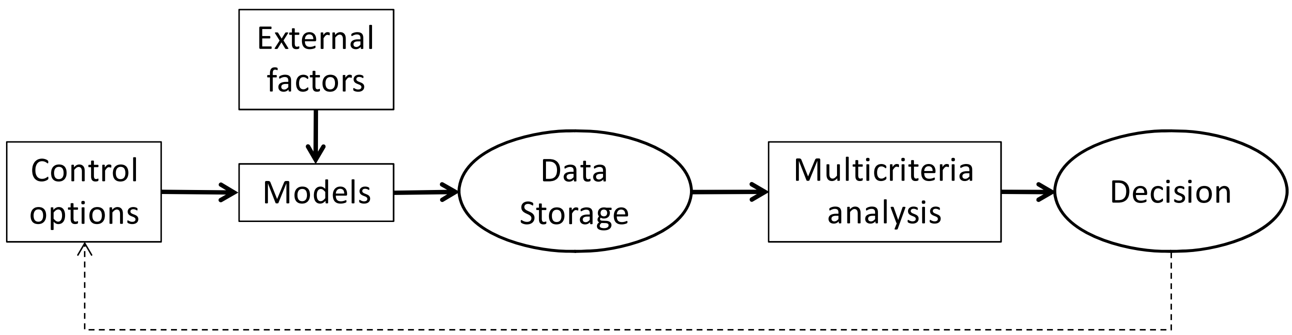

Figure 4-10 Block scheme of the DITTY-DSS

4.4 Methods based on dynamic computer models

Dynamic computer models are important tools to be used for analyzing and mapping vulnerability and risks of coastal systems to climate change. Following the previous work done by EEA, including in particular the results of a first expert workshop held in October 2010, the related ETC/ACC Technical Paper 2010/8 (ETC/ACC, 2010b), and the results of the EEA’s second expert workshop held in June 2011, the following sections (including Table 4-7 and Table 4-8) intend to further analyse the main available models. In particular, the focus will be on their application in an operational capacity at the European and Regional Sea

[9] http://www.ecolag.univ-montp2.fr/index.php?option=com_content&task=view&lang=en&id=226 (last access: 10.08.2011)

scales. Table 4-7 summarises the principal characteristics of these models (the table also includes summary characteristics for the other methods illustrated in the previous sections of chapter 4), while Table 4-8 highlights their main strengths and limitations with a view to their possible application for the assessment of coastal vulnerability to climate change at the European and Regional Sea level. The tables include information on the models analysed in ETC/ACC (2010b) and McLeod *et al*. (2010), as well as two further examples (RACE and RegIS) that were presented and discussed during the above mentioned second expert workshop. The evaluation of strengths and weakness is based on the analysis made by ETC/ACC (2010b) and McLeod *et al*. (2010) and on further literature.

Available methods based on dynamic computer modelling can be roughly divided into sector models and integrated assessment models. Sector models are those focusing on the analysis of coastal vulnerability related to a particular coastal process (e.g. coastal erosion or saltwater intrusion in freshwater systems) and therefore not directly dealing with the evaluation of coastal vulnerability to multiple climate change impacts. This technical paper briefly describes the Risk Assessment of Coastal Erosion (RACE) approach (section 4.4.1) used to evaluate coastal erosion hazards and risk in England and Wales within the National Coastal Erosion Risk Mapping Project (NCERM). RACE is included in the paper as an illustrative example of a sector model since it has been consistently applied at a close-to-national scale (England and Wales) to specifically support local and regional adaptive planning. Although RACE has been designed for high spatial resolution, it is also able to aggregate local results to inform high level assessments. Furthermore, it allows the user to address various time horizons (20, 50 and 100 years), thus supporting long term evaluation of coastal vulnerability. The main advantages and disadvantages of RACE were discussed during the June 2011 EEA's expert workshop (Hardiman, 2011). Other sector models address specific coastal systems, although they attempt to deal with various coastal processes. Examples include BTELSS and SLAMM (analysed in ETC/ACC, 2010b), which are both tailored for the analysis of coastal wetland changes and vulnerability.

Integrated assessment models[10] aim to evaluate the vulnerability of coastal systems to multiple climate change impacts, including the cross-sector analysis of the interaction among different impacts and/or considering changes in other factors affecting the coastal system (mainly the socio-economic context and adaptation measures). Examples of integrated assessment models considered in this technical paper and in previous publications (ETC/ACC, 2010b; McLeod *et al*., 2010) include: FUND, DIVA, SimCLIM and RegIS. The GIS-based DSS DESYCO, described in section 4.3.1, can also be considered an integrated assessment model, since it has been specifically developed to deal with the assessment and management (in terms of adaptation) of multiple climate change impacts on coastal areas and related ecosystems. The following sections (from 4.4.2 to 4.4.4) describe the model-based method (DIVA, SImCLIM and RegIS) that can be considered more interesting for a potential application at the scale of Europe and Regional Seas, as argued in the conclusions (section 4.5) of this chapter.

Finally, a number of two and three-dimensional models have been developed for coastal engineering applications in particular at the local and regional scale (McLeod *et al*., 2010). Although not specifically developed to deal with climate change impacts, these models can be applied for sector analysis (e.g. shoreline change and storm impacts simulations) or integrated assessment of coastal vulnerability. Relevant examples include Delft3D developed by Deltares and the MIKE 2D and 3D modelling systems developed by DHI – Danish Hydraulic Institute for complex applications within oceanographic, coastal and estuarine environments[11]. Section 4.4.5 describes Delft3D modelling suite, which has already been considered and analysed in ETC-ACC (2010b).

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[10] Note that the term "integrated assessment model" as used in this Technical Paper on coastal zone vulnerability assessment is different from "integrated assessment model of climate change" (IAM-CC). IAM-CCs combine dynamic descriptions of the energy-economy system, the climate system, and climate impacts to support the formulation of global, and possibly regional, climate policy (Füssel, 2010).

[11] http://mikebydhi.com/ (last access: 10.08.2011)

4.4.1 Risk Assessment of Coastal Erosion (RACE)

The aim of the RACE project was to develop and disseminate a robust and consistent probabilistic assessment of the hazard and risk of coastal erosion in the United Kingdom. Co-funded by the UK Department for Environment Food and Rural Affairs (DEFRA) and the Environment Agency (England and Wales), the methodology follows a source-pathway-receptor approach to risk analysis. The techniques developed within this framework include:

- Source - Assessment of potential failure of existing coastal defences over time, and the unconstrained natural erosion of coastal landforms;
- Pathway - The probability of erosion given the influence of the coastal defences, forms the hazard assessment;
- Receptor – The spatial combination of the hazard assessment with socio-economic vulnerability data to create a risk assessment. This lead to the creation of a National Coastal Erosion Risk Map for England.

In order to assess the potential failure of coastal defences and the natural erosion rate, the authors identified many techniques that might result in the same output. The complexities of the technique employed depend on the economic value, data availability, and accuracy required, but essentially, the output of this stage should be as described in Figure 4-11. In the case of Figure 4-11a, the user assesses the most likely time of failure of the coastal defence to be in 30 years, but collapse might occur as early as 20 years, or as late as 35 years. In the period before failure, there is still a chance of 1% per year (+/- 0.5%) of storm conditions that exceed the design specifications of the defences. The probability of failure of the coastal defences is also compared to the user's assessment of erosion of the coastline without defences (Figure 4-11b). In the included example, this is estimated at between 70 m and 150 m in 100 years, with a most likely estimate of 100 m.

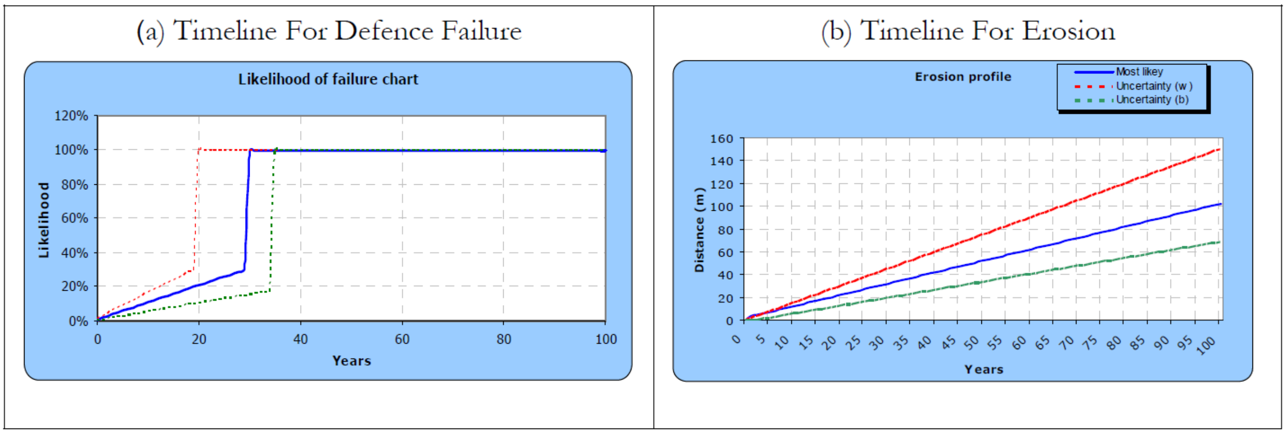

Figure 4-11 Timelines for (a) defence failure, and (b) natural erosion processes for an indicative stretch of coastline (source: Halcrow Group Ltd, 2007)

The hazard assessment considers differing erosion scenarios, following failure of the coastal defence. This 'post-failure retreat' may differ from natural coastal retreat processes in two differing ways:

a. Rapid non-linear catch-up process – whereby the erosion of the cliff happens at a much faster rate than the natural rate

b. Slow retreat rate – this is characterised by an erosion rate slower than the natural rate, possible due to remaining protection from broken defences.

Further to these assumptions of post-failure retreat, probabilities of erosion were calculated for particular location over time (Figure 4-12a), and probabilities of erosion at certain distance from the coast for a given time period (Figure 4-12b). This approach helps to identify the probability of damage to certain locations over time.

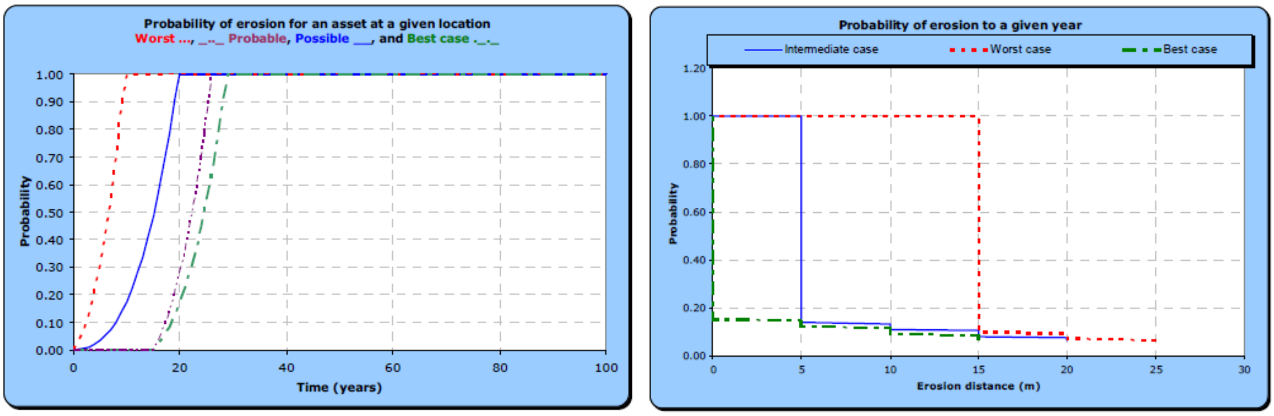

Figure 4-12 Probability of erosion for a given distance (left side) and probability of erosion for a given time (right side).

Finally, the above hazard information was used to create a risk assessment of assets in the coastal zone. While the results of this stage of the analysis have not currently been published, the RACE Part One report (Halcrow Group, 2007) recommends the visualisation of the hazard either by:

- mapping ranges of future shoreline position at various time steps, or
- mapping lines of probability of shoreline position at a given time step.

The National Coastal Erosion Risk Mapping project is taking the first of these recommendations forward by publicly displaying erosion predictions as a range for three time steps (2025, 2055 and 2105) on the Environment Agency website, and providing local authorities and other coastal managers with the supporting GIS database for use in coastal planning and assessment (see section 5).

4.4.2 DIVA

The Dynamic Interactive Vulnerability Assessment model (DIVA) is an integrated model to assess biophysical and socio-economic effects induced by sea-level rise driven by impacts on coastal zones and socio-economic development (Hinkel, 2005; European Climate Forum, 2011). The model enables the evaluation of costs and benefits related to the analysed impacts as well as pre-defined adaptation strategies. The DIVA model and tool (the most recent model version is 3.3.3) was initially developed within the DINAS-Coast project (Dynamic and Interactive Assessment of national, regional and global vulnerability of Coastal Zones to Climate Change and Sea-level Rise), which involved British, German and Dutch partners. It was specifically designed and developed to support policy and decision makers in interpreting coastal vulnerability assessment and in addressing related measures.

The specific aim of DIVA is the assessment of coastal vulnerability to sea-level rise. The model is driven by sea level changes, combining eustacy and vertical land movement due to glacial-isostatic adjustment and subsidence in delta (see McLeod *et al.*, 2010) with socio-economic scenarios until 2500. It assesses impacts on coastal zones related to the following key processes: coastal erosion (both direct and indirect), coastal flooding (including rivers), wetland change and salinity intrusion into deltas and estuaries (Hinkel and Klein, 2007; 2009). The following extract, from McLeod *et al*. (2010) provides a good summary of DIVA's approach to impact assessment:

"The loss of dry-land is assessed due to direct and indirect coastal erosion. Indirect coastal erosion can be caused when sediment flows from the open coast into nearby tidal basins, allowing the basins to keep pace with increases in sea level rise. 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 social and economic damage of coastal flooding is assessed based on data of storm surge characteristics (return periods and flood levels) as well as the exposed people, areas and assets. Sea-level rise leads to shorter average return periods of higher flood level. The damage of salinity intrusion into the coastal systems is assessed in the form of the area of agricultural land that is affected by salt water travelling up the lower reaches of rivers".

DIVA can support the dynamic assessment of coastal vulnerability to climate change since it includes the possibility to generate socio-economic scenarios. Furthermore, the vulnerability assessment in DIVA also takes into account coastal adaptation, albeit through a simplified approach. Adaptation refers to rising of defensive dikes and beach nourishment interventions but does not include other possible measures, such as those related to ecosystem management. Predefined adaptation strategies are available, ranging from no additional protection to full protection and optimal protection.

The DIVA model can be considered as a good tool for coastal vulnerability assessment at the global, regional and national levels, since the average coastal segment is approximately 70 km in length. DIVA is not considered appropriate for application at local scale, due to the model resolution (ETC-ACC, 2010b). In particular an underlying global database of 30 indicators mapped onto more than 12,000 coastal segments and 20 indicators mapped onto 300 countries may provide the user with information on the physical as well as economic consequences of key climate change impacts on coastal zones addressed by DIVA (Policy Research Corporation, 2009).

DIVA is provided with a graphical user interface providing functionalities to select data and scenarios, run the model simulation and analyse the final results. The model enables the user to: (i) explore the effects of various climate change related impacts on the coastal system, in relation to the physical environment and the socio-economic context, (ii) explore costs of impacts, as well as the costs and benefits of adaptation options, (iii) produce results that can support policy and decision making also in the perspective of cooperation at the European and Regional Sea level. Indeed, the DIVA model has been used in various applications, including also the analysis of coastal vulnerability at the scale of Europe and Regional Seas.

Richards and Nicholls (2009) used DIVA within the PESETA project to analyse the physical and economic impacts of sea level rise in the 22 EU coastal member states with and without adaptation. DIVA was also used at the European level (EU-27) by Hinkel *et al*., (2009; 2010), to assess physical and socio-economic consequences of impacts induced by sea level rise and storm surges on coastal areas. Results of the above work (see examples in Figure 4-13 and Figure 4-14) were used by EEA to draft the chapter on Coastal Zone of the SOER 2010 (The European Environment – State and Outlook 2010) thematic assessment "Adapting to climate change" (EEA, 2010a). In the CIRCE (Climate Change and Impact Research: the Mediterranean Environment project) project[12] DIVA has been used to assess coastal vulnerability for the Mediterranean Basin related to sea level rise impacts, also considering adaptation options (Avagianou *et al*., 2008). This work also aimed to review and update the global coastal database of the original DIVA tool in order to properly apply it to the Mediterranean scale.

[12] http://www.circeproject.eu/index.php?option=com_frontpage&Itemid=1 (last access: 10.08.2011)

According to Hinkel *et al*. (2011), future plans for the development and implementation of DIVA will mainly focus on the following issues: further uncertainty analysis, higher resolution segmentation of the coastline, regional applications (such as the previously mentioned one on Mediterranean), further exploration of patterns of local sea level rise and land subsidence, further adaptation options and strategies, and current adaptation deficit.

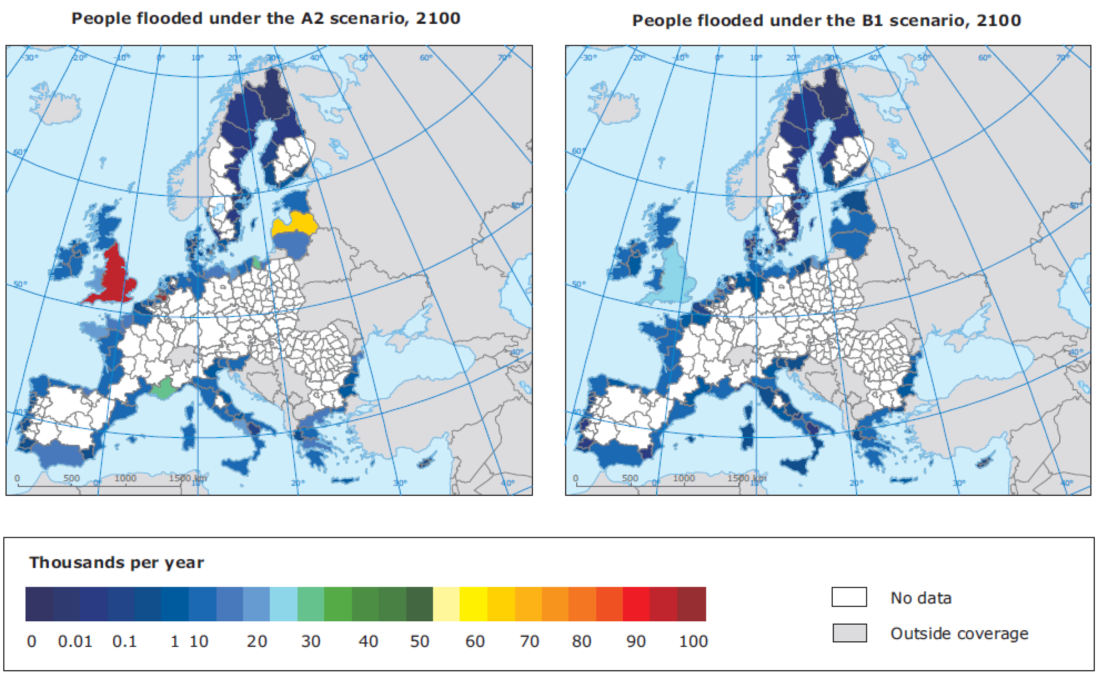

Figure 4-13 People expected to be at risk of flooding without adaptation in 2100, for the A2 and B1 IPCC SRES scenarios (source: Hinkel *et al*., 2009; Hinkel *et al*., 2010; reported in EEA, 2010).

Table 2.2 Contribution of the different impacts to the total damage cost in the EU-27 without adaptation in the medium-long term (SRES A2 and B1 scenarios)

Million EUR/year	Salinity intrusion	Land eroded and lost	Sea floods	River floods	Migration	Total damage cost
A2						
2030	1 005	4	3 501	36	218	4 767
2050	1 147	7	4 861	63	371	6 450
2100	2 010	16	13 637	283	986	16 933
B1						
2030	1 122	4	4 274	44	223	5 662
2050	1 326	7	6 398	79	386	8 192
2100	1 844	10	14 483	274	884	17 496

Note: Differences between total damage cost and sum of columns are due to rounding.

Figure 4-14 Contribution of the different impacts to the total damage cost in the EU-27 for the A2 and B1 IPCC SRES scenarios (source: Hinkel *et al*., 2009; Hinkel *et al*., 2010; reported in EEA, 2010).

4.4.3 SimCLIM

SimCLIM is a software modelling system used to link and integrate complex arrays of data and models in order to simulate (both temporally and spatially) bio-physical impacts and socio-economic effects of climate variability and change, including extreme climatic events. In this way, it provides the foundation for assessing options for adapting to the changes and reducing the risks. SimCLIM is the generic name of the "open-framework" system, developed from a "hard-wired" system originally built for New Zealand (Warrick *et al*., 2001; Kenny *et al.*, 1999; 2000), with its various "clones" (for example, the Australian version, OzCLIM)[13].

The "open-framework" features are relatively recent (Warrick *et al*., 2005) and are a distinctive advantage of SimCLIM, as they afford users the flexibility for importing their own data, customising the system for their own purposes – much like a GIS (as opposed to the older "hard-wired" system). There are tools to allow the user to import: (1) spatially-interpolated climatology and other spatial data (e.g. elevation surfaces); (2) site time-series data; (3) patterns of climate and sea-level changes from General Circulation Models (GCMs); (4) impact models that are driven by climate (and other) variables; and (5) shape files (e.g. boundaries, roads, streams). The geographical size is a matter of user choice (from global to local), as is the spatial resolution (subject to computational demands and data availability) (Warrick, 2009a).

As illustrated in Figure 4-15 (left panel), SimCLIM has a vertically-integrated, "top-down" structure that links global, local and sectoral models and data for the purpose of examining impacts on, for example, agriculture, health, coasts or water resources (Warrick and Cox, 2007). For generating projections of future climates, SimCLIM uses a "pattern scaling" method (Santer et al., 1990; Hulme *et al*., 2000; Carter and La Rovere, 2001) that involves the scaling of "standardized", spatial patterns of climate change from very complex General Circulation Models (or GCMs) with the time-dependent (e.g. year-by-year) projections of global-mean climate changes from simpler models. These changes are used to perturb the present climate (whether time-series data or a spatial climatology) and thereby create climate scenarios for a year of interest (e.g. 2050) (Figure 4-15, right panel). The SimCLIM user interface provides the user with considerable scope for choosing amongst global projections, GCM patterns, model sensitivity values and future time horizons, and thus for examining the range of uncertainties involving future greenhouse gas emissions and scientific modelling.

One set of developments were made for adaptation to changing risks from tropical cyclones in the Cook Islands. Another new development involves a linkage between SimCLIM and Danish Hydraulic Institute (DHI) models. For example, one version of SimCLIM links directly with Danish Hydraulic Institute (DHI) hydrologic models for seamless analyses (Warrick and Cox, 2007). SimCLIM's scenario generator is used to perturb input time-series data (e.g., precipitation, temperature, sea-surface level and wind speed) for DHI's simulation tools, which can easily and efficiently be re-run to examine the effects of changes in climate on model output. This capability allows a large number of questions relating to the impact of climate change on water quantity and quality to be addressed quickly. For example:

- What are the possible changes in future risks of flooding?
- How might the reliability of water supply be affected in the future?
- What is the potential change in coastline over the coming decades?
- What is the potential impact on water quality and ecology of wetlands?

[13] http://www.csiro.au/ozclim/home.do (last access: 30.05.2011)

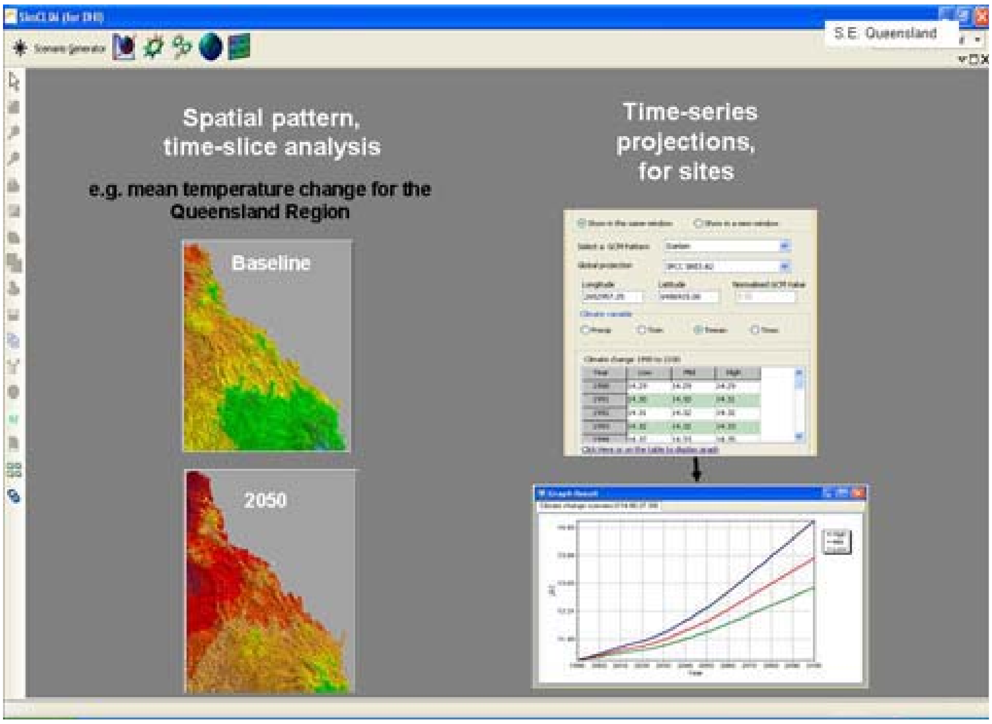

Figure 4-15 Example of spatial and site time-series projections produced by SimCLIM scenario generator (source: Warrick, 2009a).

Furthermore, SimCLIM enables examination of potential erosion and flooding in response to future climate scenarios including sea-level rise due to climate change, global warming as well as changes resulting from local land movements. Its coastal subroutine involves an erosion model that is a modified version of the Bruun Rule.

SimCLIM is designed to support decision-making and climate proofing in a wide range of situations where climate and climate change pose risk and uncertainty. The probabilities and return periods for such extreme events can also be queried for the future using an array of future scenarios of climate change, as released by the IPCC. One of the distinct advantages of using the generator is that it allows rapid generation of place-based sea level scenarios, which accounts for some uncertainties associated with emissions scenario (Kay and Travers, 2008). The coastal flood model is spatial and allows the user to examine changes in the areas of potential inundation from the combined effects of sea-level rise and extreme storm events. SimCLIM would seem to have considerable potential for application but further validation on other parts of the coast, particularly those that do not show a consistent trend of shoreline displacement, are needed. It would also be very useful if this approach incorporated shoreline models other than just the simple Bruun rule (for example those described by Cowell *et al.* 2006), and could be integrated with mapping such as that undertaken by Sharples (2004) in Tasmania, Australia.

According to the experience of the National Climate Change Adaptation Research Facility[14] in using SimCLIM, there are three major areas of uncertainty in the generation of scenarios which are treated independently and for which ranges of uncertainty can be taken into account:

- GHG emissions (which determine the rate of change of GHG concentrations and associated radiative forcing). The six key IPCC SRES marker scenarios, spanning low to high emissions, can be chosen individually in scenario generation within SimCLIM;

[14] Source: http://www.nccarf.edu.au/node/554; (last access: 4.04.2011).

- The climate sensitivity (which determines the magnitude of global warming for a given change in GHG concentrations). The "climate sensitivity" refers to the responsiveness of the climate system to changes in atmospheric concentrations of greenhouse gases. Conventionally, the climate sensitivity is defined as the equilibrium change in global-mean temperature for a doubling of CO_2. Different GCMs produce different values for the climate sensitivity due to differences in the way in which climate feedbacks – e.g. changes in snow and ice cover, clouds – enhance or dampen the direct radiative forcing from GHGs. The SimCLIM user can select from a low, "best estimate" and high climate sensitivity, a range of uncertainty corresponding to the 90% confidence interval in accordance with that used by the IPCC Fourth Assessment Report;
- Spatial patterns of change from GCMs (which determine the regional differences in changes in temperature, precipitation and other climate variables). SimCLIM has sets of results from 21 GCMs (see below), which can be used either individually or in ensembles (combinations of GCMs). For the latter, the user can select the "best estimate" (median value) or select a percentile range to represent the uncertainties.

4.4.4 RegIS – Regional Impact Simulator

The aim of the RegIS and RegIS2 projects was to simulate the effects of future climate change and socio-economic change in two regions of the United Kingdom: East Anglia and North West England. Funded by the UK Department for Agriculture (formerly MAFF and presently DEFRA), the project studied a range of cross-sectoral impacts in response to both socio-economic and climate change. These included the impacts of river and coastal flooding, agricultural land use change, coastal ecosystems, wetland habitats, and water resources. The project considered a range of global or regional socio-economic scenarios developed via stakeholder consultations, as well as climate change projections from UKCIP02. The benefits of this unique approach are that it allows decision makers to understand the impacts of different policies, such as improving coastal defences and managed retreat, on relevant issues such as coastal ecosystems, species and habitats protection, and agricultural land use. In order to communicate these complex socio-economic and climate change scenarios, the project developed the Regional Impact Simulator (also called RegIS), which is a software tool designed specifically for the stakeholder community to investigate the sensitivity of an indicator, the effects of uncertainty in the future scenario, and regional adaptive responses to climate change.

Among others, the Regional Impact Simulator analysed how climate change and floodplain management options affect designated habitats and agricultural land use in the coastal zone (Nicholls and Wilson, 2001; Richards *et al*. 2008).The potential impacts and adaptations were analysed for three habitat types in floodplains (saltmarsh, coastal grazing marsh and fluvial grazing marsh), selected species, and agricultural land use.

In addition to climate change scenarios for future sea level rise, RegIS allows the user to select four distinct, evolving, socio-economic scenarios for the 2050s:

- Regional Stewardship – strong emphasis on conserving regional assets, even at the expense of regional economic growth. Local natural assets are highly valued;
- Global Markets – potentially the most environmentally damaging. Privately funded coastal defences, protect high value economic assets, but lower standard of government protection than at present. Realignment of defences due to unplanned abandonment, rather than strategic management;
- Regional Enterprise – increasing development in both coastal and floodplain areas, likely causing environmental degradation. A 'hold the line' shoreline management plan is expected, causing reductions in sediment supply to habitats such as saltmarshes;

- Global Sustainability – implies less socio-economic pressures on habitat and ecosystems; large scale managed realignment of relatively undeveloped coastal areas, allowing autonomous adaptation to climate change; strict planning regulations on expansion of urban development.

Projections of climate change are integrated with the above scenarios and assessed with regard to saltmarsh habitat change, coastal grazing marsh change, and change in potential suitable climate space of 8 key species. The change in saltmarshes is assessed by their ability to respond by either accreting vertical if sediment is available, or by migrating inland if space is available. The impacts on coastal grazing marsh are dominated by coastal management decisions under the above socio-economic scenarios, since they are largely dependent on the presence of sea defences. A key finding from the study is that management choices have a greater potential impact on habitat viability than climate change.

The Regional Impact Simulator (Holman *et al.,* 2008) applies the impacts methodologies and socio-economic scenarios described above, along with projections of sea level rise from UKCIP02 and tidal range observations. This 'metamodel' allows the user to explore a wide range of possible adaptive responses to climate change. In the case of wetland habitats, this includes:

- No planned creation – essentially a 'do nothing' approach;
- Maintain existing stocks – current UK policy is continued, implying maintenance of existing habitats, or like for like compensation of lost habitats;
- Double existing stocks – double the present day area of each habitat type by the 2050s;
- Maximum creation – the maximum possible habitat area by the 2050s.

The RegIS tool also allows for the user to explore the impacts of various sea defence scenarios, including no upgrade, upgrade of existing defences, and enhanced upgrade of defences (see Mokrech *et al*., 2008) on the distribution of key species and habitats within the coastal zone.

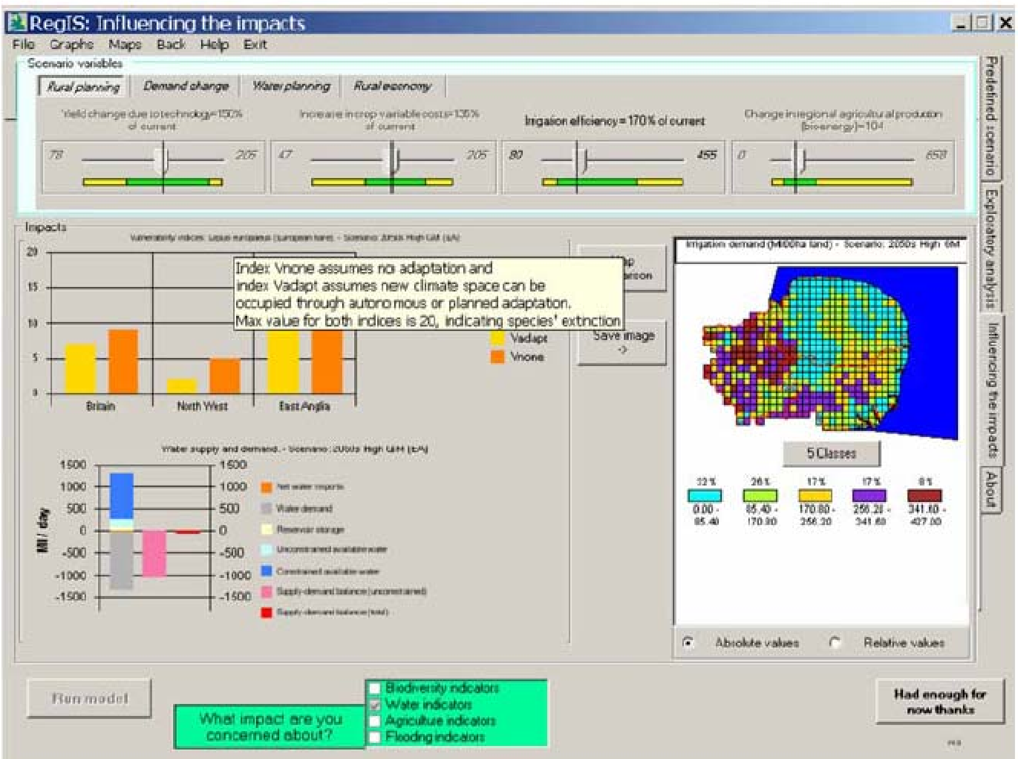

Figure 4-16 The 'influencing the impacts' screen for testing regional adaptation responses to identified impacts (source: Holman *et al*. 2008)

The authors suggested that the RegIS methodology could be expanded to cover the whole of the UK, using similar data sources. The on-going CLIMSAVE FP7 project will extended this tool at the European level at 18 km grid resolution. CLIMSAVE will use the integrated methodology developed by RegIS to evaluate cross-sectoral interactions between the key sectors that drive land cover change across Europe (agriculture, forestry, biodiversity, coastal and river flooding, water resources, urban development and transport). Furthermore, CLIMSAVE will develop a web-based platform for use by stakeholders.

4.4.5 Delft3D

Delft3D is a 2D/3D modelling suite to investigate hydrodynamics, sediment transport, morphology and water quality for fluvial, estuarine and coastal environments. It has been used for simulation of change in physical conditions along coastlines in several countries, e.g. Netherlands, USA, Hong Kong, Singapore, Australia, Italy, etc. The model seems to be under active testing and application work in different local settings in many types of environments (around the globe).

The source code of the Delft3D modules FLOW + MOR + WAVE is available as free software under GNU General Public License (GPL). User manuals and tutorials are available in interactive screencasts on the Delft3D open source community website (http://oss.delft3d.nl; last access: 9.08.2011).

In general, Delft3D has shown to be robust and accurate in predicting near-shore flows. Also, good long-shore current results can be received, when proper empirical constants are used (Hsu *et al*., 2006). Inlet migration and closure in micro-tidal, wave-dominated coastal environments with strong seasonal variations in river flow and wave climate have been studied, and fairly good results in identification, classification and quantification of these phenomena have been documented (e.g. Tung *et al*., 2009). The model has also been used successfully to simulate the effects of large scale sand mining on coastal currents (Van der Welf *et al*., 2011). The forecasting ability of the Delft3D modelling suite has been demonstrated in real time for an area in the Northern Gulf of Mexico (Edwards *et al*., 2009). Comparisons between estimated and measured wave parameters showed an underestimation in wave height by the model. Unlike bathymetry, the results showed more sensitivity to wind input and wave boundary conditions.

Due to the high calibration effort and especially the large computational time, a full three-dimensional (3D) simulation is generally not very practical with this model. Some efforts have been made for future improvements of the model's applicability. Henrotte (2008) studied implementation, validation and evaluation of a Quasi-3D model in Delft3D to achieve acceptable simulation results with less computational time. The simulation was made in near-shore areas where breaking waves cause secondary return flow currents. The results were compared to 2D and 3D simulations. According to the findings of the experiment, in the hydrodynamics section the Q3D cross-shore velocity profiles show high agreement with 3D velocity profiles in both shape and magnitude. Further, long-shore velocity profiles show the same logarithmic shaped profile for both Q3D and 3D model results. In sediment transport, Q3D equilibrium concentrations are higher than 2DH concentrations. In morphology, the profile model shows an increase in an offshore bar migration for Q3D modelling compared with 2DH and 3D. Finally, Q3D erosion and sedimentation patterns show high similarity with 3D model results.

The Delft3D package includes visualization tools. Service Packages and pre-and post-processing tools (QUICKPLOT, OpenEarth, RGFGRID, QUICKIN, Delft Dashboard) are available and an open source Delft3D community website is maintained.

Generally speaking, Delft3D is an excellent tool for robust simulation of processes in relatively simple topographic and bathymetric conditions. Although such conditions can be found in many low lying coastal areas that also coincide with dense human populations, evidence remains scarce of the applicability of Delft3D in complex coastal environments, such as the European coastline. The main arguments against using the model for political and administrative decision making throughout the European coastline are as follows:

- as a 3D model, it carries many uncertainties due to relatively preliminary stage of development of all this type of models;
- the model requires large calibration effort and computational time which reduces applicability (this can be partly avoided, however, by using a Quasi-3D form of the model – Henrotte, 2008);
- the model requires fairly detailed site specific data which is often relatively difficult to get (McLeod, 2010). Such data is currently not available for long stretches of the coasts of European seas;
- for the moment, Delft3D has not been developed to meet the requirements of topographically and climatically extreme environments, such as archipelagos or sea areas with regular ice cap in winter time.

4.5 Advantages and disadvantages of the main approaches

Table 4-7 summaries the main characteristics of the assessment methods illustrated in the previous sections of chapter 4, in particular: index-based methods (section 4.1), the Eurosion indicator-based approach (section 4.2), DEYSCO GIS-based DSS (section 4.3) and methods based on dynamic computer modelling (section 4.4). DESYCO and model-based approaches are further analysed in Table 4-8, including a short description of each method and its main strengths and limitations with a view to the possible application for the assessment of coastal vulnerability to climate change at the scale of Europe and Regional Seas.

Indicators and index-based approaches are generally simple to implement. Their application at the scale of Europe and Regional Seas essentially depends on data availability. This could be a limiting factor in the practical application of some of the discussed methodologies at the scale of Europe or Regional Seas. Adjustments of the methodology may also be needed in order to address relevant characteristics in different regions and/or to make best use of available data. Indicators or index-based approaches are useful tools for a scoping or “first look” assessment - thus supporting identification of priority vulnerable coastal areas and systems - although they are not useful for a more detailed quantitative assessment of costal vulnerability and the related identification of adaptation measures. Due to their simplified approaches, indicators and indices can be also very useful for communication purposes. Index-based approaches are not immediately transparent since the final computed indices do not allow the user to understand the assumptions and evaluation that led to its calculation. A clear explanation of the adopted methodology is therefore essential to support the proper use of these methods.

Based on the analysis of main advantages and disadvantages (Table 4-8) as well as of the main characteristics summarised in the overview table (Table 4-7), the following conclusions can be drawn in relation to the possible use of models to assess coastal vulnerability to climate change at the European and Regional Sea level. The following models are not considered to be well suited for the EEA assessment objectives:

- BTELSS, due to its focus on the local to regional scale, its focus on wetlands vulnerability and the high expertise required to run this tool, which was developed mainly for research purposes.
- SLAMM, mainly because it requires data on a large range of variables, which are not generally available at the European or Regional Sea level, and the medium-high expertise to run it (ETA-ACC, 2010b). Furthermore, similar to BTELSS this model is specifically tailored to the analysis of coastal wetland changes and vulnerability;

- RACE, like other sector models focusing on specific coastal process (i.e. coastal erosion in the case of RACE), can in principle be useful to support detailed assessment of specific vulnerability aspects. However, the use of RACE strictly depends on up-scaling the methodology to the European level. Up to now the model has been specifically developed to assess hazard and risk of coastal erosion from the local to the national scale (i.e. England and Wales).
- FUND, mainly because of its coarse spatial resolution (16 world regions only) and the difficulty of identifying and validating the underlying data sources and impact response functions.
- Delft3D, mainly for the high demand for site-specific data and expertise (e.g. for calibration) that limits its application at the European level. Analogous considerations can be made for other oceanographic and coastal models developed for coastal engineering application (e.g. MIKE 2D and 3D).

The following methods are considered suitable for EEA assessment objectives:

- DIVA can properly support coastal vulnerability assessment from global to national level, addressing various key coastal impacts and including selected adaptation strategies in the analysis. DIVA has already been applied at the European scale and its possible future development will likely improve essential features (e.g. higher resolution segmentation of the coastline, application at the regional sea scale, further exploration of patterns of local sea level rise and land subsidence, further adaptation options and strategies) for its application at this scale.
- RegIS is a tool based on an integrated approach to coastal zone impacts and vulnerability assessment. Up to now it has been applied at the regional scale in UK; its applicability over the whole UK is considered to be feasible (see section 4.4.4). The on-going CLIMSAVE FP7 project will extend this tool to the European level at 18 km grid resolution. This model is therefore considered to be relevant for EEA objectives and requirements.
- The local to regional GIS-based DSS DESYCO enables the investigation of multiple climate change impacts on coastal areas. It is a flexible tool allowing the identification of vulnerability priorities and is able to deal with the analysis of uncertainty related to data input and resulting output. Main current limitations are related to the limited availability of well differentiated test areas, in particular at the European scale. However, as expressed during the EEA experts workshop in June 2011 DESYCO can in principle be up-scaled to the European level, in a relatively short time scale and with relatively limited resources.
- SimCLIM can in principle be considered useful to support EEA objectives and requirements due to its main strengths that include scale and temporal flexibility, user-friendliness and integrated assessment. However, the use of this software modelling systems requires medium to high expertise for its customisation to new regions (ETC-ACC, 2010b). As suggested during the June 2011 EEA experts workshop the main limitation to its application at the European scale is related to limited availability of experienced users across Europe. Moreover, SimCLIM is licensed commercially; its cost depends on the specific application needs and the required expertise (ETC-ACC, 2010b; Mcleod *et al*., 2010).

Table 4-7 Overview table of main methods' characteristics

Method	Spatial scale	Spatial resolution	Temporal scale	Main driver of changes	Main climate change impacts	Coastal systems	Assessment targets	Adaptation measures	Main data input	Output
Eurosion	European scale	Indicators and indexes were calculated at the regional level, i.e. NUTS 1 or NUTS 2 depending on the country	Depending on time scale and resolution of input data	Sensitivity indicators, e.g. sea level rise, shoreline evolution, sediment budget, etc.	Coastal vulnerability to erosion	Coastal zone in general	Targets represented by the impact indictors, i.e. population, urban and industrial areas and areas of high ecological value	Partially addressed by the indicator "engineered frontage", also including protection structure	Eurosion database: terrestrial boundaries, maritime boundaries, shoreline, bathymetry, elevation, geomorphology and geology, erosion trends and coastal deference works, hydrograph, infrastructure, wave and wind climate, tidal regime, sea level rise, land cover, areas of high ecological values	Sensitivity score Impact score Finale score, i.e. exposure to coastal erosion
CVI Index	Applied at the local, regional, supra-regional scale. Theoretically it can be applied to any spatial scale; it depends on data availability	Depending on the considered spatial level and data availability	Depending on time scale and resolution of input data	Sea level rise	Coastal vulnerability to sea level rise, in particular due to erosion and/or inundation	Coastal zone in general	Physical system	Not addressed by the index	Data input depends on key variables used to calculate the CVI index. Most common ones include: geomorphology, geology, elevation, coastal slope, shoreline change rates, significant wave height, relative sea level change, tidal range	CVI tables and maps; CVI is classified in groups using percentage limits
CVI (SLR)	Applied at the local scale. It appears to be suitable for the regional scale as well. Actually spatial scale of application depends on data availability	Depending on the considered spatial level and data availability	Depending on time scale and resolution of input data	Sea level rise	Coastal erosion, flooding due to storm surges, permanent inundation, salt water intrusion to groundwater resources and salt water intrusion to rivers/estuaries	Applied to a delta area by Özyurt (2007) and Özyurt *et al.* (2008). Theoretically it can be applied to the coastal zone in general	Physical system; some component of the socio-economic (i.e. land use) and ecological systems (i.e. natural protection degradation) are considered	Considered in terms of evaluation of coastal protection structures	12 physical (e.g. geomorphology, sediment budget and water depth at downstream) and 7 human influence (e.g. reduction of sediment supply and land use pattern) parameters	5 CVI sub-indices, each one related to a specific sea level rise impact. These are integrated in a final CVI (SRL) index.
Composite Vulnerability Index	Applied at the regional scale in Brazil (State of Para). Spatial scale of application depends on data availability	Depending on the considered spatial level and data availability In the application to the State of Para, spatial resolution was the census collection area (343 in total)	Depending on time scale and resolution of input data	Natural and socio-economic parameters used to derive the index	The index assesses coastal vulnerability in general, i.e. not specifically referring to climate change vulnerability. It also considers coastal flooding that can be strongly influenced by climate changes drivers.	Coastal zone in general	Physical and socio-economic targets	Considered in terms of evaluation of coastal protection measures	Natural parameters: coastline length and sinuosity, continentality in terms of coastline density into municipal areas, coastal features (estuarine, beach etc.), coastal protection measures, fluvial drainage, flooding areas. Socioeconomic parameters: population and population affected by floods, density of population, non-local population (i.e. born elsewhere but living in considered areas), poverty, municipal wealth	Three different indices: natural, socio-economic and total vulnerability index. Indexes can be represented in maps
Multi-scale CVI	Applied from the local to the national scale. Actually spatial scale of application depends on data availability	National scale: 500 X 500 m² grid cells Regional scale: 25 X 25 m² grid cells Local scale: 1 X 1 m² grid cells Spatial resolution depends also on data availability	Depending on time scale and resolution of input data	Forcing variables contributing to wave-induced erosion, i.e.: significant wave height, tidal range, storm and modal wave height, storm frequency	Coastal erosion	Different typologies of coast (e.g. cliff, sandy beaches)	Mainly socio-economic targets	Not addressed by the index	Key variables are defined according to the specific application (location and scale). Variables refer to: (i) resilience and coastal susceptibility to erosion, (ii) forcing variables contributing to wave-induced erosion, (iii) socio-economic target potentially at risk	Three sub-indices: (i) coastal characteristic sub-index, (ii) coastal forcing sub-index, (iii) socio-economic sub-index. Final CVI index. Indices can be represented in maps
DESYCO	Mainly regional (i.e. sub-national)	Spatial resolution depends on data availability and on the processes simulated by embedded models	The method can provide assessment for any future scenarios, and specifically for 2050 and 2100 according to climate projections.	Sea level rise, storm surge, main climate change drivers	Sea level rise inundation Storm surge flooding Erosion Impacts on soil and groundwater Impacts on water quality Impacts on biodiversity	Various coastal systems, including: beaches and dunes, estuaries and deltas, wetlands, protected areas, coastal urban areas, coastal agricultural areas, fishery and aquaculture systems	Socio-economic and ecological targets	Not directly addressed by the method. It is possible to evaluate the efficacy of different adaptation measures (e.g. artificial protections, mobile barriers and dikes) in relation to different sea level rise scenarios	Climatic data, DEM//topography, bathymetry, coastline and coastline variations, land cover and land use, geomorphological maps, relevant areas of environmental interest, river and channels maps, protected areas maps, fish farming data	Hazard maps Exposure maps Susceptibility maps Value maps Vulnerability maps Risk maps Damage maps

Method	Spatial scale	Spatial resolution	Temporal scale	Main driver of changes	Main climate change impacts	Coastal systems	Assessment targets	Adaptation measures	Main data input	Output
BTLESS	Local and regional (1 km^2 - 100.000 km^2)	1 km^2	Variable time-steps (from 12 seconds to daily) Simulation time up to 100 years	Sea level rise, dry and wet conditions (extreme events), rivers discharge, ecological and physical feedbacks	Wetland changes	Wetland systems	Ecological systems: wetlands	Not addressed by the model	DEM, bathymetry, climatic data, salinity, river discharges, sediment loads, wetland land cover, habitat maps, specific data on plants (such as growth and mortality, salinity and flooding tolerance).	Maps of land changes (habitat switching), flooded and eroded areas Other maps, related to changes in salinity, sediment balance, plant productivity, etc.
SLAMM	Local and regional (1 km^2 - 100.000 km^2)	10 - 100 m; the model uses cells, usually 30 x 30 m	Time-steps of 5-25 years (based on the considered SLR scenario)	Sea level rise projections	Inundation Habitat changes: erosion-accretion, overwash, soil saturation, salinity Habitat shift	Coastal habitats, including: mangroves, other tidal wetlands, deltas, estuaries, coastal bay, barrier island, etc.	Ecological systems: coastal habitats and species Socio-economic component is not included	Not addressed by the model	SLR, tidal data, elevation (DEM and LIDAR), wetland land cover, other detailed wetland information, human infrastructures (e.g. dike location)	Maps of flooding risk for coastal ecosystem and habitats Tables and graphs
RACE	Local to national	Variable, depending on data available	Present day baseline with projections up to 2105	Failure of sea defences and natural rate of coastal erosion	Erosion impacts on multiple receptors including agricultural land, national property database, economic losses RACE project used complement tools for flood risk assessment	All coastal areas	Private property, built assets and agricultural land	Not directly assessed	Expert judgement on the probability of defence failure and the natural erosion rate, validated by existing data, and field observations where possible	Maps of coastal erosion hazard, overlaid with locations of vulnerable assets to create 'risk' maps
FUND	Regional to global	Coarse spatial resolution (16 world regions only)	From 1950 to 2300 with time step of one year	Global warming, climate change, sea level rise	Mainly economic impacts and benefits of climate change (and international greenhouse gas emission reduction policies)	It does not specifically focus on coastal systems	Economic costs and benefits	Addressed by the model	Population data and scenarios on emissions, climate condition, sea level and other impacts	Rates and statistics for decision makers
SimCLIM	Local to global; Scale can be customised by the user	The model contains a custom-built GIS and can thus be applied spatially to any geographic area and spatial resolution	Variable, depending on impact model being run	Relative sea level rise, climate variability and change (including extreme)	Inundation Coastal erosion Biophysical impacts on agriculture, coastal area, human health, water, etc.	Any kind of coastal systems	Socio-economic and ecological targets	Addressed by the model. Adaptation measures can be tested for present day conditions and under future scenarios of climate change and variability.	Elevation, climate data, sea level change scenarios Specific impact models data	Spatial and site-specific scenarios of climate and sea-level changes (including changes in the risks of extreme events) and their sector impacts. Formats include maps, time-series projections, and graphical and tabular output.
DIVA	Sub-national to global	Coastline segments of 70 km	5 years time step, simulation time up to 100 years	Global or regional sea level rise, population growth, GDP growth, land-use change	Coastal and river flooding, coastal erosion (both direct and indirect), wetland change, salinity intrusion into rivers	Coastal zone in general	Socio-economic and ecological targets	Addressed by the model	Elevation (SRTM), coastal geomorphology, coastal population, GDP, land use, administrative boundaries	Estimates of population flooded, wetland changes, damage and adaptation costs, amount of land loss
RegIS	Local to regional Climsave FP7 project will apply RegIS to European scale	5 km grid resolution, Climsave FP7 project will apply model to European scale at 18 km resolution	Depending on time scale and resolution of input data	Relative sea level rise, stakeholder derived socio-economic scenarios, land use	Coastal and river flooding, agricultural land use, water resources, biodiversity, coastal ecosystems.	Coastal ecosystems, agricultural land use	Socio-economic and ecological targets	Only spontaneous adaptation considered, no proactive adaptation. However, tools are available for assessing the effects of the adaptation response	Flood plain maps, flood risk area, sea defences, elevation, land cover, coastal habitats database, existing and proposed sites for managed realignment, tidal surge data	Maps and graphs of changes in ecosystems, species' ranges and land use in response to scenarios of socio-economic and climate change
Delft3D	Primarily local to regional, spatial scale of application possibilities are determined by data availability	Defined by the user	From minutes up to morphological time scale (100-1000 years)	Wind, wave, tide, storm surge, currents, sediment patters, sea level rise	Multi impacts: changes in physical drivers (e.g. hydrodynamics, sediment transportation, wave and tidal forces), impacts on water quality, water stratification, salinity intrusion, coastal and river flooding, coastal erosion, etc.	Any kind of coastal systems	Coastal physical system (it performs better on relatively simple topographic and bathymetric conditions)	Not directly addressed by the model	Meteorological, hydrological, topographic and bathymetric data, land use and land use planning. Detailed site-specific data are required	Model results can be represented as maps, graphs and tables Delft3D provides a flexible, modelling suite, including visualization tools

Table 4-8 Advantages and disadvantages of main GIS-based decision support systems and model-based methods (based on ETC-ACC, 2010b and McLeod *et al*., 2010)

Short description	Advantages	Disadvantages	References
DESYCO is a DSS for the assessment and management of multiple climate change impacts on coastal areas and related ecosystems (e.g. beaches, wetlands, forests, protected areas, groundwater, urban and agricultural areas). It adopts an ecosystem approach and implements a Regional Risk Assessment (RRA) methodology, based on Multi-Criteria Decision Analysis (MCDA), in order to identify and prioritize areas and targets at risk in the considered region. DESYCO includes the analysis of different climate change related stressors (e.g. sea level rise, storm surges, waves, water temperature and salinity) and affected resources (e.g. water, soil, biodiversity) in order to assist coastal communities in planning adaptation measures. DESYCO is integrated with a GIS and implements GIS functionalities based on open source libraries. The GIS in particular allows a quick visualisation and comparison of the assessment for different segments of the area of interest, and supports the prioritisation of coastal targets for planning of adaptation measures.	Investigation of cascading processes at the regional/local level Ranking of relative vulnerabilities in the examined coastal territory and definition of priorities Sensitivity analysis allowing to evaluate the influence of input uncertainty on output uncertainty DESYCO structure is not limited to a fixed suite of models and/or scenarios. The model chain can be fitted to different case studies	Building a multi-model chain requires great initial efforts in terms of time and resources and the tool is applicable only for the study area of concern. The heterogeneity of data sources, formats, and spatial scales Limited availability of well differentiated test areas, in particular concerning the local and regional scales	Torresan *et al*., 2010
BTELSS represents a landscape model specifically developed to investigate and predict the environmental factors affecting wetland habitat change within the Barataria and Terrebonne basins of the Louisiana coast for a 30-year time scale. The model links an overland flooding hydrodynamic module, using cells of 100 km^2 in size and operating at a 1 hour time-step, and a spatially articulated ecosystem module, resolving habitat type and change for 1 km^2 cells in daily time steps. Integration across different temporal and spatial scales is accomplished with interpolation routines and averaging algorithms. Forcing functions includes dominant regional processes, such as subsidence, sedimentation and sea-level rise. Main characteristic of BTELSS is the focus on wetlands. It incorporates a range of factors including: coastal and estuarine hydrodynamics, water-borne particle transport and vegetation growth; infrastructure risk exposure can be added along with feedbacks among them. Thus BTELSS can provide detailed projections of wetland habitat change at local and regional scales (McLeod *et al*., 2010).	Capacity to provide a comprehensive range of factors when applied to river basin districts, coastal and transitional waters, coastal wetlands Very useful for detailed projections of wetland habitat change at local scales	Focus on wetland and related changes Complex model to be run, requiring high expertise and not easily obtainable data Rather expensive (>$150,000 USD) It appears difficult to validate and calibrate due to the high level of aggregation and the complexity of the subsystems and their interactions; thus its primary application is for research	Reyes *et al*., 2000 Martin *et al*., 2002
Sea Level Affecting Marshes Model (**SLAMM**) was developed with EPA funding by Richard A. Park. SLAMM simulates the dominant processes involved in wetland conversions and shoreline modifications due to long-term sea level rise. Map distributions of wetlands are predicted under conditions of accelerated sea level rise, and results are summarised in tabular and graphical form. The model can be applied at scales ranging from 1 km^2 to 100.000 km^2 (local – regional). It can provide detailed information about the vulnerability of coastal habitats (e.g., mangroves, other tidal wetlands, barrier islands, beaches) and species (e.g., sea turtles, nesting birds) to changes in sea level, and can provide detailed information regarding how habitats may shift in response to these changes.	Wide application scale (from 1 km^2 to 100.000 km^2) Provides useful, high-resolution, insights regarding how sea-level rise may impact some coastal habitats Low or medium cost	SLAMM is tailored for coastal habitats (in particular wetland) and related changes Lacks feedback mechanisms between hydrodynamic and ecological systems that may be altered by changes in sea level It does not include a socioeconomic component Incorporates a large number of variables and requires medium-high expertise to be run	Park *et al*., 1989 Park *et al*., 2003 SLAMM, 2010

Short description	Advantages	Disadvantages	References
The aim of the **RACE** project was to develop and disseminate a robust and consistent probabilistic assessment of the hazard and risk of coastal erosion in the UK. Co-funded by the UK Department for Environment Food and Rural Affairs (DEFRA) and the Environment Agency (England and Wales), the methodology developed follows a source-pathway-receptor approach to risk analysis. The techniques developed within this framework include: • Source - Assessment of potential failure of existing coastal defences over time, and the unconstrained natural erosion of coastal landforms • Pathway - The probability of erosion given the influence of the coastal defences, forms the hazard assessment • Receptor – The spatial combination of the hazard assessment with socio-economic vulnerability data to create a risk assessment. This lead to the creation of a National Coastal Erosion Risk Map for England.	Innovative methodology for assessing probability of failure of coastal defences, natural erosion rates, and ranges of uncertainty Different potential rates of coastal erosion are assessed in the event of failure of coastal defences Methodology includes risk assessment of exposure of coastal assets	Because RACE is driven by risk to people and property, erosion of foreshore features is considered in the analysis of backshore erosion but is not explicitly described in model outputs Scenarios of future socio-economic development are not considered Incorporation of latest sea level rise projections has been undertaken through sensitivity testing rather than by comprehensive analysis of climate scenarios, in order to pragmatically meet project timescales.	Halcrow Group Ltd, 2007
The Climate Framework of Uncertainty, Negotiation and Distribution (**FUND**) model of climate economics, developed by Richard Tol and David Anthoff (http://www.mi.uni-hamburg.de/FUND.5679.0.html; last access: 10.08.2011), is widely used, both in research and in the development of policy proposals. FUND is an integrated assessment model of climate change. Although it is not specifically designed for coastal vulnerability and impacts assessment, it can provide information about climate change consequences in a dynamic context. It aggregates scenarios with a great variety of models (population, economics, greenhouse gas emissions, sea-level, etc.). Spanning the whole problem from demography to atmospheric chemistry and back, and covering the whole world (16 major regions are identifies) and the next two centuries, FUND evaluates the impacts and benefits (mainly economic) of climate change and international greenhouse gas emission reduction policies and identifies policy strategies that are either efficient or cost-effective from either an individual or a collective viewpoint.	Flexibility of the model allows inclusion of already developed and new modules Good option when it is required an assessment of vulnerability from an economical point of view Model covers all of Europe (in fact, it is a global model)	Coarse spatial resolution (16 world regions) Focus on economic impacts Non-user friendly interface Adaptation response to sea-level rise is more complex than the benefit-cost approach used in FUND (Ackerman and Munitz, 2011) High expertise is required to run the model to obtain useful outputs that are understandable by decision makers (ETC-ACC, 2010b)	Tol, 2006a; 2006b Narita *et al*., 2009; 2010 FUND, 2010
SimCLIM is a computer model system for examining the effects of climate variability and change over time and space. SimCLIM is based on an "open-framework" feature that allows users to customize the model for their own geographical area and spatial resolution and to attach impact models. The main objective is to support decision making and climate proofing in a wide range of situations where climate and climate change pose risk and uncertainty. Vulnerability can be assessed both currently and in the future. Adaptation measures can be tested for present day conditions and under future scenarios of climate change and variability. With the program, users can conduct sensitivity analysis and examine sector impacts of climate change. SimCLIM can be applied from local to global scales and it includes a sea-level scenario generator which allows the inclusion of regional and local parameters linked to the coastal areas and a simulation model of shoreline changes for beach and dune systems.	It supports integrated impact analysis at various spatial scales (from local to global) It is user-friendly and quick-running; it is flexible in generating scenarios and examining uncertainties It allows users to examine climate variability and extremes as well as long- term change	Sea-level scenario generator is adaptable to some General Circulation Models (GCMs), but not to all Disadvantages related to the use of GCMs More advance shoreline model, apart from the used Bruun rule, may be required to improve the assessment of coastal erosion (Cowell *et al*., 2006)	Warrick *et a*l., 2005 Warrick and Cox, 2007 Warrick, 2009a; 2009b SimCLIM, 2010

Short description	Advantages	Disadvantages	References
The **DIVA** tool is an integrated, global model of coastal systems that assesses biophysical and socio-economic consequences of sea-level rise and socio-economic development taking into account the following key impacts: coastal erosion (both direct and indirect), coastal flooding (including rivers), wetland change and salinity intrusion into deltas and estuaries. DIVA also enables to take in consideration within the assessment adaptation in terms of raising dikes and nourishing beaches (predefined adaptation strategies are used in DIVA). The first version of DIVA was developed within 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). Afterward DIVA has been progressively developed and used in different application. DIVA is currently not available for download due to a lack of resources for maintaining and supporting the software (ETC-ACC, 2010b).	Robust tool for coastal vulnerability assessment from global to national/regional level The tool enables the user to address various key impacts and possible pre-defined adaptation strategies Already used at the European level (Richards J. and Nicholls R.J., 2009; Hinkel *et al*., 2009) Open-source model	Limited model resolution, DIVA is not appropriate for local scale application It does not consider ecosystem-based adaptation measures It requires medium-high expertise	Hinkel and Klein, 2007; 2009; 2010 Hinkel *et al*., 2010 European Climate Forum, 2011
The **RegIS** project (Regional Climate Change Impact and Response Studies in East Anglia and North West England) was a first attempt to quantitatively model the cross-sectoral impacts of climate and socio-economic change within an integrated framework at a regional scale within the UK. The integrated methodology followed a Drivers-Pressure-State-Impact-Response (DPSIR) framework, and considered impacts on coastal areas, river flooding, agriculture, water resources, and biodiversity. The project also developed a software tool (the **Regional Impact Simulator; RegIS tool**) for use by policy makers to analyse the interactions between impacts with differing scenarios of socio-economic development, and different future climates. The tool also allows the user to generate an integrated assessment of the effects of different adaptation strategies. To do this, the software contains a suite of computer models within a user friendly interface that allows the user to: (i) rapidly identify the sensitivity of an indicator to climate change and/or socio-economic change, (ii) investigate the effects of uncertainty in the future scenario, (iii) investigate regional adaptive responses to future change.	Integrated approach to coastal zone impacts, considering agricultural land use, exposed population and coastal ecosystems Coastal and river flood defences are considered, allowing assessment of different adaptation measures Possible changes in coastal ecosystems are assessed due to planned coastal realignment, unplanned losses due to saltwater flooding, and potential changes in agricultural land use. Relatively high model resolution (5 km grid cells) User friendly interface for communication to regional and national policy makers FP7 funding secured for a project that extends this methodology to the European scale under the CLIMSAVE project (2010-2013)	Does not cover economic impacts, or cost-benefit analysis of adaptation Not possible to test effects of pro-active adaptation strategies Scenarios of sea level rise are based on out-dated regional sea level projections from UKCIP02 The RegIS software tool has been designed for the meta-analysis of the results of offline impacts models. In order to implement the approach at the European scale, offline impacts models would need to be calibrated, and run. This would involve some effort from the research community, in addition to the development of a new meta-analysis software tool designed for European users (this will be done by the FP7 project CLIMSAVE, finishing in June 2013).	Nicholls and Wilson, 2001 Holman *et al.*, 2008 Mokrech *et al.*, 2008 Richards *et al.*, 2008
Delft3D is a 2D/3D modelling suite to investigate hydrodynamics, sediment transport, morphological dynamic and water quality for fluvial, estuarine and coastal environments. The software is used and has proven his capabilities on many applications around the world, including for example: the Netherlands, USA, Hong Kong, Singapore, Australia, and Venice. The software is continuously improved and developed with innovative advanced modelling techniques as consequence of the research work of the developing institute. It is an open-source model composed of a number of modules, each addressing a specific domain of interest, such as: flow, near-field and far-field water quality, wave generation and propagation, morphology and sediment transport, together with pre-processing and post-processing modules. All modules are dynamically interfaced to exchange data and results	It can be primarily applied from the local to regional scale (average coastal segment of 70 km) Robustness and accuracy of the modelling suite Incorporates large sets of climate change impacts Open source platform	The validation requires continuous attention. Even though the individual components of the system have been thoroughly tested during their development, the system as a whole requires intensive testing and validation effort. It requires fairly detailed site specific data which is often relatively difficult to get (McLeod, 2010). Applicability to versatile topographic and climatic conditions (e.g. highly fragmented coastlines, variable bathymetry, ice coat) partially questionable for the moment	http://oss.delft3d.nl (last access: 9.08.2011) Hsu *et al*., 2006; 2008

5 Visualisation tools

Once appropriate vulnerability models have been run, and results produced, the information must be communicated in a clear and efficient manner in order for the information to be used successfully by the target audience. The development of web-based GIS applications has improved the usability of GIS methods and data by non-specialists. As a result of these technological improvements, a number of Coastal Web Atlases (CWAs) have been created to help the dissemination of information on the coastal zone. These CWAs provide information to a variety of regional or national level users in the coastal zone. Governments have invested heavily in geospatial data to inform both the general public and decision makers on marine and coastal affairs, therefore the effective communication of this information to users is essential. Coastal Web Atlases have been developed to provide a number of different functionalities. They may be simply tools for serving a geospatial database via a web interface. Alternatively, the most recent generation of tools links multiple servers of data together, and provides interactive tools using the latest visualisation technology. The benefits of using visualisation tools such as these in coastal vulnerability assessments are:

- They deliver information directly to the audience;
- They are visual methods of communication that convey the message faster and more effectively than a written report;
- Information relevant to a specific location can be easily retrieved;
- The selection of spatial layers allows the user to view different vulnerability factors for different parts of the coast;
- Interactive maps can assist the visualisation of multiple scenarios and time steps.

There is also a clear need for better visualisation tools to support European policy requirements. The EU Integrated Maritime Strategy aims to increase resilience in coastal and marine areas and to encourage cost-effective responses to climate change. The European White Paper on adapting to climate change (COM (2009) 147 final) also recommends better access to reliable information in order to aid the integration of adaptation into all EU policies. This is especially relevant for the coastal zone, where integrated management and policy decisions are already being made at local scales. However, despite considerable effort in some coastal regions in Europe, there is currently no Europe-wide coastal web atlas to aid integrated policy decisions in the field of climate change vulnerability and adaptation. The European Atlas of the Sea[15] (still under development) constitutes a relevant tool at the European level and a general framework to link tools more specifically oriented to climate change aspects but it is not specifically focusing on coastal vulnerability and adaptation to climate change. The following sections describe and discuss the merits of the different types of visualisation tools available, and suggest key questions to ask when designing such a tool.

5.1 Existing coastal vulnerability tools

At the level of local to regional planning, web-based tools can provide planners with detailed information on different aspects of coastal zone management. There are a number of features that are common to all of these tools (see O'Dea *et al.*, 2011), such as:

- Map area. Zoom-able and clickable map to allow the user to interrogate geographical data;

[15] http://ec.europa.eu/maritimeaffairs/atlas/index_en.htm (last access: 9.08.2011).

- Geospatial data. Either point, line or area features, or regular gridded raster data. Layers can be overlaid on top of each so that the locations of two or more datasets can be viewed simultaneously;
- Legend / layer list. Allows the user to easily interpret the data being displayed on the map;
- Atlas tools. This includes interactive features that allow the user to query information, select certain features, and possibly use simple spatial analysis tools;
- Attribute tables. Each feature of grid cell in the atlas is linked to a table of information relating to each element in the map. This can provide the user with lots more information than can be displayed in a single map;
- Metadata. Following agreed international standards via the Open Geospatial Consortium (OGC) and the EU INSPIRE Directive, geospatial data now includes basic discovery metadata that helps information systems to quickly retrieve data via queries, and informs the user of information for example regarding the data quality, data owner or data collector.
- Further information. Since most Coastal Web Atlases have strong links to science, or various policy directives, certain themes or data layers will provoke questions of how datasets are created or collected, or why a particular issue is relevant to the coastal zone.

The following Coastal Web Atlases and other Web tools presented will give an idea of the kinds that have been developed, and provide an insight into the possibilities for a tool covering the European regional seas in the field of coastal vulnerability assessment to climate change.

A simple ‘bathtub’ approach

This type of web atlas presents the simple intersection of the projections of sea level rise at either global or regional scale with elevation in the coastal zone. The advantage of this approach is that it shows the user clearly and concisely the low-lying parts of the coastal zone that are projected to become inundated at future time steps under different greenhouse gas emissions scenarios. This allows the user to understand the areas of vulnerability purely from the point of view of exposure to the hazard. A further extension of this approach is to super-impose the natural variability of the sea level over mean sea level projections to understand the possible maximum inland extent of events such as storm surges and high tides.

An example of this approach is the Met Office Relative Sea Level Rise tool (MORSE; see Figure 5-1) which displays projections of the future mean relative sea level intersected with the a high horizontal resolution DEM (SRTM, 90m). This visualises simply the areas of low-lying coast that may become inundated under different emissions scenarios at various future time steps. A significant advantage of this approach is the scalability of the visualisation. This allows the user to identify exposed low lying areas of the coast at a continental scale (i.e. a coarse spatial resolution), and to zoom into areas of interest to obtain more detailed information (at finer spatial resolutions). An example of the tool can be seen in Figure 5-1 below.

Figure 5-1 Hazard classification of coastal areas that are vulnerable to time-averaged relative sea level rise. This map, of the island of Java, Indonesia, shows different levels of exposure to sea level rise in 2099, under the A1FI IPCC SRES scenario (source: De Gusmao *et al*., 2009)

A geospatial data viewer approach

This approach displays geospatial data layers, and is interoperable with other online geospatial data archives. This allows the user to select appropriate geospatial datasets, and query information. Some of these layers maybe the direct results from vulnerability models, or derived indicators from geographical analysis. The emphasis of these tools is to serve data in order to inform either the general public, or local coastal zone management.

One such tool is the UK Coastal and Marine Resource Atlas (CAMRA; available at http://magic.defra.gov.uk; last access: 30.05.2011). CAMRA is part of a wider project called MAGIC which is a geospatial data viewer that brings together information on key environmental schemes. It is a partnership between six UK governmental organisations that have responsibilities in rural policy making and management. MAGIC provides GIS tools to allow people to view and query the available data. Users do not require specialist software and can access maps using a standard web browser. MAGIC also provides links to other sources in order to make best use of the wide range of information available on different websites and Internet portals. This varies from simple hotlinks to web pages containing supporting information to more complex searches between different websites or applications, where data searches can be sent from one website to another. Another tool that presents GIS data and tools is the Erosion Vulnerability Assessment tool (EVA) of the Virginia Institute of Marine Science (available at http://ccrmgis.wetlan.vims.edu/eva_maryland/viewer.htm; last access: 30.05.2011). This is a mapping tool that displays information on the Chesapeake Bay shoreline. The purpose of EVA is to identify coastal areas that have demonstrated historic patterns of instability with regard to erosion, and currently support valued natural, social, or economic resources. As a planning tool, EVA projects shoreline position in 50 years, where resources will be vulnerable, and where the opportunity for shoreline stabilisation or restoration may have the greatest benefits. Other similar tools include:

- Massachusetts Ocean Resource Information System (MORIS; available at http://www.mass.gov/czm/mapping/index.htm; last access: 30.05.2011)
- Marine Irish Digital Atlas (MIDA; available at http://mida.ucc.ie/; last access: 30.05.2011).

Interactive tools

This is a further development of the two previously described methodologies, with the improvement allowing the user to explore in an interactive manner a range of different scenarios, their impacts, and associated confidence in these projections. An example of such a tool is the Sea Level Rise and Coastal Flooding Impacts Viewer from the US National Oceanic and Atmospheric Administration (NOAA; available at http://www.csc.noaa.gov/slr: last access: 30.05.2011). The purpose of this data viewer is to provide coastal managers and scientists with a preliminary look at sea level rise and coastal flooding impacts. The viewer is a tool that uses nationally consistent data sets and analyses to advise the user of the impacts of a range of different scenarios of sea level rise. Data and maps provided can be used at several scales to help gauge trends and prioritize actions for different scenarios. The visualisation tool allows the user to view low lying coastal areas, similar to the 'bathtub approach' discussed earlier, which would be inundated given a certain level of sea level rise. This approach is more sophisticated because the user can move a slider to instantly see the map change. The slider can also be used to assess confidence in the projections of coastal inundation, and inundation displayed on photographs at particular locations. Additionally, the tool displays information on socio-economic vulnerability, changes in marshland habitats, and areas of existing exposure to coastal flooding. The sidebar of the visualisation tool provides an overview description of the data, a section on 'understanding the map', and links to additional information. Another example of a similar tool is the MARCO Portal from the US Mid-Atlantic Regional Council on the Ocean (available at http://maps.tnc.org/MARCO/index.html; last access: 30.05.2011).

One driver for the development of the RACE methodology described in section 4.4.1 was to model erosion predictions consistently around England and Wales to inform planning and policy development. Another reason was to provide a consistent, user-friendly way of communicating coastal erosion risk to the general public, so they could make more informed decisions about where to live and how to engage in discussions about adaptation to coastal change. This has led to the development of the National Coastal Erosion Risk Mapping (NCERM) web visualisation tool. NCERM is being hosted on the England and Wales Environment Agency website[16] alongside already existing maps showing river, sea, surface water and reservoir flooding. Alongside the web tool are various links both to other maps and to a wide range of contextual information about coastal processes, local information, planning and management, and government policy and adaptation assistance programmes. The user sees a UK map as a raster layer showing land use and built assets, and can view any part of the coast they choose. They also see a line denoting the overall management approach being taken for that stretch of shoreline (agreed in strategic "Shoreline Management Plans" by local authorities and other coastal managers in consultation with the public), described in a legend. Clicking on the coloured line at the desired location brings the user to a summary table showing the name of the Shoreline Management Plan (with direct links to the Plan itself), the local authority responsible for managing coastal erosion in that locality, the management approach being taken, erosion predicted over different timescales and a brief explanatory note.

The strength of NCERM's approach lies in relaying complex messages – for example about uncertainty surrounding predicting erosion, and about the ways authorities respond to it – in a simple way to the public, whilst allowing plenty of opportunity for the user to find out more. In this way, the policy driver to increase awareness and understanding of coastal risk and its management should be achieved over time. It will be updated to ensure it takes account of the latest monitoring of coastal change, and "joins up" properly with the Flood Map on the same website. Because it is focussed upon risk to people and property, it does not show erosion of foreshore features – although this could be considered in time.

[16] The NCERM web visualisation tool is not yet on-line at the time of writing this Technical Paper. The following address provides a link to the general England and Wales Environment Agency's Interactive mapping tool: http://www.environment-agency.gov.uk/homeandleisure/37793.aspx (last access: 06.10.2011)

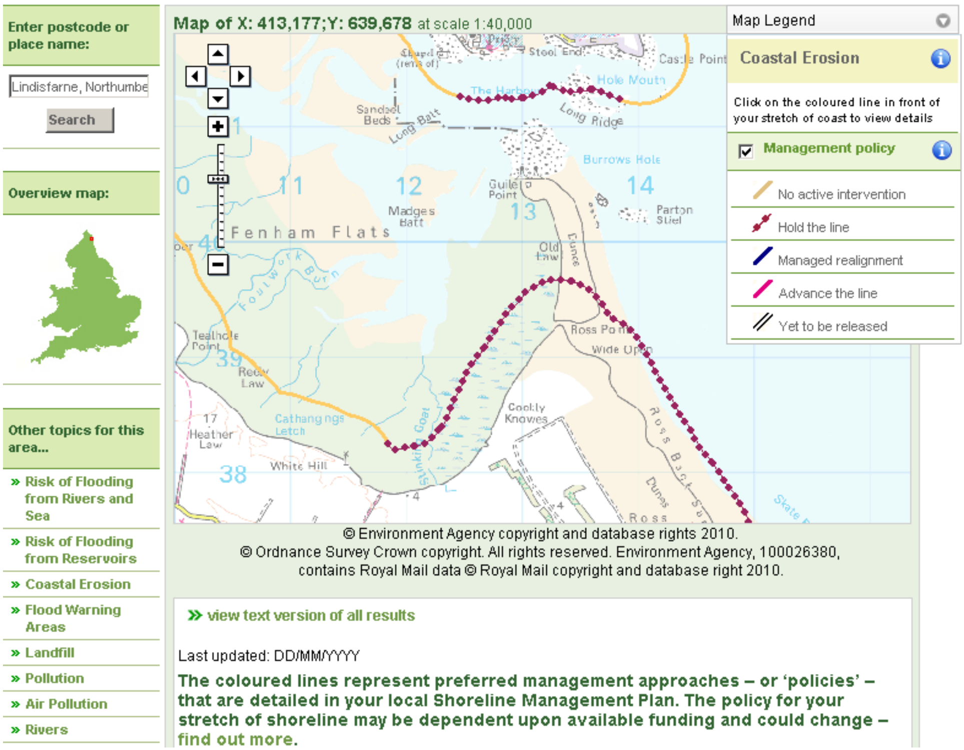

Figure 5-2 Example of an interface of the National Coastal Erosion Risk Mapping (NCERM) web visualisation tool

5.2 Important characteristics of a European Coastal Web Atlas

Any tool produce for the European regional seas should have the goal of clearly presenting indicators developed in a user-friendly interface, but with clear access points to descriptions of the data, and links to further information. The Coastal Vulnerability Assessment approach chosen will also influence the method of presenting the information, but most approaches will produce indicators, and sub-indices that can be visualised in a geospatial web portal. The ability to view multiple scales of information will allow the inter-comparison of different locations at a variety of scales.

O'Dea *et al*. (2011) addressed issues related to the design of a Coastal Web Atlas. Primarily questions such as the following should be asked:

- who is the audience and what are their skills and interests?
- will it be a tool specifically for coastal practitioners or for a much broader audience?
- what resources are available for development and maintenance?
- what data and information should be included?
- what technology and standards should be used?
- how will the system and its content be managed?
- how will the atlas be sustained and updated in the long term?

A cost-benefit analysis should be performed that takes into consideration the cost of web mapping and database software (both proprietary and open source) as well as the programming and maintenance resources which are required in both the short and long terms. The possibility of building on existing technology and mapping applications may further help to reduce costs.

6 Data availability and data needs

Each method requires specific input; however, some input data will be required by the majority (if not all) of the available methods. The present chapter of the paper briefly illustrates the availability and gaps (at the European and Regional Sea context) of those data, basically updating and integrating what is described in the ETC/ACC Technical Paper 2010/8 (ETC/ACC, 2010b).

6.1 Sea level rise

The most comprehensive EU-wide coastal vulnerability assessment was conducted within the PESETA project (Richards and Nicholls, 2009). This assessment applied the DIVA model to a uniform low, medium and high sea level rise scenario for Europe. The values, comprising the whole range, are taken from the global sea level rise projections from the third IPCC report (IPCC, 2001). In the PESETA coastal report the regionalisation is done on basis of relative movement of land (glacio-isostatic adjustment as estimated by Peltier's (1999) geophysical global model and deltaic subsidence, where appropriate, e.g. the Rhone, Po and Ebro deltas) to sea water height. Components that play an important role in semi-closed seas (in particular the Mediterranean and Black Sea), such as salinity and river run-off, are not taken into account. For these seas the global average is applied instead.

The approach based on global average projections allows relative good approximation of sea level rise for the European seas adjacent to the Atlantic Ocean, such as Baltic and the North Sea, especially for the lower bound of the projections. This applies for the absolute sea level, or the level that takes into account only the elevation of the water surface itself, resulting from the changes of the volume of the world's oceans due to changes in temperature and salinity. Relative sea level rise, measured at the coast, is the net effect of changes in absolute sea level and changes in land level. The latter includes different vertical land movements at different time scales, such as sediment compaction, redistribution of mass in the oceans and on the continents due to melting of ice sheets and change in ocean volumes, and vertical tectonic motion causing uplift or subsidence of the coast,

The Baltic Sea is directly connected with the Atlantic Ocean through the Danish Straits. Changes in the sea level in the Atlantic are thus transmitted to the Baltic Sea. Changes in the sea level of the Baltic Sea are, however, also affected by several climatic and non-climatic factors at the regional and local level. These include weather patterns, the circulation pattern within the Baltic Sea and its sub-basins, the fresh water inflow affecting the water balance and the local land uplift. As a result, not all areas of the Baltic Sea will be equally affected (BACC Author Group, 2008). The most serious impacts will most likely affect the south and east parts of the Baltic Sea (Persson *et al*., 2004). In the Gulf of Finland, for example, modest sea level rise can be counterbalanced by the isostatic land uplift, which can reach up to 1 m per century in the Gulf of Bothnia (Johansson *et al.*, 2004). However, extreme sea-level rise scenarios indicate the possibility of sea level rise in the Gulf of Bothnia after 2050 (Leppäranta and Myrberg, 2009).

The factors described above play a role in the other European seas adjacent to the Atlantic Ocean, too. The UKCP 09 projections[17] calculated average sea level rise change at the end of 21st century around the UK in the 12 – 76 cm range. A low-probability high-impact scenario was added that raises the upper bound to 2 m and accounts for massive input from the melting ice sheets. The UKCP 09 scenario projects different local sea levels for different parts of the British Isles. For example, the medium relative sea level rise is 44 cm for London and 30 cm for Edinburgh.

[17] http://ukclimateprojections.defra.gov.uk/ (last access: 9.08.2011)

If big ice sheets on Greenland and Antarctica would start to contribute more and sea level changes according to the upper bound of the projections, for the seas adjacent to the Atlantic Ocean the so called "ice sheet fingerprints" would have bigger impact, which has not been taken into account in most of the studies so far.

When ice masses on land melt, the released fresh water is not distributed evenly over the oceans. Large land-based ice masses exert a gravitational pull on the surrounding ocean, yielding higher relative sea levels in the vicinity of the ice mass. When the ice mass shrinks, this pull decreases, and sea level will actually drop in the vicinity of the ice sheet (the "near field") as water is redistributed away from it. Farther away from the land ice mass, in the "intermediate field", sea level does rise, but this rise is smaller than the global mean rise that would result from equal distribution of the melt water. In the "far field", local sea level rise becomes larger than the global mean rise. Moreover, the solid Earth deforms under the shifting loads and this deformation affects the gravity field, the distribution of the ocean water, and the vertical position of land. As a result of these local gravitational and elastic changes, a shrinking land ice mass yields a distinct pattern of local sea level rise sometimes referred to as its "fingerprint" (Mitrovica *et al*., 2001; 2009).

The elastic and gravitational effects can be incorporated by multiplying each of the global mean contributions from ice melt from glaciers and ice sheets by their respective relative fingerprint ratios. For the coast of the Netherlands, for instance, a fingerprint ratio of 0.45 and 1.2 of Greenland and Antarctic Ice Sheets respectively were adopted in an assessment for the Dutch Delta Committee (Vellinga *et al*., 2008). Farther to the north the fingerprint of Greenland will be even smaller and that of the Antarctic Ice sheet bigger, while for the Mediterranean sea the fingerprint of Greenland will be close to 1, while the fingerprint of Antarctic Ice Sheet will be the same as for the Netherlands. This means that the melting of Greenland will be felt almost as a "global average" in the Mediterranean sea, while the melting of Antarctic Ice Sheet will be 1.2 times the average.

Sea level rise in the cascading Mediterranean and Black seas will change very differently from the global mean for other reasons, too – they are connected with each other and the Atlantic ocean via narrow straits, which will moderate the impact of global mean changes. This distinctive behaviour can be observed now – while Mediterranean sea level is not changing or even decreasing (especially in the Eastern Mediterranean) the sea level in the Black sea is rising faster than the global mean. The reasons for this difference are different for each of these seas. The Mediterranean Sea is a semi-closed, very deep basin, exchanging water with the Atlantic Ocean through the Gibraltar Strait, a narrow passage of approximately 14 km width at its narrowest section and of about 300 m depth. It is a concentration basin where the evaporation greatly exceeds the precipitation and river runoff, thus influencing salinity. A possible increased salinity is one of the physical parameters that may lead to a partial drop in sea level in the Mediterranean because the related possible increase of water density would lead to a decrease in volume. This process represents the halosteric component of the sea level variability (Cazenave and Nerem, 2004). For the lower bound of global sea level projections this could sustain lower regional sea level or can delay the rise by a few decades (Tsimplis *et al*., 2006). A further rise in global mean sea level will cause the corresponding regional sea level to harmonize with the global trend, however; rate of induced changes in the Mediterranean sea level is not fully understood at the moment, also depending very much on the not-very-well known behaviour of the Strait of Gibraltar, thus deserving further investigation (Vellinga *et al.*, 2010), also in relation to the related impacts on the Mediterranean coasts.

The CIRCE project (EU FP6 project)[18] has developed specific modelling scenarios for the Mediterranean (in particular considering climatic variables and the steric component of sea-level change – i.e. the temperature and salinity driven component), by improving resolution, process and feedback representation specifically for the Mediterranean area, on the basis of the extensive modelling experience already available. The ensemble

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[18] http://www.circeproject.eu/index.php?option=com_frontpage&Itemid=1 (last access: 10.08.2011)

of high resolution projections (under the SRES A1B emissions scenario) from CIRCE shows that an average drop of the steric component of the sea level (-0.06 cm/yr) occurred in the recent control period (1961-1990), ranging from a minimum value of about -0.57 cm/yr to a maximum of about +0.17cm/yr. Combining tide-gauge observations and satellite data, Calafat *et al.* (2009) suggest that the steric effects in the Mediterranean Sea might have produced a trend of sea-level change of 0.3 cm/yr for the 1993-2000 period and 0.1 cm/yr for the 1961-2000 time interval. A positive trend (of the steric component) of on average 0.24 and 0.31 cm/yr will dominate in two successive simulated 30-years periods (1991-2020 and 2021-2050, respectively) (Gualdi *et al*., in press; Gualdi *et al*., submitted). The detected trends in both cases are consistent with GCM results reported by Marcos and Tsimplis (2008) and Tsimplis *et al*. (2008). Again under CIRCE simulations, the CMCC model was also forced to cover the period 2050-2100, projecting a rise at a rate of about 0.23 cm/yr of the steric component. Around the year 2080, a plateau is reached in the time-series of absolute sea level rise due to the steric effects. This means that mean sea-surface height values vary similar to the one simulated in the previous period and maintaining the level constant until the end of the modelling period (2100) (Dobricic, 2011; Gualdi *et al*., in press).

The Black Sea is a nearly enclosed basin connected to the Mediterranean Sea by the narrow Bosporus Strait. In contrast to the Mediterranean Sea it is an estuarine basin with low salinity, because its catchment area is about five times larger than the sea, resulting in a very high flux of freshwater (3 × 102 km^3 $year^{-1}$) (Stanev 2005, Kosarev 2008). The total freshwater flux is much higher than evaporation and the inflow of much saltier water from the Mediterranean Sea. The Black Sea, even though directly connected to the Mediterranean Sea, showed an increasing sea level trend since the beginning of 20th century (Stanev and Staneva, 2002), which is in contrast to the observations for the Mediterranean. This specific trend is due to internal (smaller scale) physical processes not related to the global ocean behaviour. However, there are no sea level rise projections for this sea for 21st century. As this basin is nearly enclosed, the impact of global warming will be governed here by changes in river run-off rather than by changes in global mean sea level, at least up to a certain rate of global sea level rise.

In relation to the availability of sea level rise observations and projections (see also Annex 2 of ETC/ACC 2010a) it is possible to derive the following conclusions. The most recent reconstructions of global average sea levels cover the period from 1880 to 2009 (Church and White 2011). They are based on satellite altimeter data and coastal and island sea-level measurements, corrected for glacial isostatic adjustment. Sea level rise projections published after the publication of the 4th IPCC report in 2007 have been mainly at the upper end of the range and beyond the IPCC projections and have been mainly based on semi-empirical approaches and physical constraints. They extend the upper bound of physically plausible sea level rise by the end of the 21st century to about 2m, with the full range becoming 20 cm – 2 m (see for instance Table 6-1 and the review in Nicholls *et al*., 2011).

UK climate projections provided the most recent sea level rise projections for the Atlantic around UK (Lowe *et al*., 2009). For the Mediterranean, Marcos and Tsimplis (2008) produced projections, based on the output of GCMs. These projections cannot resolve the water mass transfer via the narrow Gibraltar strait however. The recently finished FP6 project, CIRCE, has generated new sea level projections for the Mediterranean, based on more detailed, regional model output. Some processes such as the mass transfer via Gibraltar and Bosporus straits, river run-off, vertical mixing and some others are however still insufficiently resolved (Vellinga *et al*., 2010). In conclusion, more realistic scenarios of sea level rise in several European regional seas are needed.

Table 6-1 Recent sea-level rise projections (m/century). (Source: Nicholls *et al*., 2011)

Sea level rise (m/century)	Methodological Approach	Source
0.5 to 1.4	Semi-empirical projection[2]	Rahmstorf, 2007
0.8 to 2.4[1]	Palaeo-climate analogue	Rohling *et al*., 2008
0.55 to 1.2	Synthesis[2]	Vellinga *et a*l., 2008
0.8 to 2	Physical constraint analysis[2]	Pfeffer *et al*., 2008
0.56 to 0.92[1]	Palaeo-climate analogue	Kopp *et al*., 2009
0.75 to 1.86	Semi-empirical projection[2]	Vermeer and Rahmstorf, 2009
0.91 - 2.15	Semi-empirical projection[2]	Grinsted *et al*., 2009

[1] *A higher rate is possible for shorter periods*

[2] *For the 21st Century*

6.2 Land subsidence

In order to make projections of local relative sea level rise, data about projected land subsidence (as well uplift for understanding relative sea level drop) are needed. Changes in the Earth's surface can be measured using radar interferometry (e.g. Massonnet and Feigl, 1998). For monitoring purposes space-borne synthetic aperture radar (SAR) and Advanced SAR (ASAR) from the European Radar Satellites (ERS-1 and ERS-2) and ENVISAT images can be used. They are able to scan areas about 100 km^2 with a spatial resolution about 20 x 20m. Analysis of synthetic aperture radar measurements can allow the assessment of land subsidence with an accuracy of 1 mm.

For more realistic long term projections these observations are not enough, however, because they cover only the last decades and therefore are not appropriate for identification of the needed long-term trend (e.g. 50 - 100 years). In this case more realistic palaeo-geographic reconstructions of the coast are needed to identify subsiding and uplifting segments.

Although there are many reconstructed long term subsidence data sets at the regional and local level (e.g. for England Shennan and Horton, 2002; for the Netherlands Kooi *et al*., 1998 and Zagwijn, 1989; for Italy Antonioli *et al*., 2009; for Venice Carbognin *et al*., 2004) a European-wide data set is still lacking. The SubCoast FP7 project aims at developing a GMES-downstream service (based on satellite data, in-situ measurements and geoscientific models) for assessing and monitoring subsidence hazards in coastal lowland areas around Europe[19]. The project in particular focuses on three pilot areas (Rhine-Meuse delta in the Netherlands, Southern Emilia Romagna in Italy and Baltic States) and data integration at the European level. SubCoast is expected to contribute to fill the knowledge gaps on subsidence through assessing, mapping and monitoring subsidence and delivering data and information on the extent and impact of subsidence, in particular in coastal lowland areas.

[19] http://www.subcoast.eu/ (last access: 9.08.2011)

In addition to the reconstruction of historical subsidence, projection of future land subsidence requires also projection of socio-economic developments, which can have an impact on land subsidence, as the historical ones may not play a role in the future, while new ones could also emerge. Examples of past anthropogenic impacts on land subsidence are for instance ceasing of water pumping that contributed considerable to land subsidence in Venice in 20th century (Carbognin *et al*., 2010) and draining of lands and gas extraction in the Netherlands. Such developments have to be identified and quantified on a regional/local scale for construction of future land subsidence data set for European coasts. In the PESETA project, a uniform annual subsidence of 2 mm in deltas was adopted (Hinkel *et al.,* 2010). This very simplified approach allows some rough assessment of vulnerability and adaptation costs, but it is not enough for adaptation planning purposes.

6.3 Projection of other climate change drivers

Extreme sea levels pose a significant threat to coastal areas. They arise from the combination of high tide, and storm surge, the latter being the effect of wind and atmospheric pressure on sea level. With climate change the regional distributions of storm surges might change due to rising sea level and changing storm tracks. Moreover, when mean sea level rises, storm frequency may increase in some regions and decrease in others (Solomon *et al*. 2007). In Europe the consequences of climate change on future storminess have been largely studied for the North Sea, the Irish Sea and the Adriatic Sea (Von Storch and Woth, 2008). On the other hand there are no regional scenarios for the Black sea.

Using different combinations of global scale general circulation models (GCM), regional climate models (RCM) and regional hydrodynamic surge (or wave) models, a number of studies (e.g., Lowe *et al*., 2001; Hulme *et al.* 2002; Woth *et al.*, 2005; Grabemann and Weisse, 2008; Debernard and Roed, 2008; Lowe *et al*., 2009) have found the future change of storminess in the North Sea to be of the same order as the natural climatic variability. These studies identify certain areas where there is an increase in surge magnitude in future climate scenarios, but there is no agreement among them over magnitude of expected change and the regions which will be affected.

Changes in storm surges are governed by both changes in wind speed and wind direction. Along the Dutch coast northerly winds are most important and cause maximum water levels, as they have the longest fetch, blowing all the way down from the Norwegian Sea into the southern North Sea. Future projections suggest however that increasing wind speeds are limited to south-westerly directions, and therefore climate change would not affect surge heights along the Dutch coast considerably (Sterl *et al*., 2008). For the latest UK climate projections storm surges with return periods of 2, 10, 20 and 50 years were studied. They suggest lower wave heights for the northern UK coast and slightly larger wave heights for the south-western coast as a result of southwards movement of future storm tracks (Lowe *et al.,* 2009). For the southwest coast of the UK 10 cm increase of the storm surge of 50-year return level have been calculated over the 21st century. The results of Bengtsson *et al.* (2009) corroborate these findings.

More significant changes in water heights are projected for the German coast. Von Storch and Woth (2008) showed, however that anthropogenic impacts such as local changes in bathymetry caused by erosion and sedimentation and waterworks may be much larger than climate change, as it is in Hamburg, a port city, situated 140 km land-inwards at the end of a large estuary. A similar conclusion is drawn for Venice, situated at the northern coast of the Adriatic Sea, for which there is no convincing evidence for more stormy conditions in the future due to climate change (e.g. Lionello *et al*.,2010).

In the Baltic Sea winds affect the sea level as shown by Suursaar *et al*. (2006a), but on average the effect is fairly modest, not more than an increase of about 10 cm. The more important effects of wind and weather patterns are related to air pressure differences, progressive waves and seiches, especially when their effects are combined (Leppäranta and Myrberg, 2009). There have been a number of studies related to these extreme events, which in the near absence of tides are a significant cause of variation of water level in the sea. The most extreme recorded event occurred in St Petersburg in 1824, when the sea level was 4.21 m above the zero level, but levels of 2 m have been recorded in several sites (Leppäranta and Myrberg, 2009). In the coastal region factors such as fresh water input affect the sea level as demonstrated by detailed studies of storm surges on the Polish coast (Kowalewska-Kalkowska and Wiesniewski, 2009; Kowalewski and Kowalewska-Kalkowska, 2011). This interaction between different phenomena has also been documented for the Estonian coast in an analysis of the effects of the cyclone Gudrun, which caused coastal flooding in several parts of the Gulf of Finland (Suursaar *et al*., 2006b). Elken *et al*. (2011) further demonstrated the complexity of water level variation and circulation in the Gulf of Finland, which is one of the major bays in the Baltic Sea.

The current gaps in storm surge studies may be summarised as follows:

- Short historical records, not allowing proper modelling of natural variability (Von Storch and Woth, 2008, Lionello *et al*.,2010, Lowe *et al.,* 2009).
- Coastal features such as mud flats are not taken into account by the models while they can have significant impact on the wave height (Von Storch and Woth, 2008)
- The local bathymetry is not well represented in the models (Sterl *et al*., 2008, Lowe *et al*., 2009);
- There is still high uncertainty about the basic dynamics of shifts in the strength and path of the mid-latitude storm track (Lowe *et al*., 2009).
- There is still no agreement on the most appropriate methods for downscaling of global projections to a regional/local scale (Lowe *et al*., 2009).

6.4 Topographic and bathymetric data

DEM and DTM

The most significant Digital Elevation Models (DEMs) for Europe come from global datasets (ETC/ACC, 2010b). Of these global datasets, the most appropriate for the assessment of coastal vulnerability is the Shuttle Radar Topography Mission DEM (SRTM; Farr *et al*., 2007). This dataset covers approximately 80% of the earth's land surface, between 60°N and 60°S. Elevation is mapped using a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. The SRTM data are available as 3 arc-second (approximately 90 m horizontal resolution at the equator), with a vertical error reported to be less than 16 m (Gorokhovich and Voustianiouk, 2006). Despite these seemingly large error estimates, further work has shown that the vertical accuracy depends on slope, meaning that flatter areas have a much higher vertical accuracy (Falorni *et al*., 2006). This is beneficial for coastal vulnerability assessments because the areas that might be considered low-lying and coastal mainly fall into the category of having a low slope. The application of the SRTM product in the coastal zone is further enhanced by the availability of the SRTM-derived coastline dataset. This dataset defines the global coastline at a resolution that directly matches the resolution of SRTM, and consequently covers the same land area as SRTM. This allows the SRTM data to be used in conjunction with satellite imagery for sea level rise studies (see for example Demirkesen *et al*., 2007).

Various sources are available for downloading the SRTM dataset, however the most appropriate for a pan-European study is the CGIAR-CSI[20] dataset, which distributes a "void-filled" version of the SRTM version 4 raw dataset (Reuter *et al*., 2007). This dataset uses a range of techniques to fill-in voids in the raw SRTM

[20] http://www.cgiar-csi.org/data/elevation/item/45-srtm-90m-digital-elevation-database-v41 (last access: 30.05.2011)

data that arise from the radar method of data collection. The CGIAR-CSI server also provides derivative products from the SRTM dataset, resampled to 250, 500 and 1000 m horizontal resolution. The SRTM90 DEM is provided in 5° x 5° tiles for easy use and mosaicing; all data are available in both ArcInfo ASCII and GeoTiff format to facilitate their use in image processing and GIS applications.

Another well assessed resource is the GTOPO30[21] global DEM from the United States Geological Survey (USGS). This dataset has a horizontal resolution of 30 arc-second (approximately 1 km at equator), and is collected from a variety of sources. The USGS has organized these into 33 tiles identified by longitude and latitude. The USGS HYDRO1K Elevation Derivative Database[22] is a version of GTOPO30 which has been corrected using hydrology data and also includes elevation derivatives (such as slope and aspect). The EEA has compiled a corrected version of GTOPO30 clipped to Europe at 1 km resolution[23]; while the ETOPO5 dataset, a 5 arc-minute horizontal resolution (approximately 10 km) is also available at the EEA website[24]. Subsequently, ETOPO5 has been replaced firstly by ETOPO2v2 (2 arc-minute, or approximately 4 km resolution) and more recently by ETOPO1 (1 arc-minute, or approximately 2 km resolution) global relief models available at the U.S. National Geophysical Data Center[25,26] under various GIS-compatible formats, and useful as integrating land topography and ocean bathymetry.

For the assessment of coastal elevations across Europe, it would of course be preferable to use the higher spatial resolution, high vertical accuracy, and consistency of the SRTM dataset. This is not totally feasible, however, for pan-European studies because the northern limit of the dataset excludes the majority of Scandinavia. One way to resolve this problem is to combine both datasets together, at a horizontal resolution of 30 arc seconds, so the vertical accuracy and consistency of SRTM is still utilized, in addition to the extra coverage of the GTOPO30 dataset. This dataset has been compiled, processed (additionally deriving slope and aspect classes) and made available at the International Institute for Applied Systems Analysis[27] (IIASA; Fischer *et al*., 2009).

Finally, another high resolution topographic dataset with a global extent has recently been produced from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) imaging instrument that flies onboard the NASA 'Terra' earth observing satellite. In this case, stereo optical images have been used to produce a Global Digital Elevation Map[28] (GDEM). Produced by Japan's Ministry of Economy, Trade and Industry (METI) and the NASA Jet Propulsion Laboratory (JPL) in 2009, the GDEM was created using 1.3 million scenes from the ASTER, covering the Earth's land surface between 83°N and 83°S latitudes. The GDEM is produced with a 30 meter horizontal resolution, and is distributed in 1° x 1° tiles as GeoTIFF files. Each GDEM file is accompanied by a Quality Assessment file, either giving the number of ASTER scenes used to calculate a pixel's value, or indicating the source of external DEM data used to fill the ASTER voids. There is a fairly complete coverage of the world at this relatively high resolution and the data are free with access via the NASA WIST[29] site through a free registration. The GDEM data is currently available as 'research grade', meaning that there are a number of issues identified in the validation process that currently prevent it being useful for detailed continent-wide studies such as the assessment of coastal vulnerability. For example, validation exercises (such as Erten *et al*., 2005; Santini *et al*., 2009; and ASTER GDEM

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[21] http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info (last access: 30.05.2011)

[22] http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30/hydro (last access: 30.05.2011)

[23] http://www.eea.europa.eu/data-and-maps/data/digital-elevation-model-of-europe (last access: 30.05.2011)

[24] http://www.eea.europa.eu/data-and-maps/data/world-digital-elevation-model-etopo5 (last access: 30.05.2011)

[25] http://www.ngdc.noaa.gov/mgg/global/etopo2.html (last access: 30.05.2011)

[26] http://www.ngdc.noaa.gov/mgg/global/global.html (last access: 30.05.2011)

[27] http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/global-terrain-slope.html (last access: 30.05.2011)

[28] http://asterweb.jpl.nasa.gov/gdem.asp (last access: 30.05.2011)

[29] https://wist.echo.nasa.gov/api/ (last access: 30.05.2011)

Validation Team, 2009) have identified a global vertical accuracy of approximately 20 m (at 95% confidence). This apparently large error is due to linear or curvilinear artefacts that have been introduced into the elevation data due to the tiling of individual ASTER scenes. This is further compounded by areas of low image acquisition, and the influence of clouds. A global vertical accuracy of 20 m may initially appear too large for applications in coastal vulnerability assessment, however, it is worth noting that the vertical accuracy does vary spatially (according to terrain and land cover type, number of available images and cloud cover), and there have been relatively few validation points in the coastal zone[30]. It is clear that currently for coastal vulnerability assessments at continental scales, there are still major inconsistencies in the GDEM dataset. For smaller scale studies (especially those above 60°N), the GDEM data, once validated against a reference dataset, may offer a cost-effective high resolution alternative to GTOPO30. While the GDEM dataset may be updated in further releases, the SRTM dataset is still regarded as a more stable, vertically accurate and complete source of global elevation information for coastal vulnerability assessment than either GTOPO30 or GDEM.

Despite the seemingly large vertical errors in the above global datasets, a number of large scale studies on vulnerability to sea level rise have used GTOPO30, and more recently SRTM, without reporting the vertical accuracies of these elevation datasets (see Gesch *et al*. 2009, page 33). For national, or sub-national scale studies, where higher resolution data is available, the vertical accuracy is more frequently reported (see Gesch *et al*. 2009, page 34). These higher resolution elevation datasets are based on aerial or ground-based surveys, and provide better horizontal and vertical accuracy. While these approaches also allow the quantification of vertical errors, the costs of acquiring such datasets are considerably larger. Furthermore, they may also provide information on the structure of vegetation, height of buildings, and height of the underlying land surface. These datasets may be based on airborne LIDAR (Light Detection And Ranging) sensors, or land-based topographic survey and are generally held by national mapping agencies.

Bathymetry

The General Bathymetric Chart of the Oceans (GEBCO) is a 1 arc-minute global grid (Jones, 2003) that includes land elevations from the International Geosphere-Biosphere Programme (IGBP) GLOBE database. GEBCO's aim is to provide the most authoritative, publicly-available bathymetry for the world's oceans. It operates under the joint auspices of the Intergovernmental Oceanographic Commission (IOC) and the International Hydrographic Organization (IHO). Two GEBCO gridded bathymetric data sets can be downloaded from the British Oceanographic Data Centre (BODC)[31] as netCDF files. They are:

- The GEBCO One Minute Grid, a global 1° resolution grid, largely based on the most recent set of bathymetric contours contained within the GEBCO Digital Atlas.
- The GEBCO_08 Grid, a global 30 arc-second grid generated by combining quality-controlled ship depth soundings with interpolation between sounding points guided by satellite derived gravity data. The GEBCO_08 Grid is currently a development product which will undergo periodic update.

Coastlines - Shorelines

As with DEMs, there are also a number of world coastline datasets that can be used for pan-European studies. Currently, no global dataset is available to map the difference between high and low water marks, and documentation as to the criteria used for defining the coastline is weak. However, of the datasets available, the most noteworthy is the SRTM-derived coastline produced by the Conservation Science group of WWF for the HydroSHEDS project (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales). This provides a coastline that is consistent with the SRTM elevation data. Despite this considerable advantage, the HydroSHEDS coastline also only extends to approximately 60°N.

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[30] http://www.ersdac.or.jp/GDEM/E/image/ASTERGDEM_ValidationSummaryReport_Ver1.pdf (last access: 30.05.2011)

[31] https://www.bodc.ac.uk/data/online_delivery/gebco/ (last access: 30.05.2011)

Another useful coastline dataset is the World Vector Shoreline (WVS); it is a digital data file at a nominal scale of 1:250,000. The WVS contains the shoreline of the world and sub-regions of the world can be extracted using the online extractor tool available at: http://www.ngdc.noaa.gov/mgg/coast/ (last access: 30.05.2011).

Finally a recently updated version of the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS; Wessel and Smith, 1996) is also considered. This dataset is based on the World Data Bank (also known as the CIA Data Bank), and the WVS. The data have undergone extensive processing and the vector datasets are free of internal inconsistencies such as erratic points and crossing segments. Multiple resolutions are available and can fit to different study scales: 0.04 km, 0.2 Km, 1km, 5 km and 25 km. However, since GSHHS is based on multiple sources of data, there may be differences in mapping scales between countries, resulting in similar features being mapped differently for different parts of the coastline.

6.5 Soil characteristics

When quantifying or simulating climate driven impacts on coastal areas, function of both biophysical and anthropogenic factors, and primarily due to the interactions between the sea level rise and the hydrogeological processes (including groundwater dynamics, erosion, floods, pollution, sediment transport and deposition etc.) the role of soil is crucial. Indeed, besides the land morphology (DEM based) indicating the main direction of superficial water flow, it is well known how physical, biological and chemical soil characteristics determine its rapidity to accumulate or transfer water (vertically and horizontally) and its suspended sediments or substances, as well as its ability to support coastal/wetland ecosystems. This is the reason why modelling the complex system of coastal processes (coastline evolutions etc.) requires reliable and as much complete as possible datasets on soil characteristics. Among the most complete soil datasets available at spatial resolution suitable for coastal studies, two are particularly noteworthy.

The first is the European Soil Database (ESDB)[32], the main source of information from which most other data information and services are derived. It contains four discrete datasets:

- the Soil Geographical Database of Eurasia at scale 1:1,000,000 (SGDBE)
- the Pedotransfer Rules Database (PTRDB)
- the Soil Profile Analytical Database of Europe (SPADBE)
- the Database of Hydraulic Properties of European Soils (HYPRES)

Soil information consists of 73 attributes (both primary and derived from pedotransfer rules) at 1 km raster resolution and the ESDB is freely available to the public after user registration.

The second is the Harmonized World Soil Database (HWSD)[33] (FAO *et al*., 2009), compiled thanks to a joint effort of The Land Use Change and Agriculture Program of IIASA and FAO, which merged the most recent regional and national updates of soil data (SOTER, ESD, Soil Map of China, WISE) with the information contained within the 1:5’000’000 scale FAO-UNESCO Soil Map of the World in order to build the HSWD. The HWSD is a 30 arc-second (about 1 km) raster database with over 16’000 different soil mapping units and their characteristics (e.g. organic Carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry).

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[32] http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB/ESDB_data_intro.html (last access: 30.05.2011)

[33] http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ (last access: 30.05.2011)

6.6 Socio-economic data

Land use and land cover

Although land use datasets are more suitable than land cover information to characterize the multiple responses of a territory to climate stressors and their consequences (e.g. flooding), most of available datasets refer to the latter. This is due to the easier and faster identification of land cover typologies (such as vegetation, water and urban coverage) made possible by the use of remote sensing techniques, more suitable than time-consuming censuses and/or ground reliefs to compile large extent (e.g. continental, supra-regional) databases. However, thanks to the advances of technologies in remote sensing data acquisition, spatial-temporal resolution and image classification, the boundary between land cover versus land use definition becomes less and less explicit (e.g. croplands can be now differentiated into rain-fed and irrigated areas, as well as into permanent or not cultivated areas).

A good example of such datasets is the CORINE Land Cover, the only homogenous dataset at Pan-European scale that, given its spatial resolution and its detailed land cover classification including 44 categories, can be assimilated to a land use layer. CORINE land cover data, including changed areas from 1990 to 2000 and from 2000 to 2006, are available for downloading at the EEA website[34] in raster format at 100 m and 250 m resolution, and in vector format separately for each of the 44 classes. Given the importance of vegetation cover and soil moisture for evaluating coastal soil response to climate drivers, another useful and recently updated dataset is the Global Land Cover 2009[35], downscaled from 1000 m to 300 m resolution, and including a 23 class legend giving importance in particular to the density of vegetation cover and to the flooded/irrigated areas. Moreover, although it is characterised by a coarser resolution (0.005°, about 500 m), the land cover IGBP (International Geosphere Biosphere Programme) classification contained in the MOD12C1 products[36], including up to 17 classes, has the advantage to be freely available and yearly delivered from 2001 to now, and so helpful to detect land cover changes for coastal studies.

EEA already assessed the noteworthy changes in land cover/use from 1990 to 2000 (EEA, 2010b). In order to produce vulnerability/risk scenarios not only future climate but also land use changes shall be simulated. To this aim, a lot of spatially explicit land use/cover change model applications are valuable. Good example are the CLUE-S model (Verburg *et al*., 2002) and its modified versions as the LUC@CMCC (Santini and Valentini, in press) that can support the dynamic updating of land use/cover information to feed coastal impact models and vulnerability assessment tools. A recent work by JRC (Lavalle *et al*., 2011) focused in particular on producing land use projections for coastal areas using the EUClueScanner model, which is based on the same dynamic and spatially-explicit approach as the two above cited tools, and evaluating two opposite development scenario alternatives (sustainable and unsustainable), in order to support the assessment of a representative range of impacts on coastal systems.

Demography and economic data

Demographic and economic tables can be compiled from data provided directly by the national statistical offices to EUROSTAT, in particular for the following variables: (i) total population living in coastal regions, (ii) population by gender and age, (iii) population projections, (iv) labour forces, (v) GDP and added values at yearly time steps[37]. Specifically for demographic data, they are available at NUTS3 level as already used in

[34] http://www.eea.europa.eu/data-and-maps/data/ (last access: 30.05.2011)

[35] http://ionia1.esrin.esa.int/ (last access: 30.05.2011)

[36] http://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=10004 (last access: 30.05.2011)

[37] http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database (last access: 30.05.2011)

the ESPON-CLIMATE project[38]. Population data in each country can be then available at municipal level (NUTS4 - NUTS5), while more detailed data (e.g. rural vs. urban areas) are available only for a few countries. The others among above listed socio-economic variables, at the European level are only available by NUTS0 (EU Member State national level); while NUTS2 (Regions) or NUTS3 (Province) administrative units can be extracted from national statistics and national censuses. However not all the EU Member States follow the same methods for collecting the statistical information, especially those countries that have joined the EU more recently. Concerning long term demographic projections (e.g. up to 2100), comparable with the time frame of climate scenarios, useful information are expected from the DEMIFER[39] project.

The Joint Research Centre (JRC) in collaboration with the EEA calculated the population density disaggregated in connection with the CORINE land cover classes for the year 2000 (while the future goal is to make the same for CORINE 2006). This methodology provides approaches to combine municipal population with land cover data to produce an EU-wide population density grid, where each 100 m x 100 m pixel value is the estimated density of inhabitant per km^2 (Gallego, 2010). Furthermore, 2.5 arc-minute (about 5 km) population and population density data (including projection up to 2015) are available at the Socioeconomic Data and Applications Center (SEDAC)[40], where also preliminary (alpha release) data from the Global Rural Urban Population Mapping project (GRUMP) (CIESIN *et al*., 2004) are available at 30 arc-second (about 1 km) resolution. Of particular interest are the Low Elevation Coastal Zone (LECZ)[41] urban-rural estimates, consisting in country-level estimates of urban, rural, total population and land area in a low elevation coastal zone generated globally using GRUMP alpha population and land area data products and the SRTM DEM (30 arc-second) resolution (McGranahan *et al*., 2007). The zone was derived from the DEM by selecting all land contiguous with the coast 10 meters or less in elevation. Zone statistics were generated for urban, rural and total population and land area for the country as a whole and within the LECZ. Follow-up analyses using higher resolution data for local estimates are currently being performed.

<u>Accessibility</u>

Data regarding the spatial distribution and/or clustering of those places and structures where people live and move are a key-layer when one wants switching from vulnerability to risk assessment, i.e. quantifying likely damages on human life, services and economies, mainly in terms of immediate effects from like e.g. inundation or surges. On the other hand, including information on transport networks is also crucial to face emergencies and improve early warning systems.

For these reasons, relevant socio-economic information to evaluate coastal vulnerability and risk include accessibility data, in particular related to the distance to cities and to transport infrastructures (railways, roads). These can be easily calculated through GIS functionalities. For example, distance in terms of travel time is the focus of the global map of Accessibility produced by JRC[42] (Nelson, 2008). Data are in ESRI GRID format with a resolution of 30 arc-seconds, with pixel values representing minutes of travel time. Input layers for this product were, among others, populated places (with more than 50,000 people), roads, railways, navigable rivers, and shipping lanes, whose sources are indicates in the dataset documentation and relies in particular on the Vector Map Level 0 (VMap0)[43] database. Focusing on transport infrastructures, also Open Street Map derived data are available on the web[44] as vector layers.

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[38] http://www.espon.eu/export/sites/default/Documents/Projects/AppliedResearch/CLIMATE/ESPON_CLIMATE_revised_interim_report_22-03-2010.pdf (last access: 30.05.2011)

[39] http://www.espon.eu/main/Menu_Projects/Menu_AppliedResearch/demifer.html (last access: 30.05.2011)

[40] http://sedac.ciesin.columbia.edu/gpw/global.jsp (last access: 30.05.2011)

[41] http://sedac.ciesin.columbia.edu/gpw/lecz.jsp (last access: 30.05.2011)

[42] http://bioval.jrc.ec.europa.eu/products/gam/index.htm (last access: 30.05.2011)

[43] http://www.mapability.com/index1.html?http&&&www.mapability.com/info/vmap0_download.html (last access: 30.05.2011)

[44] http://www.mapcruzin.com/free-europe-arcgis-maps-shapefiles.htm (last access: 30.05.2011)

6.7 Ecosystem targets

An in-depth knowledge of protected areas is crucial for consistent comparisons among different vulnerability/risk degrees of coastal zones, given that various types, levels and management of protected areas are possible. Indeed laws and guidelines transposed from European directives are often fitted to the peculiar characteristics of the areas at national or sub-national level. This is the reason why a comprehensive database accounting for multiple directives and criteria is desirable.

One such database is the Natura 2000 site dataset, whose vector maps are available at the EEA web site[45]. Natura 2000 is the key instrument to protect biodiversity in the European Union. It is an ecological network (based on EU 1979 Birds Directive and 1992 Directive) of protected areas aiming at ensuring the survival of most valuable species and habitats of Europe. A further source of information relies on the World Database on Protected Areas (including marine) accessible at http://www.wdpa.org/ (last access: 16.09.2011).

6.8 Adaptation measures

The immense complexity and chaotic nature of the climate system seriously challenges the construction of reliable projections about the magnitude and pace of this change. This deep uncertainty accompanying climate change projections hampers the accurate quantification of key climate variables, required for long term policy decisions. While decision makers require PDFs (probability density functions), science is not able to provide probabilities of different projections yet, as they are subject to unquantifiable uncertainties (e.g. Stainforth *et al*. 2007). A step forward was made with latest UK scenarios (UKCP 09), where model frequencies from a multi-model ensemble were used to construct Probability Density Functions (Murphy *et al*., 2009). For sea level rise the probabilistic methodology was not applied however, and the values for sea level rise were presented as ranges, without assigning probabilities to them.

In this case a special approach has been developed for Thames Estuary within the TE2100 (TE2100 Flood Risk Management Plan)[46] project to incorporate flexibility into its adaptation strategy. Rather than making irreversible decisions and deciding now which individual measures are appropriate for successful adaptation to climate a route-map approach envisages a sequence of different measures. These can be implemented over time in such a way that the system can adapt to climate change, while options are left open to deal with a range of possible sea level rise scenarios. This approach requires identifying key thresholds over the level of sea level rise at which certain sea defences fail. In the case of the Thames Estuary the engineering limit to adaptation has been identified to be 5 meters mean sea level rise, with a number of intermediate thresholds. In the next step planners could explore a series of adaptation pathways that would be appropriate to cope with a range of climatic changes and to draw up a route-map for the selected pathway.

If adaptation planners want to deploy this approach, they need information on:

- Costs and benefits associated with different adaptation options;
- What are the trade-offs of specific local social, environmental and economic factors;
- At what timeframe a particular adaptation option becomes cost-effective;
- What are the thresholds for decision-making about optimal timing for different options for effective adaptive investment and risk management.

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[45] http://www.eea.europa.eu/data-and-maps/data/natura-1 (last access: 30.05.2011)

[46] http://www.environment-agency.gov.uk/research/library/consultations/106100.aspx (last access: 30.05.2011)

Coastal areas have always been threatened and therefore there are a number of options for defending the land from the sea. The costs and benefits, as well as the trade-offs of most traditional options are known (e.g., Linham and Nicholls, 2010). Climate change poses new challenges, requiring better understanding of the appropriate timing of implementation of these options. With the exception, for example, of the Thames Estuary, many of these challenges have yet to be addressed.

7 Conclusions

The following conclusions are based on the description and analysis of coastal assessment methods included in this technical paper as well as on the results of the EEA expert workshop on “Methods for assessing coastal vulnerability to climate change at the European scale” held in Copenhagen in June 2011.

The scientific literature provides a wide variety of methods for the assessment of coastal vulnerability to climate change, which differ in scope, approach, complexity and application scale. The definition of the assessment objective and the problem to be evaluated (i.e. the policy questions) are key factors in choosing the most appropriate assessment method. These factors also influence the complexity of the approach to be used:

- Indicators and index-based methods are generally simple to calculate. They provide useful tools for a scoping or first look assessment, thus supporting identification of priority vulnerable areas. Due to their ease of understanding, indicators and indices can be also very useful for communication purposes. These approaches however are not indicated for a more detailed quantitative assessment of costal vulnerability and the related identification of adaptation measures.
- Sector models enable detailed quantitative analyses of coastal processes or specific coastal systems. They are capable of assessing non-linear effects and to consider interactions between different processes. They are most useful for addressing specific key factors of coastal vulnerability, in particular at the local and regional scale.
- Integrated assessment models can evaluate the vulnerability of coastal systems to multiple climate change impacts. They can include the cross-sector analysis of interaction among different impacts and the synergetic effects of changes in climate and in other key variables affecting the coastal system (such as socio-economic development and adaptation measures). The ability of a fully integrated assessment of coastal vulnerability, also considering dynamic interactions between sectors and/or processes, makes integrated assessment models very useful in supporting policy and decision making at various scales. However, given the complex nature of such models, their implementation can require significant expertise. In some cases (e.g. RegIS and DESYCO) further effort from the research community is still needed to up-scale the applicability of integrated assessment models to the European scale.

The selection of an assessment method to be applied in a particular context is also strongly dependant on availability of relevant data, which is still a key issue at the European level. The discussion during the EEA expert workshop highlighted the following further considerations as being very important for coastal vulnerability assessment:

- Coastal vulnerability assessment must consider the socio-economic system not only as one of the target of climate change related impacts, but also as a very relevant driver influencing coastal vulnerability itself. Assessment methods shall attempt to consider a dynamic socio-economic system; indeed pressures of socio-economic activity may even generate more severe effects than those from climate change and sea level rise.
- The consideration of existing and/or planned adaptation strategies is crucial for realistic assessments of the level of (residual) risks. However, realistic simulation of adaptation is complex, and human decisions are not fully predictable. For large-scale (national, continental, global) assessments often not even the adaptation baseline (i.e. the current level of coastal protection) is known. Coastal vulnerability assessments that do not explicitly include adaptation can be very useful to analyse potential hazards, vulnerabilities and risks in order to select regions for more detailed analysis but their results should not be interpreted as projections of future developments.

- Coastal vulnerability assessment often assumes an anthropogenic perspective. Sustainability requires that ecological needs are also taken in consideration. For example, hard protection of coastal infrastructure can protect human settlements and infrastructure against erosion or flooding but may be counterproductive for ecological processes and ecosystem dynamics.

Based on the work jointly promoted by EEA and ETC-CCA, the June 2011 experts' workshop identified DIVA, RegIS and DESYCO as the most promising approaches for EEA's objectives related to coastal vulnerability assessment at the European or Regional Sea scale. The following considerations for these three integrated assessment methods appear to be relevant:

- The global DIVA model has already been applied at the European scale, in particular in the PESETA project. Ideas for improved analysis at the European scale include consideration of regional/local sea-level change scenarios, higher spatial resolution using high-resolution datasets for Europe, and extended sensitivity analysis.
- The RegIS methodology has been applied to two regions of the United Kingdom so far. The on-going CLIMSAVE FP7 project will extend this tool to the European scale at 18 km grid resolution.
- The local to regional GIS-based model DESYCO can in principle be up-scaled to the European level. According to relevant experts participating in the EEA expert workshop (Torresan *et al*., 2011), such an up-scaling is only a matter of a few months' work.
- A comparative analysis among the most promising assessment approaches (DIVA, DESYCO and RegIS) would be very useful. A first comparison could be done for the Mediterranean Sea, since DESYCO will be applied to this region and DIVA has already been used for this region. A comparison of model results with the outcomes of existing vulnerability assessments of the coastal zone (e.g., Eurosion project) would also provide useful indications of the robustness of results using different approaches.

As addressed in the technical paper, there are many other methods that are very useful for application at the local or regional level. Monitoring of these experiences is very important to constantly assess their transferability to other regions and their scalability to the European level. Furthermore, local to regional methods can be very useful to complement continental scale assessment with specific case studies around Europe, focusing on specific coastal systems (e.g. deltas, estuaries, coastal lagoons, coastal cities, coastal and marine protected areas, and harbours).

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