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# Coastal flood protection: What perspective in a changing climate? The THESEUS approach☆

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ABSTRACT

Coastal areas are vital economic hubs in terms of settlement, industry, agriculture, trade and tourism to mention some key sectors. There are already many coastal problems including erosion, flood risk and long-term habitat deterioration. As economies continue to develop the asset base at risk will grow, while accelerating climate change will increase the likelihood of damaging extreme events, as well as accelerate habitat decline. Existing coastal management and defence approaches are not well tuned to these challenges as they assume a static situation.

THESEUS project is developing a systematic approach to delivering both a low-risk coast for human use and healthy habitats for evolving coastal zones subject to multiple change factors. The project examines innovative mitigation and adaptation technologies and integrate the best of these technical measures in a strategic policy context through over-arching guidelines. THESEUS activities are carried out within a multidisciplinary framework using 8 study sites across Europe, with specific attention to the most vulnerable coastal environments such as deltas, estuaries and wetlands, where many large cities and industrial areas are located.

This paper describes THESEUS approach, and specifically: the Source-Pathway-Receptor-Consquence model for coastal risk assessment; the engineering, social, economic and ecological mitigation measures under analysis; the participatory approach with end users and coastal authorities for the selection and identification of the appropriate defence strategy to be planned in sudy sites.



## 1. Introduction

Coastal areas are great zones of settlement and play a vital role in the wealth of many nations. The European Union's coastline extends for some 170,000 km across 20 of 27 Member States and coastal areas cover about 2 million km$^2$ (Gazeau et al., 2004). Over the past 50 years the population living in European coastal municipalities has more than doubled to reach 70 million inhabitants in 2001. The total value of economic assets located within 500 meters of the European coastline was estimated between € 500 and 1000 billion in 2000 (EUROSION, 2004). It is worth remembering that many of Europe's largest cities—such as London, Hamburg, St. Petersburg, and Thessaloniki—are built on estuaries and lagoons. Harbours and industrial areas are situated or built at the coast and even on the sea: there are 15 port cities with more than 1 M people within the EU (Nicholls et al., 2007a), and many smaller coastal port/industrial cities.

Large stretches of European coasts are already exposed to erosion and flooding. During the worst sea surge recorded in the modern European history, the North Sea Surge in 1953,

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more than 2000 people lost their lives in England and the Netherlands, while 300 people died in Germany in 1962. More recently, a major surge in November 2007 reminded inhabitants around the North Sea of the threat posed by the sea, while the highest tides in Venice for more than 20 years in December 2008 and the sea storms hitting the Mediterreanean coasts in March 2010 and along Cantabria coast in November 2010 (Fig. 1) made global news!

All the available assessments up to the most recent IPCC Assessment (RESPONSE, 2009; WATCH, 2011; COPRANET, 2006; Alcamo et al., 2007; Nicholls et al., 2007b) show that Europe's coasts are threatened by sea-level rise and climate change in a variety of ways. Deltas, low-lying coastal plains, islands and barrier islands, beaches, coastal wetlands, and estuaries appear most affected by an acceleration in sea level rise, although the local response will depend on the total sediment budget. The low tidal range of the Mediterranean and Baltic coasts suggests that they will be more vulnerable to sea-level rise (SEAREG, 2005; CIRCE, 2011) than the Atlantic Ocean and North Sea coasts (Nicholls and Klein, 2005).

Climate change combines with and amplifies non-climate stressors on coastal ecosystems (Nicholls et al., 2007b,c) that are already seriously stressed in many areas of the world due to intense development and overpopulation, poverty, internal conflict, fragmentation and loss of habitat, over-fishing, pollution, and spread of invasive species. These non-climate stressors will impair the resilience of ecosystems, i.e., the ability of the ecosystem to maintain its integrity and to continue to provide critical goods and services to coastal communities.

Within this challenging coastal context, the recently launched (December, 2009) THESEUS project (www.theseusproject.eu) is developing a fully integrated approach aiming to deliver both a low-risk coast for human use and healthy coastal habitats. This paper presents such approach through five main sections. The first section provides a short project overview in the present policy and management context. The second and third sections examine respectively the approach to coastal risk assessment and mitigation in the uncertainties of future scenarios. The fourth section discusses how to bring science into operational coastal management. Some conclusions are finally drawn.

## 2. THESEUS approach

### 2.1. THESEUS context and baselines

The recently adopted EU Floods Directive (2007), triggered by the major river floods in Europe since 1998, requires Member States to assess by 2011 the watersheds and coastal areas that are at risk from flooding; to map by 2013 the flood extent and assets and humans at risk in these areas; and to take by 2015 adequate and coordinated measures to reduce this flood risk. Such measures have to be set-up with specific on the ''working with nature'' approach (Habitats Directive, 1992; Birds directive, 2009; EIA, 1997; SEA, 2001) to promote resilient habitats and societies. This approach to defence planning along the coastal area has been already promoted since a decade withi the Integrated Coastal Zone Management (ICZM) framework.

Thanks to EU Demonstration Programme on ICZM (1996–1999), significant steps had been made with respect to:

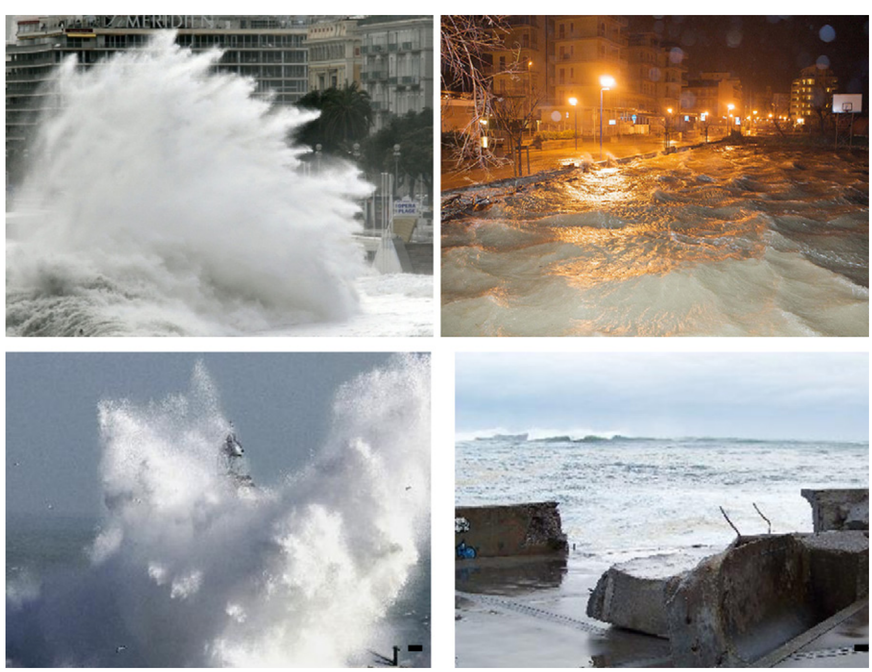

Fig. 1 – From top to bottom, from left to right: storm along the French Riviera, Nice, from *Le Figaro*, and along the Emilia Romagna beach, Lido di Savio, Italy, March 2010; storm along Cantabria coast, waves overcome the lighthouse at Santander harbor and create a breach in the breakwater in Luarca from *Publico*.

- awareness of long-term coastal challenges;
- moving from traditional to sustainable planning;
- participative elements in decision making.

A key achievement of the EU ICZM Recommendation (CEC, 2002a,b) has been to codify a common set of principles that should underlie sound coastal planning and management.

The efforts spent in other more recent projects on coastal risk and/or defence (a non-exhaustive list is provided in Table 1) focused – at different scales – on

- assessment of coastal erosion -and limitedly to some areas also of flooding- under climate change conditions (projects SURVAS, DINAS-COAST, BRANCH, SEAREG, FLOODsite, SafeCoast) or under extreme events (project MICORE);
- analysis of vulnerability and resilience concepts (projects SURVAS, DINA-COAST, Eurosion, FLOODsite, MICORE);
- analysis of mitigation technologies (''hard'' defences: DELOS, CLASH, FLOODsite; ''soft'' defences: Eurosion, Conscience, FLOODsite, SafeCoast; ecologically based tehcnologies: BRANCH, FLOODsite, SafeCoast);
- analyisis of adaptation strategies (project SafeCoast).

The implementation of ICZM however (COM, 2007) showed to be a slow long-term process and still reveals varying interpretations and understanding across Europe. The tools in place to address coastal issues are nowadays fragmented in up to the 50% of the Member States and the lack of a coherent responsibility chain at national and local scale delays the makes real advances in ICZM implementation. A fundamental problem remains achieving effective long-term support and commitment for integration in a context of predominantly sectorally organised administrations. Another barrier to the development of sustainable plans and integrated decision-making processes consists of the gaps in the collection and analysis of specific indicators of the coastal zone and the lack of effective information-sharing systems. The recently adopted INSPIRE Directive (2007) provided the legal framework for a more effective infrastructure for gathering, analysing and disseminating spatial information and informing the relevant decision-makers and the public at large.

To face these challenging issues, the Commission Green Paper on Adaptation to Climate Change (2007) and the Integrated Strategy on Disaster Prevention (2008) recently contributed to further promoting adaptation to possible risks related also to climate change in Europe's coastal zones.

In this combined environmental and policy context, a versatile and adaptable alleviation strategy which through a multifarious response to risk and vulnerability can cope with the increasing uncertainty caused by climate change needs more than ever

- multidisciplinary research, including engineering, environmental, social and economic dimensions together in a fully dynamic dialogue;
- overall European dimension, to promote discussion coastal risk assessment and mitigation strategies;
- participatory analysis with coastal managers and stakeholders, to promote feedback between research and policy implementation;
- focus on the combined problems of coastal erosion and flooding;
- dissemination at public level.

The THESEUS project was thought and proposed to make advances contemporarily in these still existing gaps. THESEUS is the acronym for ''Innovative coastal technologies for safer European coasts in a changing climate'', the largest integrated project totally devoted to coastal risk funded by the European Commission within FP 7 Environment (8,530,000 €, project cost; 6.530.000 €, EC funding). The project started on Dec.1st, 2009 and will work for four years (http://www.theseusproject.eu).

## 2.2. THESEUS approach

While in the media and the public mind, coastal floods and erosion are often seen as unnatural and non-allowable, they are natural occurrences, and no amount of investment can reduce risks to zero—an acceptable level of residual risk must always be defined. While new defence technologies have the potential to reduce costs and risks and increase our portfolio of management tools, we do not see technical solutions alone as the answer. Rather the need is to integrate the best of technical measures in a strategic policy context which also considers the environmental, social and economic issues raised in any coastal area. It is in this spirit that THESEUS project will advance the state-of-the-art in applying innovative technologies to reduce risks on coasts.

### 2.2.1. The objectives

THESEUS aim is to deliver a safe (or low-risk) coast for human use/development and healthy coastal habitats as sea levels rise and climate changes (and the European economy continues to grow).

The primary project objective is to provide an integrated methodology for planning sustainable defence strategies for the management of coastal erosion and flooding which addresses technical, social, economic and environmental aspects.

THESEUS objectives are governed by three specific goals, which concern: (a) Risk assessment, (b) Response strategies and (c) Application. More specific project objectives under these goals are:

(a) Risk Assessment
   - to develop probabilistic tools for estimating hazard scenarios related to climate variability and change;
   - to improve the knowledge of vulnerability and resilience of coastal defences and of coastal environment for the purposes of mitigation plans;
   - to evaluate coastal flooding damages to infrastructure, environment and human activities; impacts on society, including change of social cohesion, livelihoods, and opportunities.

(b) Response strategies
   - to analyse innovative mitigation measures of erosion and flooding risk as the latest insights in coastal defence structures and coastline stabilization technologies (as reefs, resilient dikes, over-washed structures);

**Table 1 – Non-exhaustive list of recently EU funded (coastal or river) flood and erosion risk management related projects.**

| EU Research FP 5–7 | Focus | Interreg North Sea | Focus | Interreg West | Focus | Interreg East | Focus | Interreg South | Focus |
|---|---|---|---|---|---|---|---|---|---|
| DELOS | Integrated design of coastal structures | Chain of safety | Transnational crisis management | BAR | Coastal erosion | Beachmed | Coastal erosion and ICZM | Deduce | ICZM |
| CoastView | Coastal monitoring | Comcoast | Coastal management concept | Branch | Climate change impact on the environment | Coastance | Coastal monitoring | Sustain | Sustainability and operational policy |
| Consience | Beach nourishment | Comrisk | Coastal flood risk management | Copranet | Practictioners network | Cadsealand | Coastal monitoring | Regioclima | Sustainable flood management |
| Survas | Climate change at the coast | Flows | Flood plain land use | Corepoint | ICZM | | | | |
| Dinas-Coast | Coastal vulnerability | Frame | Flood risk in estuaries | Espace | Space for water | | | | |
| Encora | Coordinated knowledge network | Norvision | Spatial planning | Flapp | Flood awareness and prevention | | | | |
| Floodsite | Flood risk science and management | Response | Coastal erosion and climate change | Floodscape | Space for water | | | | |
| Motiive | Data harmonisation | Safecoast | Coastal risk management and adaptation | Messina | Monitoring and valuation | | | | |
| Newater | Adaptive water management | Suscod | ICZM | Nofdp | Nature and flood prevention | | | | |
| Spicosa | ICZM | | | Sail | ICZM | | | | |
| SESAME | ICZM | | | | | | | | |
| MICORE | Coastal risk | | | | | | | | |

- to propose and analyse a completely innovative solution such as the use of wave energy converters close to the shoreline for contemporary attenuating wave attacks and produce a secondary benefit;
- to design the engineering solutions in a way that minimizes environmental impact and maximises wider benefits;
- to evaluate ecologically based measures as the role of habitat creation (reinforcement of saltmarhses and dunes, biogenic reefs) and the environmental effects of storm surge relief areas;
- to examine and set-up adaptation strategies as promotion of social resilience, insurance programs, spatial planning, evacuation plans and post-crisis response, managed realignment.

(c) Application

- to set-up ''best practices'' and prepare guidelines for the integrated design and application of efficient, equitable and sustainable coastal defence technologies;
- to set-up a portfolio of mitigation options for the society and the economy;
- to develop an integrated approach to select the sustainable defence strategy to face with coastal erosion and flooding in a given coastal area;
- to implement this approach into a decision support system tool GIS-based and validate it through applications in study sites, representative of different environmental, social and economic condition;
- to promote coastal flooding resilience and disaster preparedness through education, training and dissemination of project results;
- to strength international cooperation in order to provide globally an effective and constructive contribution to the implementation of the recently adopted EU Floods Directive (2007).

#### 2.2.2. *The consortium*

THESEUS partners come from all over Europe, since coastal erosion and flooding are wide-spread across the EU, with different characteristics and impact depending on the environmental and socio-economic conditions. Moreover, the expected worsening of climate change (and thus increasing severity and frequencies of storm surges and coastal floods) differs across the EU. As a consequence, but also to enhance the dissemination of the concepts and frameworks developed in the project, THESEUS consortium consists of 31 partners, of which 25 are from 12 Member States, 4 are from International Cooperation Partners Countries (China, Mexico, Russia, Ukraine) and 2 are Third Countries (Taiwan and USA). Because the assessment and mitigation of risk due to coastal erosion and flooding requires interdisciplinary research, the consortium involves partners with different expertise and backgrounds: coastal and civil engineering; ecology; social sciences and economics; meteorology and climate change; computer science and GIS.

#### 2.2.3. *The study sites*

The overall strategy of THESEUS is to learn from the experiences in selected study sites, develop innovative ''climate proof technology'' and propose an integrated approach for selecting among these technologies the proper mitigation option in the study sites. This overall strategy allows

- strong relation with end users and coastal managers;
- continuous feedback between research and practice;
- high quality of scientific research on innovative technologies;
- real improvement of safety and economic development in given coastal areas.

Study sites have been selected within European large urban and/or industrial areas, estuaries and deltas because of their specific erosion and flood risk management challenges, their high vulnerability to erosion and flooding, their meaning from a European point of view as well as the availability of data and opportunity to link directly into existing 'local' management teams.

The study studies (see map in Fig. 2) from West to East are: Santander spit, Atlantic Ocean, ES; Gironde estuary, FR; Plymouth Sound to Exe Estuary, English channel, UK; Scheldt estuary, NL-BE; Elbe estuary, North Sea, DE; Po delta plain and adjoining coast, Mediterranean Sea, IT; Vistola flood plain, Baltic Sea, PL; Varna spit, Black Sea, BG. The sites are characterised by

- a variety of environments (estuary, delta, coastal lagoon, protected or unprotected beach);
- different wave climate conditions and sea level rise expectations (Atlantic Ocean, North Sea, English Channel, Baltic Sea, Mediterranean Sea, Black Sea);
- different social and economic conditions (urbanised and industrial areas).

Main physical, ecological, social and economic characteristics of the site and potential mitigation options to be investigated are synthesized in Table 2.

## 3. Conceptual framework for coastal risk assessment

The conceptual model for coastal risk assessment proposed in THESEUS is based on the Source-Pathway-Receptor-Consequence (SPRC) model that is widely used in the fields of waste


**Fig. 2 – THESEUS project: map of study sites.**

**Table 2 – Overview of THESEUS study sites, including possible defence technologies for mitigation purposes to be analysed and designed during the project.**

| Site | Sea | Urban centers | Industrial activities | Coastal defence technologies |
|---|---|---|---|---|
| Santander spit | Gulf of Biscay, Atlantic Ocean | Santander | Harbor, fisheries, airport | Dredging and nourishment strategies<br>Reinforcement of salt marshes/ dunes<br>Wave energy converters<br>Over-washed structures |
| Gironde Estuary | Atlantic Ocean | Bordeaux<br>Verdon, Pauillac, Blaye, Ambès, Bassens | Harbor, marina, fisheries, refinery, nuclear power station | Dredging operations<br>Upgrading of dikes<br>Submerged structures<br>Wave energy converters<br>Early warning systems<br>Managed realignement |
| Plymouth Sound to Exe Estuary | English channel | Slapton, Teignmouth, Plymouth, Exeter | Harbor, fisheries, railway line, 'major port and naval base' | Beach reprofiling or managed retreat<br>Defence upgrade<br>Early warning systems<br>Reinforcement of salt marshes/ dunes<br>Dredging strategies |
| Scheldt estuary | North Sea | Antwerp<br>Harbor | Antwerp<br>Harbor | Upgrading/ Reinforcement of dikes<br>Reinforcement of salt marshes<br>Dredging operations |
| Elbe Estuary | North Sea | Hamburg | Hamburg<br>Harbor, fisheries | Artificial outer sandbanks<br>Dredging strategies<br>Over-washed dikes |
| Po delta and adjoning coast | Mediterrenan Sea | Venice<br>Ravenna | Harbor, Petrochemical and chemical industry | Floating structures<br>Reinforcement of salt marshes/dunes<br>Submerged structures<br>Nourishment strategies |
| Vistula delta plain | Baltic Sea | Gdànsk, Sopot, Gdynia | Harbor, fishery, Chemical industry, ariport | Dune reinforcement<br>Over-washed dikes<br>Dredging and nourishment strategies<br>Buffer flooded areas |
| Varna spit | Black Sea | Varna | Harbor, Chemical industry, power plants | Nourishment strategies<br>Submerged structures<br>Floating structures<br>Buffer flooded areas |

and pollution management (DEFRA, 2002; Cowell et al., 2003; Thorne et al., 2007; FLOODsite, 2009). The SPRC model is a simple linear conceptual model for representing flood systems and processes that lead to a particular flooding consequence. Effectively, the SPRC approach is being used to evaluate how the Sources (waves, tide, storm surge, mean sea level, river discharge, run-off) through the Pathways (coastal defence units) affect the Receptors (inland system) generating economic, social, environmental Consequences, see Fig. 3.

Understanding the interaction between socio-economic and biophysical system components is very complex and subject of research, because terms, methods, and scales of analysis differ between natural and social science and are often not comparable (Adger et al., 2004). These data have to be related to each other in a way that makes sense for analysing vulnerability in a specific region and society on a scale that is useful for delivering outputs that can be transferred into decision making processes. To operationalise vulnerability and resilience and to create vulnerability profiles the identification and quantification of a variety of indicators on different scales have to be further developed (Brooks et al., 2005).

### 3.1. *Defining spatial extent and flood system components*

The proposed risk analysis is based on initially dividing the coastal system into a number of homogeneous flooding and morphodynamic systems (Whitehouse et al., 2009), according to local wave, wind and long wave dynamics. This is followed by a division of the coast line into homogeneous coastal defence units. This approach allows splitting up the complex problem of flooding and erosion risk at a particular area in a number of sub-scale simple linear SPRC problems, making the integration of the risk more straightforward.

Initially, the identification of individual features of interest and the coastal management questions associated with them will inevitably be the focus of interest. However, the underlying systems approach of the model encourages the exploration of the wider environmental setting, physical functioning of the site and spatial and temporal variability (DEFRA, 2002; Cowell et al., 2003; Thorne et al., 2007).

The meetings with THESEUS stakeholders and coastal managers in all the study sites already provided useful data as starting point to define the flood system components: historical erosion patterns and shoreline position; flooding mechanism (overtopping, breach, blocked drainage, drainage backflow); historical extreme events and, when available, frequency, depth and duration of flooding events and management decisions. The identification of existing management helped in defining the flood plain (and therefore receptors) and routes for floodwaters not directly related to coastal mitigation measures but to urban management (such as storm drains, culverts or sewers).

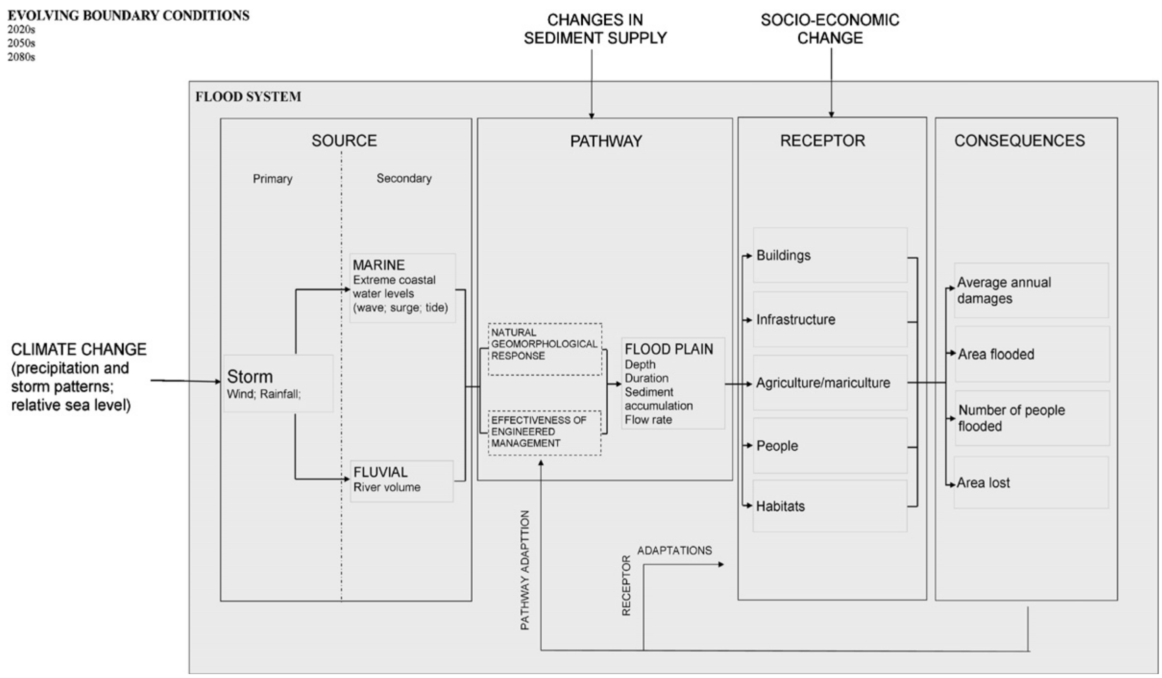


**Fig. 3 – Source-Pathway-Receptor-Consequence model adopted in THESEUS project for risk assessment.**

### 3.2. *Defining sources and mechanisms*

Sources have been divided between primary and secondary. The primary sources are the weather-related phenomena which generate water that could cause flooding. The secondary sources are the physical manifestations of the above which may cause flooding, e.g. wave, surge, and changes in river volume and flow. For environmental purposes, Sources are essentially classified in three groups according to duration: short-term processes (storm surge, wind waves, tides, run off due to downpours); seasonal – river high/low waters; long-term processes (sea level rise, local land surface vertical movements).

In THESEUS statistics of sources are defined in study sites by compiling existing (PRUDENCE3 or HIPOCAS4 or the IPCC AR4 archive5) and new data through a number of hindcast and downscaling activities. This approach enables THESEUS to deliver a comprehensive picture of present and potential future climate changes in the study sites and to provide an assessment of uncertainties associated with these changes. The assessment of climate conditions includes: extreme sea levels and wave heights; long-term variation of extreme sea levels occurrence; annual frequency distribution of extreme sea levels for different return periods; extreme sea levels; statistics of storm surges; spatial distribution of astronomical tide; sea level pressure fields of major flooding event; present and extreme river discharges.

### 3.3. *Drivers and scenarios*

Evaluation of coastal flood risk is a key requirement in hazard management and planning at national, regional and local scales (see for instance: Bates et al., 2005; Purvis et al., 2008; Ferreira et al., 2009; Martinelli et al., 2010). From a local or regional perspective such scales are determined by the specific characteristics of flood prone areas and their flood protection systems; land use and related values; and the nature and extent of the coastal problems. From an overall planning perspective, coastal risks may need to be considered on larger geographical scales in order to take account of the interaction and interdependencies between coastal areas and to set priorities based on national objectives. While individual floods are short-term events, our engineeering and planning scale is concerned in assessing and preparing for floods up to a century in the future. A scenario analysis is therefore needed (Nicholls and Tol, 2006) to account for economic and spatial developments and climate change.

Following DINAS-COAST (2004), SAFECOAST (2008), and FLOODsite (2009) approach, THESEUS also adopts a scenario analysis that considers other than the present situation (2010), three scenarios: short (2020s), mid (2050s) and long-term (2080s). In THESEUS, coastal risk assessment is performed at high resolution scale.

Key drivers of flood events identified in previous projects (e.g. Thorne et al., 2007) are: climate change which can affect Sources such as sea level, storm frequency and intensity and rainfall patterns (increasing or decreasing the extreme water levels during a flood event), sediment supply, which influences Pathways and ecological receptors, coastal geomorphology and ecosystems, and socio-economic change, which can alter the type and extent of human receptors within the flood plain. Once the drivers have been determined, the relative importance of each needs to be evaluated. This methodology uses expert judgment to assess potential impacts on future flood risk based on current understanding of how the different drivers function (see an example in Table 3). The methodology

**Table 3 – Drivers, their impact in the flooding system and example "native" parameter.**

| DRIVER | Impact in flood system | | | Examples of "Native" parameters |
|---|---|---|---|---|
| Climate change | Wave | Source | Alters flooding probability | Wave height; wave period |
| | Surge | | | Water level for different return period storm events |
| | Sea level change | | | Relative sea-level change |
| Sediment supply | Geomorphology | Pathway | Alters flooding probability | Beach width, dune height |
| | Habitat | | | Area; species |
| Socio-economic | Engineered management | Pathway | | Defence standard |
| | Buildings | Receptor | Alters consequences of flooding | Number and type of houses; building density; area |
| | People | | | Number of people; social structure |
| | Infrastructure | | | Area |
| | Habitat | | | Area; species |
| | Agriculture | | | Area |

follows the approach used in Evans et al. (2004) and Thorne et al. (2007). It allocates a score to each driver impact according to its influence on flood risk (altering probability or consequences) under the given driver scenario and time slice.

### 3.4. *Defining existing management strategies and pathways*

Pathways are the route and processes which are active during a flood event and there must be at least one pathway between the source and receptor otherwise no consequences can occur. Pathways include the components of the flood system and management through or over which flood waters flow to create the flood plain as well as hydrodynamics and other relevant processes such as sediment dynamics, dislodgment; distribution of particulate organic matter; changes in salinity levels; changes in redox potential (see Table 2).

It is worthy to remember that, although SPRC is a linear model, an individual pathway may have multiple receptors and individual receptors, multiple pathways; particularly when more than one type of pathway exists. The latter is largely relevant to the different failure mechanisms, such as the overtopping vs. the breaching of a defence, which can produce different flooding patterns or storm surge vs. sandy dunes that can be affected through both erosion and inundation processes.

### 3.5. *Receptors: habitat*

Environmental receptors include both valuable habitats (i.e. protected species, species providing food and recreation) and habitats that offer coastal protection (such as salt-marshes, dunes, seagrasses). Mapping is carried out using field measurements or topographic, lithological, geomorphological and soil maps, vegetation types, present moisture regime maps, aerial photographs, fine-resolution satellite images etc. Mapping is based on abiotic features: altitude/depth, relief, exposure (orientation to prevailing source action), relief slope, lithology/substratum type, soil type, soil humidity and other moisture regimes (for terrestrial habitats). Biotic features are used to determine conservation status and percentage of protected species in relation to total number of identified species and includes identifying species, communities and botanical associations, identifying the abundance, density, and occurrence of each species within community.

The approach for calculating the areas of the habitats affected differs according to the different sources. For instance, when it comes to Short-term and seasonal processes, if the affected habitat area undergoes inundation, it is assumed that it is a temporary process. Therefore, water inundation will retreat at a certain moment. This imposes the need for identification of several possibilities of key species/populations regeneration and habitat recovery (resilience). In this case, only the area that is subjected to inundation due to the negative natural process/hazard will be considered. On the other hand, if the water inundation comes as a result of long-term processes (e.g. sea level rise) it is assumed that the water masses will not retreat. Therefore, while losing terrestrial habitat areas, the same will be gained by aquatic habitats. On the other hand, if the landward boundary of the affected terrestrial habitats has a possibility for moving landward (habitat retreat), these newly occupied territories may be considered as gained habitat areas. Where there is no possibility for habitat retreat due to certain limitation factors, such as existence of natural or anthropogenic barriers, the areas of lost terrestrial habitats cannot be compensated.

For each habitat against each pathway (Gornitz et al., 1994; Thieler and Hammar-Klose, 1999), the Environment Vulnerability Index EVI will be identified. Thresholds at which the index passes over into a higher value will be determined through manipulative experiments and observation of the survivabilities of key species in changing media.

Finally, it will be considered how to calculate the habitat value that is actually a conditional concept, especially when discussing rare or threatened species. In certain cases, for example industrial species, this value may be easily calculated using the species market prices. For non-commercial species it will be assumed that their value can be formed on the basis of the regulations embedded in the existing environmental legislation. For example failure to achieve the requirements of Articles 13 and 14 of COUNCIL DIRECTIVE 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora is the imposition of a fine which can be used as a proxy for value. National legislation for Member States define scales of fines related to killing/destruction of these species in the wild; deterioration of breeding sites or resting places; cutting, uprooting or destruction of plants per specimen.

### 3.6. *Receptors: society and economy*

Social vulnerability is a complex phenomenon and no single measure comprehensively covers the whole spectrum of how vulnerability is manifested (Adger et al., 2004, 2005).

Recently, the social vulnerability index (SoVI) provided a comparative spatial assessment of human-induced vulnerability to environmental hazards (Cutter et al., 2003; Wisner et al., 2004). The SoVI is based on a large set of measurable variables that can be grouped into main common factors such as: population structure, gender, income, socio-economic status, renters (www.csc.noaa.gov/slr). Analysis and mapping of social vulnerability should also consider to identify critical facilities or resources (such as schools, hospitals, transportation) to help prioritize potential hazard mitigation.

Since results of previous research (FLOODsite, 2009) demonstrated, it would be dangerous however to adopt a straightforward use of this methodology in different sites because

- vulnerability is highly context-specific;
- there is no single variable, which explains the vulnerability of specific social groups coherently and for all of the disaster phases;
- no specific group is *per se* highly (or less) vulnerable: the same group may be vulnerable at a certain point in time of the flood event and not vulnerable at others, or in one place but not in another or in relation to certain aspects – e. preparedness, risk awareness, capacity to receive help during the event, flood impact – and not vulnerable in relation to others.

In essence, some relationships between social characteristics and vulnerability are far from linear.

Risk is both real and socially constructed: it is a mix of relevance claim, evidence claim, and normative claim. Coastal risk perception studies often limit themselves to surveys and descriptive statistics of the survey results, whereas a finer analysis of the determinants of perception and their relative importance is needed (Fig. 4) to answer relevant issues such as: how do societies deal with probability and the lack thereoff? How do societies deal with consequences and how do societies rank consequences? What is the vunerability that matters for society?

Moreover, existing approaches tend to neglect or simplify the number of distinct dimensions of social vulnerability (individual, household and institutional) which are worth further investigations.

THESEUS will therefore base social vulnerability maps on SoVI but also analyse in depth risk dimensions and risk perception, in order to provide a more comprehensive risk assessment methodology. To achieve this goal, the following steps are under way: (A) explore coastal flooding risk perception in study sites by local communities and by different groups of stakeholders involved in flood mitigation, planning and dissemination of knowledge; (B) address the local cultural, socio-economic and historical factors influencing the process of public perception of risks; (C) measure flood risk perception and acceptance from population; (D) relate social risk perception to community resilience. On a methodological standpoint, historical coastal floods are being analysed in study sites as reference events in education and information of citizens and local governments. Semi-structured interviews are under way within groups composed of local stakeholders involved in planning process or responsible for coastal protection and people involved in education and dissemination. Focus groups are also under way to elicit stakeholders' opinions on the present situation and to promote dialogue on future mitigation/adaptation options.

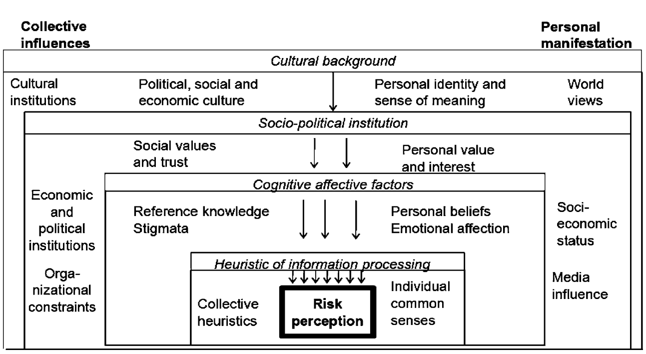


**Fig. 4 – Schematisation of the complex process of coastal risk perception to be analysed in THESEUS.**

In the economic vulnerability analysis, major sectors of economy and the primary centers of activity in those sectors have been identified in each of the study sites. These economic centers are areas where hazard risks could have major impacts on the local economy and therefore would be ideal locations for targeting certain hazard mitigation strategies. The Economic Vulnerability Index EcVI will be also calculated (Guillaumont, 2009), based on a composition of the following seven indicators: (1) population size, (2) remoteness, (3) merchandise export concentration, (4) share of agriculture, forestry and fisheries in gross domestic product, (5) homelessness owing to natural disasters, (6) instability of agricultural production, and (7) instability of exports of goods and services.

Homogeneous methods to evaluate direct (tangible and intangible) and indirect (tangible and intangible) damages due to coastal flooding and erosion will be derived by a combination of surveys (with different methodologies, a.o. Cost Benefit Analysis and Choice Experiment), focus groups, semi-strucured interviews, verification of coastal flooding damages in study sites, for historical or occurring events, and governmental compensation.

### 3.7. *Integrated risk assessment*

Hydraulic, environmental, social and economic risk assessment will be integrated through a MultiCriteria Approach MCA to provide coastal managers with an adequate decision support system for planning local defence strategies.

The MCA (Malczewski, 1999, 2006; Meyer et al., 2009) will be used in THESEUS at both stages of the risk management process:

1. Multicriteria risk assessment, MRA where risk magnitude and spatial distribution are identified. In contrast with most current approaches that focus on economic risks, THESEUS will include in ranking risk areas also environmental and social risks.
2. Multicriteria project appraisal, MPA. Mitigation measures will be evaluated accounting for both direct costs and monetary benefits (damages avoided) and nonmonetary benefits, i.e. reduction of environmental or social risks as evaluation criteria. The evaluation criteria will consist of

the multiple risk reducing effects as well as the costs of these alternative measures.

Among the two basic types of MCA, THESEUS project will build on the MultiAttribute Decision Making (MADM) approach, which solves a problem by choosing the best alternative among a limited set of given alternatives, i.e. a so called discrete decision space (Zimmermann and Gutsche, 1991). These given alternatives are compared regarding their attributes and each attribute is used to measure performance in relation to a given objective.

The MCA involves four crucial metholodigical issues that are usually the most time-consuming and controversial part of MCA, especially when several decision makers are involved (RPA, 2004; Roca et al., 2008) and need further research

- selection of criteria;
- weights of criteria;
- decision rule;
- selection of participants to the decision making process.

Due to the multidisciplinary participatory approach under development in THESEUS, stakeholders and coastal managers in study sites include different groups. Actually who determines the criterion and/or their weights considerably influences the total outcome of the MCA. Based on Penning-Rowsell et al. (2003), a cluster analysis will be applied in order to identify groups (clusters) of stakeholders/decision makers which have a similar weight assessment.

It will be explored the possibility to adopt a dominance strategy/Hasse-diagramm technique for a first screening and selection of mitigation options without having any information about the decision makers' preferences on the relative importance of the criteria, i.e. without knowing any criterion weights (Sørensen et al., 2004).

Tentatively a disjunctive approach (Zimmermann and Gutsche, 1991) will be adopted as decision rule. The decision maker has to define for each risk criterion a critical value which defines the border between low/acceptable risk and high/unacceptable risk. The results would be a map of the selected ''high risk''-areas and a simple ranking of the selected areas. Actually the crucial point of this methodology lies in the definition of the threshold values that requires the decision maker is familiar with the measures of the criteria which allow him to develop a clear preference for what level would define e.g. an annual average damage as no longer acceptable.

### 3.8. *Uncertainties in risk assessment*

Uncertainties in the results of risk assessment are often ignored. Although sophisticated methods in all parts of risk analysis and assessment have been elaborated over the past decades in order to give a reasonably exact estimation of flood risk, the results of risk assessment are still to some degree uncertain or imprecise (Nachtnebel, 2007). Inaccuracies and uncertainties are naturally inherent in all parts of flood risk analysis, for instance:

- probabilities of flood events: errors may occur e.g. through the extrapolation of short time series flood discharges;
- inundation area and depth: imprecision e.g. due to generalised digital terrain models or because of difficulties in estimating failure probabilities of flood defences;
- type and location of elements at risk: inaccuracies e.g. because of generalisations in spatial resolution and categorisation of land use data;
- value of elements at risk: values are often approximations or have to be disaggregated or have to cope with non-marketable elements such as valuable habitats or lifes;
- susceptibility of elements at risk: damage functions are often derived from poor empirical data.

Hence, the decision matrix or the criterion maps which form the basis for MCA contain uncertainties. These uncertainties are often not communicated to the decision makers, i.e. a non-existent precision of estimation is pretended. This might facilitate the decision for the decision maker but reduces the scope of decision and could lead to a solution which is not optimal. Within THESEUS, these uncertainties will be documented by a range, i.e. a lower and upper and perhaps a mean value, or, by a standard deviation around the mean value or a probability distribution.

## 4. Mitigation measures: towards sustainability

In recent times, coastal protection and water management in lowlands has been concerned to 'keep water out', 'defend property from water' and 'live on dry land'. Globally, and especially in parts of Europe, there has been a change in attitude towards coastal protection in response to the growing risk and uncertainty generated by climate change. Traditional technical flood and erosion defences have shown their limits. In recent years, greater attention had been paid to the design and selection of coastal defence structures and technologies based on an integrated analysis of their performance and on their environmental and socio-economic implications (Zanuttigh et al., 2005; Burcharth et al., 2007). Moreover, what society expects from defences is changing (e.g. widespread moves from hard to soft defences to 'hold the line'), and these needs will continue to evolve, and at the same time, climate change is increasing risks. Sustainability for a given coastal system requires:

- efficient protection to life and goods, and preserving socio-economic development and opportunities of coastal areas;
- maintaining environmental assets;
- short, medium and long-term scenarios accounting for climate change effects.

Defence design should be aimed at providing ''continuity of daily life''–before, during and after a flood, to avoid the detrimental social and economic impact that would otherwise result (LIFE project, 2009). A development that intrinsically provides flood resilience, through an adequate defence planning strategy, should give insurers and financiers the confidence to offer affordable, long-term policies and investments.

THESEUS examines new mitigation measures or combination of existing ones within coastal engineering, ecology and socio-economy. Few examples are shown in Fig. 5.

### 4.1. Coastal structures and sediment management

With the expected sea level rise, thousands of kilometres of coastal dikes will be probably exposed in Europe to waves with height greater than the design value, in particular all the structures built in shallow water where the depth imposes the maximal amplitude because of wave breaking. Moreover the sea level rise associated with large waves will induce greater overtopping. Sea level rise will therefore lead to problems in terms of function, mechanical stability and safety of goods and persons.

The level to which a dike or levee should be designed depends on the intended risk reduction or allowable risk. This implies that the design is based solely on an economic optimum but in most cases the availability of funds defines the achievable level of risk reduction. Schematically, with the progressive increase of damages, the stakeholders will adopt one of the several scenarios: repairing dikes as they presently are, upgrading technology of the existing defences or changing structure dimensions and occupation in protected areas, strategic retreat and decommissioning.

To improve dike performance under extreme conditions of water levels and waves, Comcoast project (2007) provided some innovative solutions including overtopping resistant dikes (i.e. any water that is washed over the top can be temporarily stored and drained away) and different dike covers (a.o., made of sand and made of grass) placed on top of the inner dike slope to increase dike stability. Destructive tests on dikes have been recently carried out at prototype scale using an innovative device, the Wave Overtopping Simulator (Van der Meer et al., 2009) that allows to derive new results on overtopping flow, dike design, dike erosion and failure.

Within the Comcoast project (2007) it was also proposed for the first time to create in between two lines of dykes multifunctional areas (i.e. buffer zones) where enhancing environmental tourism and habitat biodiversity.

A similar integrated approach was already proposed by DELOS project (2003) project, which analysed the possibility to couple coastal protection, and specifically low crested breakwaters, with environmental, social and economic issues. These structures

- have by definition a minimal visual intrusion that makes them a valued solution in particular in zones with strong aesthetic constraints;
- are generally more stable than traditional breakwaters, and the potentially smaller material requirements produce a lower cost of construction;
- can be used in front of existing structures for rehabilitation purposes;
- assure a high water renovation in the protected cell and thus a satisfying quality for recreational waters, especially in tideless seas, and water oxygenation for colonizing coastal assemblages (Moschella et al., 2005);
- can be designed for specific purposes and with different kind of materials, as it happens in case of artificial reefs for creating marine parks and/or surfable spots that include a variety of schemes adopting geotubes, geobags, reef balls, aquareefs and are popular along the coasts in Japan and in Australia (Pilarczyk, 2003; Ranasinghe and Turner, 2006; Jackson et al., 2007).

Due to the progressively increasing importance given to the reduction of environmental impacts, beach nourishment developed as one of the main solution to cope with coastal erosion processes (Nicoletti et al., 2006). In the Netherlands, sand nourishments to maintain sediment volumes within the active coastal zone have been applied as a structural measure since 1990 (presently amounting to 12 $Mm^3$ per year). In other countries, reduced river sediment supply and anthropogenic impact raised the problem of searching sand for beach maintenance. These problems motivate the identification of off-shore borrow areas and the planning of combined intervention of sand dredging and nourishment, measures investigated within the framework of the Interreg IV-C Beachmed-e (2008). Measures proposed by the Eurosion project (2004) to adapt to coastal erosion include the designation and maintenance of strategic sediment 'reservoirs'. The reservoirs considered would act as buffer zones directly protecting land from the sea, or aim to secure sufficient volume of sediment within active coastal sediment cells to allow the shore to keep pace with sea level rise. Different management modes could be applied to deal with the various reservoir types (results from Conscience project, 2008) such as 'active conservation' or 'restrictive' regarding activities that would decrease available sediment budgets.

Within coastal engineering, THESEUS project is proposing to use wave energy converters for beach defence purposes. Key issues in this application are the design reliability and the installation distance from the shore to contemporarily obtain incident wave attenuation and maximize secondary benefits (Zanuttigh et al., 2010). Knowledge about how to reduce incident wave energy on the shores with multi-purpose structures characterised by low environmental impact as artificial reefs and bottom vegetation will be incrementally advanced. Insights and critical review of dike design optimization in the two perspectives of increase structure resilience (over-washed structures with proper reinforcement) and decrease overtopping (overtopping resistant dikes with different cover layers) will be provided. Plans of dredging and nourishment operations, management of borrow areas, reactivation of the littoral drift, estimation of plume dispersion will be also analysed.

### 4.2. Ecologically based mitigation measures

Despite the recently proposed flood alleviation strategies (i.e. "no defend" approach) and the concerns about predicted increases in sea level and in the frequency of storm events, our understanding about the ecological impacts of flooding by seawater is relatively sparse. The activities within THESEUS project will be addressed to fill this gap. From a management perspective it is indeed essential to identify the habitats that should be protected so that measures can be put in place to reduce the risk of flooding and also to identify those habitats where little or nothing should be done. Key features to be considered are the hydrological conditions, the spatial extent of habitat that may be inundated, the likely timing of the event, the depth of water, together with its likely velocity and quality, and, if the event is transient, its expected duration. The perspective here needs to be the conservation of habitats and species at a national or European level rather than the wholesale preservation of habitats in their current form.

Among the habitats to be preserved, there are specific habitats whose maintenance and reinforcement may act as environmental-friendly coastal defence, a.o. for instance: salt marshes, dunes and natural reefs. The extent to which these habitats offer coastal protections and the extent to which such protection can be enhanced and managed is one of the issues under analysis within THESEUS.

Saltmarshes in Europe cover about 3000 $km^2$ and are sites of primary productivity, much of which may be exported into adjoining marine ecosystems (Adam, 1990). Saltmarshes can be in two ways effective coastal defences: (i) in wave exposed areas, marsh vegetation can be capable of dissipating over 90% of incident wave energy over tens of meters (Möller, 2006) and (ii) in more sheltered up-stream estuarine areas, the marsh offers water storage volume during spring tides or high river discharge. An important aspect in wave attenuation is that the root system of the marsh vegetation stabilizes the sediment against wave attacks (Barbier et al., 2008). The efficiency of hydrodynamic attenuation varies with plant community structure and with the density of vegetation canopy (Bouma et al., 2005). The reduction in flow energy stimulates sedimentation and allows a majority of salt marshes to keep pace with sea level rise (Morris et al., 2002; Kirwan and Temmerman, 2009). However, the sea level rises will potentially lead to an increase in salinity across the upper marsh system, whose unique ecotonal conditions may be lost as more frequent marine inundation causes the supralittoral zone to be squeezed out, between the sea and adjoining coastal defences or agricultural land (van der Wal and Pye, 2004; Wolters et al., 2005a,b). The current effort to restore marsh systems in Europe and elsewhere represents graphic evidence of the political and managerial value placed on the goods and services provided by this ecosystem.

The principle of 'managed realignment' and 'managed retreat' is one of allowing salt-marsh areas that were historically converted to alternative use for anthropogenic purposes (e.g. agricultural land or tourist development) to return to their natural state and area cover (Rupp-Armstrong and Nicholls, 2007; Garbutt and Wolters, 2008). Cost benefit analyses typically show a net advantage of managed realignment over other constructed defence options (Spurgeon, 1998; Turner et al., 2007). This approach reduces the cost involved, as well as the wave action depressing the development of the vegetation. However full restoration of natural ecosystem function is sometimes difficult or impossible: the substrates and biodiversity of pristine salt marshes is often markedly different from an artificial or restored system, even 100 years after natural processes have been allowed to operate (Hazelden and Boorman, 2001).

Coastal dune ecosystem is of strong patrimonial and landscape interest, but also act as a barrier to storm surges and flooding, protecting landward development. Dunes are important stocks of sediment: sand released by dune erosion nourishes the beach and the foreshore provisionally reducing vulnerability of the cross-shore profile to further erosion. Due to strong anthropic pressures, the 25% of European coastal dunes disappeared in the last 50 years (Heslenfeld et al., 2004). Dunes in Europe now cover a total area around 5300 $km^2$ and are characterized by high ecological diversity due to geomorphological characteristics, environmental heterogeneity, species variability (Martinez et al., 2004). Dune destruction takes place under storm waves, in particular when a high sea level occurs simultaneously (Heslenfeld et al., 2004). The vulnerability of coastal dunes to flooding depends on the characteristics of the dune system itself (height, width, conservation status), on the intensity of the event (sea level rise, storm intensity) and on the conservation (essentially width) of the backshore. Dune resilience to flood is dependent on the sediment supply in the area and on the intensity of human impact that in turns affect coastal habitats (Martinez et al., 2004) and specifically dune vegetation, which plays a key role in the integrity and preservation of a stable dune (Araujo et al., 2002). Reinforcement or reconstruction of dune systems is in some cases limited – as well as nourishment- by the availability of compatible sand and by the vegetation development. Therefore depending on the coastal ecosystem, this technology has been widely performed in the Northern Europe (Healy and Doody, 1995) and has been recently adopted in selected cases in the Mediterranean (Gomez-Pina et al., 2002; De Lillis et al., 2004; Valpreda, 2006).

Natural biogenic reefs have a major functioning role in European coastal and deep seas, providing a range of goods and services, such as storm protection and flood control, disturbance regulation, erosion control and sediment retention, nutrient cycling, refugia and recreation (Moberg and Rönnbäck, 2003; De Groot et al., 2002). In a significant study, Costanza et al. (1997) valued 17 ecosystem services offered by habitats throughout the world, particularly pertinent for reefs. By extrapolating these services to economics, a value of \$6075 $ha^{-1} yr^{-1}$ was attributed to tropical coral reefs. The authors estimated that 45% (\$2750 $ha^{-1} yr^{-1}$) of this value could be attributed to disturbance regulation in the form of sea-defence. While tropical reefs are obviously exceptional, the same relative importance in terms of disturbance regulation and consolidation of sediments through the presence of their structure can be attributed to reefs in other habitats. However, the contribution of temperate reefs around Europe has been largely understudied.

Despite the increase in scientific publications on seagrasses in the last 35 years (Orth et al., 2006), the level of public awareness, as reflected by the number of reports on seagrass ecosystems in the media, is far less than that for other coastal habitats. Much of this disconnect between available information and public awareness undoubtedly stems from the invisibility of seagrasses and from the avoidance of their very shallow habitat by many boaters. Seagrasses are sometimes labeled ecosystem engineers (Wright and Jones, 2006), because they partly create their own habitat: the leaves slow down water-currents increasing sedimentation, and the seagrass roots and rhizomes stabilize the seabed. Seagrass beds are highly diverse and productive ecosystems, and can harbor hundreds of associated species from all phyla, for example juvenile and adult fish, epiphytic and free-living macroalgae and microalgae, mollusks, bristle worms, and nematodes. Their importance for associated species is mainly due to provision of shelter (through their three-dimensional structure in the water column), and for their extraordinarily high rate of primary production. Segrasses are threatened by human disturbance, most notably eutrophication, mechanical destruction of habitat, and overfishing. There is a critical need for a targeted global conservation effort that includes a reduction of watershed nutrient and sediment inputs to seagrass habitats and a targeted educational program informing regulators and the public of the value of seagrass meadows (Kenworthy et al., 2006; Walker et al., 2006; Waycott et al., 2009).

### 4.3. *Resilient societies and economies*

Innovative approaches to coastal flood mitigation–as recently proposed by the ongoing LiFe project (2009)- incorporate design features within a development which allow floodwaters to pass through the landscape, with minimal risk to life and properties. This approach is a shift from an approach of defending land and property from flooding, whatever the cost to one that ensures continuity of everyday life before, during and after a flood. A non-defensive approach to flood risk management that works with natural processes can help to reduce the ongoing maintenance costs associated with defences, reduce the residual risk and increase awareness. A resilience approach makes coastal system less prone to disturbances, enables quick and flexible responses, and is better capable of dealing with surprises than traditional predictive approaches (Arjan Wardekker et al., 2010).

Work in study sites showed (Smit and Wandel, 2006; Steinführer et al., 2009) that advances in coastal resilience approach are affected by key issues such as

- lacking awareness;
- missing pro-active mentality among the population;
- unclear legal responsibilities between residents and government;
- absence of flood management protocols;
- conflicts among existing policies.

Formally, residents who choose to live in area exposed at coastal erosion and floods are assumed to take this risk knowingly and willingly. However, residents perceive the government to be responsible for flood protection, and the exact legal responsibilities for property damage are unclear. Additionally, (new) residents may lack awareness of the risks of living in such an area. They are not actively informed, since no party is responsible for doing so. This 'legal uncertainty' could make these areas less attractive and enhance societal disruption after floods. Unclear responsibilities thus function as a feedback that worsens impacts.

Moreover, coastal zones face many other developments that call for adaptation: urbanisation and housing, economic development, and mobility/accessibility pose significant challenges with uncertain spatial claims. Uncoordinated communication by various governmental units results in 'information overload'. Governmental anticipation on changes is slow, and public support for adaptation policy is lacking due to low participation.

THESEUS analyses and develops the contributions of social science and economics at addressing the challenges of transforming the concept of resilience into a portfolio of tested operational innovative tools for policy and management purposes of coastal risks. Risk mitigation will be achieved essentially through the advance or improvement of the methodologies synthetically recalled below and divided into three main categories depending on the way risk is addressed.

1. Modification of the exposure to hazard:
   a) through spatial planning and controlled urbanisation (Penning-Rowsell, 2001; Pottier et al., 2005). Focus has to be paid not only in improving methods, but also and especially in setting up the appropriate governance arrangements needed to guarantee that the appropriate spatial planning and controlled urbanisation systems will (a) be put in place and (b) will be sustained over the several decades that will be necessary for them to be effective;
   b) through flood resistant adaptations to buildings or local sites in flood areas that are not (sufficiently) protected by flood defences. These options are sometimes referred to as 'dry proofing' (e.g. buildings on poles, floating houses, dwelling mounds, local protection) and 'wet proofing' (reduce damage by making buildings water proof).
2. Reduction of hazard impact.
   a) innovative methods of siting, designing and managing business operations might minimize the need for (or the design standards of) the kinds of major coastal defence structures that otherwise would be needed in the future with climate-change induced sea level rise. Risk mitigation can take a variety of forms, for instance: building redundancy into infrastructure systems (water supply, power supply, etc.); building access and egress routes so that vulnerable business premises can continue to operate at times of hazard, or recover more rapidly.
   b) through evacuation plans. Regarding this measure, the available research and data at European scale so far are limited and do not allow for a cost-benefit analysis (Parker et al., 2007; Penning-Rowsell and Wilson, 2006; Olfert, 2007).
3. Increase of social resilience and adaptive capacity:
   a) through risk communication and education. Networks and institutions that promote resilience to present-day hazards also buffer against future risks, such as those associated with climate change. Effective multilevel governance systems are critical for enhancing the adaptive capacity to deal with disturbance and to build preparedness for living with change and uncertainty (Berkes et al., 2003). The development of best practices on how to communicate flood risk and to promote preparedness requires a preliminary investigation of coastal risk perception (see Fig. 4) by local communities and by different groups of stakeholders involved in flood mitigation, planning and dissemination of knowledge.

b) through preservation of resilience of coastal ecosystems that are essential for human livelihoods and societal development (Folke et al., 2002; Walker et al., 2004).
c) through insurance system that offers much-needed support to accelerate economic and social recovery following a disaster, but it can also contribute to impact limitation (point 2) by using pricing or restrictions on availability of cover to discourage new development in hazard-prone areas. The overall aim should be the design of efficient insurance programs and the contemporarily identification of the necessary incentives for their adoption by property owners, that will encourage loss reduction measures against natural hazards and provide recovery funds to disaster victims.
d) through post-crisis units that provide a proper support by a psychological guide (Rhoads et al., 2006) to face anxiety, depression and general psychological distress (Ottoa et al., 2006). The European Policy Paper ''Psycho-social support in situations of mass emergency'', 2001, concerning different aspects of psycho-social support for people involved in major accidents and disasters, offers decision-makers a methodological guide and a coherent model for psychological and social support in in the acute and in the transition phase of mass emergency.

## 5. Coastal risk management and planning strategies: from science to practice

### 5.1. *A strategical coastal master plan*

Considering the long term and large-scale aspects of coastal risks, the development of defence strategies should be based on a hierarchical planning approach, ranging from a top down national (master) planning level to the analysis of individual flood prone areas and the consideration of specific strategies and measures within these areas (Holman et al., 2008). The master plan MP should facilitate the necessary communication between coastal defence managers, contingency planners and crisis managers and warrant the continuity of coastal risk management policies, the protection measures and the related operational procedures (i.e. in terms of financing; institutional arrangements; legal rights/obligations; and operational responsibilities).

In general, the development of coastal protection strategies involves the following steps.

(1) Specification of detailed regional scenarios.

Regional scenarios should provide more specific and detailed information with respect to:

- the regional translation of the various aspects of climate change (to be included in the regional specification of hydraulic loads);
- spatial and infrastructural developments based on specific regional development potential; existing plans; and specified development priorities;
- already planned developments in flood/erosion protection systems.

The regional scenarios should reflect the main scope of possible developments and capture the major uncertainties in developments driving future risks and the possible effects of measures and strategies to reduce these risks.

(2) Problem assessment and identification of promising measures.

The problem assessment refers to establishing the extent of future coastal risks and carrying out a flood risk assessment for the relevant regional scenarios as specified in the previous step.


**Fig. 5 – Defence technologies analysed within THESEUS project: from top to bottom: and from left to right: wave energy converters, salt marshes (photo courtesy of Prof. Marcel Stive), houses on the beach and resilient houses.**

The feasibility of mitigation measures to be considered depends on many factors related to the natural and socio-economic characteristics of the coastal area, the existing flood protection system and the coastal management context (as affected by political, institutional and cultural conditions). Within the directives provided by the master plan, a screening exercise should be performed to identify possible measures that are more plausible or promising than others, given the specific characteristics and conditions pertaining to the coastal area considered.

(3) Analysis and evaluation of alternative strategies.

Alternative strategies regarding the protection and management of the coastal area should be based on various combinations of promising measures, each strategy representing a logical and coherent mix of measures. Assessment of the relevant impacts of the alternative protection and management strategies in terms of societal costs and benefits has to be carried out. In order to deal with the various (large) uncertainties, the impacts of possible strategies need to be considered for different regional scenarios. The evaluation should not so much aim at selecting the 'best' strategy within a specific scenario, but rather to identify the most 'robust' strategy, showing an acceptable performance (in terms of meeting required objectives or achieving anticipated benefits) across all relevant scenarios. Hence, the primary aim of the evaluation would be to minimise the risk of selecting a wrong strategy.

### 5.2. THESEUS participatory approach

To overcome the problems of integrating science into practice, THESEUS is developing a fully participatory approach to coastal defence planning and design. The project starting point in fact is the analysis of present conditions in study sites, including existing defences, policies and regulations through direct contacts and meetings with stakeholders and coastal authorities.

A questionnaire was used during the first project year for interviewing local policy makers and managerial authorities or administrators to gather data for systems analysis in the 8 study sites. The goal was to obtain sufficient information to assess per study site the coastal system (including its flood defence systems) and its resilience on the short, medium and long term (see Section 2). The questionnaire consisted of five parts:

- description of the geographical use of the study site area, including land use and spatial planning;
- physical characteristics of loads and the flood defence system;
- current policy, management and planning strategy in relation to erosion and flood risk management;
- institutional map which indicates all the parties involved in flood risk management with their responsibilities;
- sustainability of the flood defence infrastructure and resilience of the natural coastal system against floods.

A flood risk analysis, institutional map, inventory of coastal policies and an estimate of their sustainability have been obtained so far in each study site. Moreover, the observation of the local situations in the sites prompts the following recommendations to strength synergies between policy and science.

- Clearly define national and regional coastal risk management goals in a broad and long-term perspective.
- Reduce and better manage uncertainty in coastal flood and erosion risk assessments. Further research should aim to understand and identify methods to explicitly include uncertainty in all decisions relating to coastal management.
- Further develop the integrated planning approach to manage coastal risks. Important common aspects for further research include the integrated development of: scenario specification procedures; coastal risk assessment methodology, with specific focus on ecosystem-society resilience and social risk perception; and the hierarchical planning approach for coastal risk management, linking short and long term time horizons and different geographical scales.
- Increase the focus of coastal planning procedures at the participation of local communities and authorities. The purpose of this local participation is twofold. On the one hand, optimal use is made of the know-how and skills of local communities, taking into account their wishes and needs. On the other hand, the involvement and shared responsibility of local parties in the coastal risk management planning process will guarantee a sound social basis for the management plans to be developed.
- Continue the international cooperation and learning process, due to the similarities in coastal problems and possible solutions, and the commonality in methodological approaches.

In a later stage of the project (2012) an additional questionnaire and analysis will be carried out to determine how long the current policies, defence management and strategies will remain effective with respect to the possible climate change, demographic, ecological and economic developments, subsidence, changes in social values and so on. The mitigation measures developed within the project will be also discussed with local authorities in order to identify the best solutions for each study site, providing a very useful feedback of local policy makers and managerial authorities on the research.

THESEUS is developing standard integrated practices for the selection of mitigation measures in study sites after the estimation of their engineering, environmental and socio-economic effects. Scientific outcomes will be integrated into design guidelines for defence design and in a decision support system GIS-based tool for coastal risk assessment and management. THESEUS will thus ultimately contribute to implement an integrated protocol for coastal risk management.

## 6. Conclusions

Large stretches of the European coasts, which are highly populated and economically essential, are already threatened by coastal erosion and flooding. Climate change and sea-level rise will increase the frequency and severity of flooding and erosion events, while socio-economic changes are increasing the threatened assets. While in the media and the public mind, coastal floods and erosion are often seen as unnatural and nonallowable, they are natural occurrences, and no amount of investment can reduce risks to zero – an acceptable level of residual risk must always be defined.

While new defence technologies have the potential to reduce costs and risks and increase our portfolio of management tools, we do not see technical solutions alone as the answer. Rather the need is to integrate the best of technical measures in a strategic policy context which also considers the environmental, social and economic issues raised in any coastal area. It is in this spirit that THESEUS project (2009–2013) will advance the state-of-the-art in developing a fully integrated methodology for risk assessment and in applying innovative technologies to reduce risks on coasts.

Within coastal engineering, THESEUS examines how to reduce incident wave energy on the shores with structures characterised by low environmental impact (as bottom vegetation), overtopping resistant dikes and multipurpose structures (as artificial reefs and wave energy converters). THESEUS also addresses the issue of coastline stabilization through dredging and nourishment operations, management of borrow areas, reactivation of the littoral drift.

Within ecological science, THESEUS examines the extent to which natural biogenic habitats offer coastal protections and the extent to which such protection can be enhanced (salt marshes, dunes) and managed. THESEUS advances the knowledge of the environment vulnerability to sea water inundation that is essential to proceed with no-defend options (inundation in controlled areas). Evaluation of natural habitat management is considered alongside the ecological effects that coastal engineering intervention produce on marine habitats, providing guidelines and best practices for minimizing their impact through a proper design.

Within THESEUS social science and economics address the challenges of transforming the concept of resilience into a portfolio of tested operational innovative tools for policy and management purposes of coastal flooding risks. Ground tested guidelines for innovative coastal risk governance in terms of insurance schemes, land use planning, private sector strategies, post crisis management, knowledge mobilization and crisis planning protocols are under development.

THESEUS will finally integrate scientific outcome into design guidelines for defence design and in a decision support system for coastal risk assessment and management. This GIS-based tool operating at high spatial resolution will allow coastal stakeholders to rapidly assess local risk level, to identify mitigation measures and related costs and benefits, to select and check the challenges of adaptation strategies, to organize early warning and evacuation plans. Risk assessment and mitigation are being carried out in the study sites in strict cooperation with policymakers, local authorities and major stakeholders.

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