CONHAZ

Costs of Natural Hazards

Methods for Estimating the Costs of Coastal Hazards

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The ConHaz EU project

Cost assessments of damages of, prevention of, and responses to natural hazards provide crucial information for decision support and policy development in the fields of natural hazard management and planning for adaptation to climate change. There is a considerable diversity of methodological approaches and terminology being used in costs assessments of different natural hazards. This complicates the assessment of comprehensive, robust and reliable costs figures, as well as comparison of costs across hazards and impacted sectors. This report is part of the EU project ConHaz. The first objective of ConHaz is to compile state-of-the-art methods and terminology as used in European case studies. This compilation will consider coastal hazards, droughts, floods, and alpine hazards, as well as various impacted sectors, such as health and nature. It will consider direct, indirect and intangible costs. ConHaz further examines the costs and benefits of risk-prevention and emergency response policies. The second objective of ConHaz is to evaluate the compiled methods by considering theoretical assumptions underlying cost assessment methods and issues appearing in application of the methods, such as availability and quality of data. ConHaz will also assess the reliability of the end results by considering the accuracy of cost predictions and best-practice methods of validation, and will identify relevant gaps in assessment methods. The third objective of ConHaz is to compare available assessment methods with end-user needs and practices, so as to better identify best practice and knowledge gaps in relation to policy-making. A final objective of ConHaz is to give recommendations about best practices and to identify resulting research needs.

Structure

1 Introduction

Prevention and mitigation of natural hazards have gained much attention in recent years. In the context of climate change, damages caused by extreme events such as floods, droughts and storms have often led site managers, planners and policy makers to adopt new measures and strategies, and the economic evaluation of these damages has been recognized as being essential in decision-making processes. This report will attempt to provide a better overview of existing methods to assess the costs of natural hazards in coastal zones. The frequency of events and coastal hazards has increased dramatically over the last decades, at least for what concerns cyclones (Webster et al., 2005). The associated damages have been aggravated, notably because of the assumed increased vulnerability due to the population growth and to the infrastructure development in coastal areas, and the rise in sea level due to global climate change (IPCC, 2007). The current report will first attempt to define the terminology related to coastal hazards, and will then compile and evaluate different methods which enable the valuation of costs of storms and related coastal hazards, as well as the costs of mitigation and adaptation measures to coastal erosion, future extreme events and accelerated sea-level rise due to climate change. The terminology of natural hazards and associated costs (direct and indirect costs, intangible effects, costs of mitigation and adaptation), the availability and quality of data, as well as approaches to the assessment of costs, have been first introduced in the previous project reports for each cost type and natural hazard investigated by ConHaz, and will be further studied in this report in the context of coastal hazards and related damages.

Objective

The objective of this report is to compile the terminology related to the costs of damages caused by storms and induced coastal hazards: direct and indirect costs, intangible effects, costs of mitigation and adaptation. Subsequently existing methods used to assess the damage of extreme events in coastal zones, as well as the costs of mitigation and adaptation to coastal hazards will be compiled and evaluated.

2 Terminology

2.1 Preliminary definitions

A coastal hazard can be defined as “a natural phenomenon that exposes the littoral zone to risk of damage or other adverse effects” (Gornitz, 1991). Even though coastal hazards include natural events such as tsunamis or coastal subsidence, a significant part of the natural disasters affecting coastal areas - i.e. high winds, coastal flooding, high velocity flows, damaging waves, significant erosion, and intense rainfall - can result from storms (Watson and Adams, 2010). In this context, a particular focus on storms and induced coastal hazards (suggesting a relation of cause and effect) is therefore appropriate to refer to a wide range of disasters affecting the coastal environment. Given that coastal storms may have significant impacts on coastal natural resources and communities, they are also largely considered in coastal risk management. In the socio-economic literature, hazards resulting from coastal storms can be classified mainly in two forms: wind storm (Schwierz et al., 2010; Heneka and Ruck, 2008) and storm surge floods (Danard et al., 2003; Benavente et al., 2006; Friedland, 2009). To better illustrate the difference between these two forms of hazards, it is necessary to observe their main impacts and associated damages: while for wind storm these are principally related to wind characteristics such as wind speed, these are mainly related to water characteristics such water depth for coastal flooding. However, there exist other hazard characteristics to be taken into account (e.g. peak gust wind speed, flood velocity and duration, etc.). Examples of related damages will be developed in paragraph on impacts of coastal hazards (cf. paragraph 2.2). Actually there exist a variety of approaches to study coastal storms and related damages and costs, insofar as damages result from the combined effects of these two forms of hazards. It is also noticeable the fact that a wind storm is generally associated with high waves, unless the wind would be blowing in a direction opposite to the effective fetch in the area. However, in the socio-economic risk literature the cost of damage due to waves is rarely considered, as this often corresponds to a loss in beach volumes which is normally experienced on annual basis after the event. To notice that as Ferreira et al. (2009) pointed out, the approach to coastal risk in the EU is not uniform and often the only perception of risk related to storms is flood-related.

Danard et al. (2003) define a storm surge as “an abnormal, sudden rise of sea level associated with a storm event”; while a wind storm, in its broad sense, may equally affect coastal and inland areas. In reality, wind storms and storm surge floods are closely related since coastal flooding is often the consequence of strong winds, wave overtopping and coastal submersion. However, their distinction is often necessary when assessing the costs of coastal storms, because cost assessment methods are rarely developed simultaneously for wind and flood hazards. As regards to the objectives of the report, only damages and costs of storm surges, coastal storms and associated flooding will be considered in the present paper, i.e. the report will consider cost assessment methods developed either for wind, flood or both hazards (expect one case dealing with tsunamis), which are only applied for coastal areas. The main reason is that the cost assessment methods for inland storms do not integrate any combined flood effects resulting from coastal storms, as it is generally the case in coastal areas.

2.2 Impacts of coastal hazards

Coastal storms may cause considerable impacts on coastal buildings and infrastructures, as well as impacts on coastal environment and communities. This section describes the impacts caused by storm surges and/or associated flooding.

(1) *Morphological impacts*: negative morphological impacts resulting from coastal storm surges are closely related to beach and dune erosion. They make coastal environment and communities vulnerable to the risk of submersion. These impacts may include beach erosion, shoreline retreat, dune destruction and overwash (Van Dongeren et al., 2009; Ferreira et al., 2009), coastal flooding and changes in beach profiles (Ciavola et al., 2007; Bosom and Jiménez, 2011); while other morphological impacts can vary from sand accumulation to no significant change (Pirazzoli et al., 2004).

(2) *Impacts on buildings and infrastructures*: the main direct impacts of coastal hazards (i.e. the impacts caused during the hazard event) include impacts on building and infrastructures. Coastal buildings and infrastructures are subject to storm surges and related flooding; and associated damages are both wind- and flood-related. Therefore, the main elements at risk in coastal areas may differ accordingly. But associated damages generally result from this combination of wind and flood impacts. Main impacts of wind storms are impacts on buildings including damages to doors, windows (Vickery et al., 2006), damage to roofs, damage to walls, collapse of buildings (Heneka and Ruck, 2008), etc.; while water elevation rather affects building's basement and first floor(s), impacts on vehicles, etc. (FEMA, 2006). In reality, all these categories of damages are not exclusively caused by one or the other hazard. On the contrary, they can be caused by both wind storms and floods, and this combined effect intensifies total damage to buildings and infrastructures. Because buildings and infrastructures have specific characteristics and attributes, they are impacted by the disaster in different ways, depending on their exposure to the disaster. For example, vulnerability to floods highly depends on base floor elevation. The Saffir-Simpson Hurricane Scale already gives indications about possible damages to buildings and structures, depending on the degree of storm severity; while storm surge intensity has been defined by USACE (U.S. Army Corps of Engineers, 1996, p.II-3) for each category of hurricane, on a scale from category 1 to category 5. As an example, as storm surge severity is function of wind intensity, water levels have been respectively defined as varying from 4 feet above normal tide levels for category-1 hurricanes to greater than 18 feet for category-5 hurricanes. In terms of structural damages, if we refer to this combined classification, low lying coastal roads are first exposed to inundation by sea water for lowest degrees of wind intensity. On the contrary, for higher degrees of intensity of wind and associated storm surge, there may be considerable damages to coastal structures. Evacuation of residences within a defined distance from the shore is possibly required in case of storm surge of 9 to 12 feet above normal tide levels. While for low degree of intensity, winds affects building and infrastructures such as mobile homes and poorly constructed frame homes, for the highest degree of intensity, winds create storm surges capable of causing major damage to lower floors of structures near shore (U.S. Army Corps of Engineers, 1996, p.II-3). On the other hand, extreme winds may cause damages or even destruction of residential, commercial and industrial buildings (National Hurricane Center, 2010).

(3) *Impacts on natural environment*: the impacts of coastal storms on the natural environment result in damages and losses including damage to trees, soil erosion (mainly caused by floods), and losses of natural habitats such as forests or wetlands (Dosi, 2001). In addition, coastal erosion and salt water intrusion in coastal habitats and aquifers may also result from storm surge events (McKenzie et al. 2005). In the context of climate change, environmental impacts such as flooding of low-lying coastal lands or accelerated cliff and beach erosion may be aggravated by sea-level rise and human pressure on the natural environment (UNEP/MAP-Plan Bleu, 2009, p.9). In terms of losses, these environmental impacts are often difficult to quantify as they are intangibles. These impacts characterized by associated intangible damages can be defined as the impacts on goods and services for which market values do not exist (McKenzie et al. 2005), and can be assessed by using specific methods.

(4) *Impacts on humans and society*: coastal storm or hurricane impacts on humans may be considerable, as they can result into deaths and injuries. Coastal storms may, for example, make the water unavailable for several days to a few weeks after the storm. These water shortages are likely to increase human suffering (National Hurricane Center, 2010). They also impact society by causing damage to power lines which can result in power outages for a period of time. In addition to traffic disruptions due to road damages, these water shortages and electricity disruptions are therefore likely to cause additional economic losses, since they also affect production processes. Thus, impacts on humans and society are both direct and indirect impacts. Indirect impacts of coastal hazards may be defined as the changes in flows of goods and services induced by direct damage and disruption after the disaster (McKenzie et al. 2005). For example, indirect impacts not only affect transportation, but also economic sectors such as recreation and agriculture. Indirect impacts of coastal hazards also include impacts on tourist income (Granger, 2003), and may produce railway disruption, or other losses such as response costs (ABI, 2006). At last, indirect impacts of coastal flooding may also have consequences that occur outside of the area directly affected by flooding or erosion (Milligan et al., 2005).

2.3 Terminology for the costs of coastal hazards

The previous paragraph gave an overview of impacts of coastal disasters and their associated potential damages. The main objective of the paper is to compile and evaluate the cost assessment method enabling the evaluation of their costs. Different types of damages induced by natural hazards have also been preliminarily defined from literature and synthesized by ConHaz. Evaluating the costs of coastal hazards consists in evaluating the socio-economic and the environmental losses resulting from the impacts of the natural hazard. These can be defined and classified as follows:

- *Direct tangible costs* are damages to property due to the physical contact with the disaster, i.e. physical destruction of buildings, stocks, infrastructure or other assets at risk caused by coastal storms.
- Costs due to *disruption of production processes* are losses in industrial, commercial and agricultural sectors, which occur in areas directly affected by the disaster. Business interruption takes place, for example, if people are unable to carry on their work activities because their workplace is destroyed or unreachable due to the disaster. In the literature, such losses are sometimes referred to as “direct” damages, as they occur due to the im-

mediate impact of the disaster. On the other hand, they are often also referred to as "primary" indirect damages, because these losses do not result from physical damage to property but from the interruption of economic processes.

- *Indirect costs* are only those resulting from either direct damages or losses due to business interruption outside the affected area. This includes induced production losses of suppliers and customers of affected companies, the costs of traffic disruption, the welfare costs of changes in price of consumer goods and services, the effects on other markets, etc.
- *Intangible costs* are damages to goods and services which are not, or at least not easily measurable in monetary terms because they are not traded in a market. The intangible effects of the natural hazards include for instance: environmental impacts, social impacts, health impacts, and impacts on the cultural heritage.
- Costs of *adaptation and mitigation* measures provide an overview of approaches for storm surge risk prevention and their associated costs. Costs of mitigation refer to the costs of reducing the risks, while costs of adaptation refer to the costs of modifying the hazards.

In coastal studies, different types of costs resulting from coastal hazards exist. For example, in their research on economics of coastal disasters, Gaddis et al. (2007) differentiate resulting losses according to four types of capitals:

- *Built capital*: also called physical capital. It includes losses to public, commercial, industrial, agricultural and residential infrastructure. Determining a monetary value of these losses is often complicated by discrepancies between insurance estimates of replacement cost and actual costs of rebuilding, unaccounted for or uninsured losses and estimating market value of properties not restored.
- *Human capital*: The human toll is often quantified in terms of human lives and represents a direct loss to the human capital stock. In addition to the loss of human lives, the depletion of the human capital stock may also include the reduced capacity of individual output resulting from losses in public health, education or social services. At last, we can also include in this the cost due to the resettlement of people including professionals, families and skilled workers.
- *Natural capital*: It is important to note that losses to environmental capital may be accentuated by previous perturbations to natural systems, placing such losses at the intersection of natural disasters and human induced vulnerability. Agricultural losses are typically the only form of natural capital assessed in classic disaster cost accounting. Losses to other capital stocks are rarely included in disaster damage assessments even though they can be quite large.
- *Social capital*: Social capital is embodied in the web of relations among people living in particular spatio-temporal contexts such as a town, a nation or an internet-based virtual community [sic].

This classification provides good definitions as regards to the differentiation of costs associated with coastal hazards. For example, Costanza and Farley (2007) used in their study of ecological economics of coastal hazards the same terminology and classification related to costs of coastal hazards. Given that many studies use same or similar terminology to classify losses due to coastal hazards (Costanza et al., 1997; Glavovic, B.C., 2008), such a classification using definitions of different capitals, gives an overview of existing definitions as found in literature, and represents a good tool to approach the issues related to the economics of coastal hazards. These types of losses of capitals are examples of direct and indirect losses or, in economic terms, these could be translated into direct and indirect costs. One of the main objectives of the current report is precisely to give an overview of existing methodologies which enable the economic valuation of these losses. The main terminology often considered in the methods used to assess the economic costs of coastal hazards can therefore be summarized as follows (Table 1):

Table 1. Evaluating the economic costs of coastal hazards: main terminology

Coastal hazard	Potential losses	Cost types
▪ coastal storm (wind storm) ▪ storm surge flooding	▪ built capital ▪ human capital ▪ natural capital ▪ social capital	▪ direct costs ▪ costs due to disruption of production processes ▪ indirect costs ▪ intangible costs ▪ costs of adaptation and mitigation

This terminology, related to coastal hazards and associated costs, represents an important premise necessary to define the different notions at stake when valuating economic losses resulting from natural hazards. Of course, this terminology is basic, not conventional, and varies slightly within different coastal impact or related cost assessment studies. As the case may be, hazard-related losses can then be different; for example, the HAZUS-MH model (cf. chapter 3) classifies losses induced by hurricane wind and flood according to (1) physical damages, (2) economic losses and (3) social impacts. Other examples of costs of coastal hazards are also precisely classified by the H. John Heinz Center in Table 2, according to direct or indirect costs.

Table 2. Major categories of costs of coastal hazards

Costs category	Examples	Direct or indirect
Built environment	▪ insured/uninsured property loss: residential, commercial, industrial buildings, building contents; communications and transportation infrastructure ▪ transportation stock: autos, trucks, rail cars, planes, boats, ships	mostly direct
Business community	▪ interruptions and failures: insured and uninsured ▪ transfer of benefits and income (two-way)	mostly indirect

Social, health, and safety	▪ loss of human life ▪ psychological trauma ▪ disruption of social services ▪ safety including preparation and response	direct and indirect costs (mostly intangible)
Natural resources and ecosystems	▪ loss of crops and forest resources ▪ short- and long-term environmental degradation ▪ temporary and permanent loss of ecosystem services	direct and indirect costs (mostly intangible)

Source: adapted from H. John Heinz Center, 2000

In the context of coastal flooding, Smith and Ward (1998), as well as Penning-Rowsell et al. (2003), also used the following terminology for damages from floods (Table 3):

Table 3. Classification of flood damages with examples

		Measurement	
		Tangible	Intangible
Form of damage	Direct	Physical damage to assets ▪ buildings ▪ contents ▪ infrastructure	▪ loss of life ▪ health effects ▪ loss of ecological goods
	Indirect	▪ loss of industrial production ▪ traffic disruption ▪ emergency costs	▪ inconvenience of post-flood recovery ▪ increased vulnerability of survivors

Source: adapted from Smith and Ward 1998; Penning-Rowsell et al. 2003

Both of these latter classifications for coastal or flood hazards are illustrations of cost types as those defined by ConHaz, which further considers the costs of adaptation and mitigation measures as further categories of loss. In addition, some sea-level rise issues will be considered, mainly because it plays an important role in coastal risk management plans, and within adaptation and mitigation policies. However, its effects in cost assessment methodologies are relatively difficult to approach, given that only simulation or predicting models may possibly include it as input parameter to evaluate the costs of future storm surge events.

3 Overview of costing methods for coastal hazards

In this section, we provide an overview of methods for assessing the different types of costs related to coastal hazards – direct, indirect and intangible costs. Some of the methods serve for estimating only one cost type (e.g., only direct costs), while others may be used to assess several cost types. For each methodology, it will be indicated whether damages resulting from wind storms, flooding, or a combination of both are assessed. Table 4 presents the main methodologies for evaluating the costs of coastal hazards, as well as the main parameters used for their estimation.

Table 4. Overview of main methodologies for evaluating the costs of coastal hazards

Method	Hazard and type of cost assessed		Main factors considered for loss estimation
Multivariate Model	hurricane	(in)direct	Public assistance expenditures
Damage Function Approach	hurricane	direct	Flood- or wind-damage functions
Zone-based Damage Estimation	storm	direct	Distance to the shoreline
Probable Maximum Loss	tsunami	direct	Repair or replacement costs
Input-output Model	hurricane	indirect	Input-output tables
Contingent Valuation Method	flood	intangible	Willingness to pay
Hedonic Pricing Method	flood	intangible	Property price and location

These methodologies have been compiled and analyzed because these have concretely been applied for evaluating the costs of natural disasters in coastal areas. Assessment methods specifically designed for evaluating the costs of flood hazards have been studied in ConHaz, while methods for evaluating the costs of inland storms are not part of the objectives of the current study.

3.1 Multivariate Model

The multivariate model is principally based on multiple regression analysis. A standard regression analysis consists of a statistical technique enabling the understanding of how much a dependent variable changes when an independent variable changes. Generally used in statistical science, the technique can be used as a basis in empirical multivariate models. Based on regressions using a large number of explanatory variables, a multivariate model is applied to estimate public costs resulting from disasters. In the context of coastal storms, under such an approach, many independent variables e.g. measuring meteorological, socio-economic, and physical conditions related to a specific storm can be correlated to total damage costs (direct storm damages can be estimated, for example, on the basis of approved public assistance damage claims), and used in a predictive multivariate model to estimate future economic costs resulting from potential future coastal storms. While existing estimation methods mainly rely on deterministic models of damage to structures, the particularity of multivariate models lies in the fact that other elements of the local costs of hurricanes, including debris removal and provision of emergency protective services are taken into account. In addition, this method derives cost estimates from empirical data from previous storms rather than from theoretical models of the relationships between the physical forces of storms, the structural characteristics of buildings and facilities, and resulting damages. As an example, by using correlations between different variables, factors such as population and wind characteristics (maximum sustained surface wind speed, the tropical cyclone angle of approach, etc.) can explain a certain percentage of the variance in total costs resulting from a storm. According to Boswell et al. (1999), these two factors (wind speed and population), are good indicators for total public assistance expenditure resulting from storms.

Example:
Boswell, M.R., Deyle, R.E., Smith, R.A., Baker, E.J. (1999). A Quantitative Method for Estimating Probable Public Costs of Hurricanes. Environmental Management Vol. 23, No. 3, pp. 359-372.

• *Explanation*: The method estimates probable public costs resulting from damage caused by hurricanes, including wind and flood damages. It uses a multivariate model developed through multiple regression analysis of a range of independent variables (e.g. wind, population density, housing unit value, etc.) that measure socio-economic and physical conditions related to landfall of hurricanes. Public costs of response and recovery are predicted and multivariate models are tested and developed for different expenditure categories of public assistance.

• *Cost types addressed*: Direct (e.g. repair and replacement costs) and indirect tangible costs (e.g. debris cleaning costs and costs of emergency response measures); the assessed damage results from wind storms, hurricanes and associated flooding.

• *Objective of the approach*: (1) Providing guidance for anticipating national, regional and local expenditures that would be needed for the full range of possible hurricanes; (2) making policy makers able to evaluate the implications of alternative policies providing public assistance to jurisdictions that experience hurricane damage; (3) providing information in order to develop financial system for assuring sufficient funds to communities.

• *Impacted sectors*: Built capital (public and private structures and properties) in jurisdictions subject to storm surge forces.

• *Scale*: Lee County (local jurisdiction), southern Gulf Coast of Florida, USA; Time scale: Depending on temporal limitations due to historic records.

• *Effort and resources required*: Low. The objective is limited to estimating public costs and the approach only requires few data and estimates for broad categories of expenditures.

• *Expected precision (validity)*: Reasonable. Specifically to this study, the model could be enhanced by testing additional variables in the constructed data set. For example, rainfall and tornado activity associated with hurricanes could be considered. To provide further examples of imprecision, the paper pointed out that historical records may be difficult to obtain; finally, proxies such as population and population density were used to measure intensity of development.

• *Parameters used for determining costs*: Dependent variables: total approved public assistance expenditures for debris removal, protective measures, roads, signs, and bridges, water control facilities, buildings and equipment, public utilities, parks and recreation (i.e. hurricane response and recovery); and independent variables across four categories of factors associated with the public costs that result from coastal storms: meteorological characteristics of the storm, socio-economic variables, development variables, and physical variables.
• *Results and result precision*: Results are the potential public costs and expected annual public costs for hurricane damages for different categories of hurricanes and wind speeds.
• *Is the method able to deal with the dynamics of risk?* Yes, the approach is designed to support probabilistic risk analysis of the full range of possible storms.
• *Skills required*: Econometrics.
• *Types of data needed*: Population, records for recent and historical disaster (landfall dates), hurricane categories. Dependent variables: public expenditures resulting from coastal storms. Independent variables associated with the public costs including: storm variables (meteorological characteristics of the storm), socio-economic variables (measuring population and housing value characteristics), development variables (land development of the coastal area), and physical variables (measuring geographic characteristics).
• *Data sources*: Statistics offices (land planning and community development agencies, national weather services, previous scientific research).
• *Who collects the data*: National weather centers, County and State planners, emergency planners, insurers.
• *How is the data collected*: By examining current and historical records, archives and computer database; by examining summaries of approved public assistance damage claims.
• *Is data derived ex ante or ex post*: Ex post (empirical data from previous storms and public expenditures).
• *Data quality*: Depends on the availability and quality of public cost data and historical records data. In addition, no systematic data are available for local costs of disasters that do not qualify for disaster declarations.

3.2 Damage Function Approach

Loss estimations based on damage functions have been proposed by the Federal Emergency Management Agency (FEMA) through applicable standardized and general methodologies called HAZUS-MH (Multi-hazard Loss Estimations), and performed with different models for losses resulting from earthquakes, hurricanes, and floods. Potential losses estimated by these models include physical damages, economic losses, and social impacts. Applying such loss estimation models requires specific data which depend on the characteristics of the study region and the type of disaster. For example, regional hydrologic and topographic data are required for flood cost estimates, especially when using of GIS-based applications. In the context of coastal storms, the HAZUS-MH Hurricane Wind Model is applied for hurricanes, while the HAZUS-MH Flood Model does not only estimates riverine, but also coastal flooding and related damages (vehicles, agricultural crops, etc.). In order to link hazard characteristics with expected damages, the model uses wind damage functions. For example, the flood model associates the cost of interior damages to the quantity of water that has entered into the building. Flood losses may also be correlated with water depth, duration and velocity. The flood model does not only estimate physical damages to structures and contents, as well as associated repair and replacement costs (i.e. primarily direct economic damage), but it also enables the estimation of losses due to the disruption of production processes (cf. HAZUS-MH MR5). These are calculated on the basis of relocation expenses, capital related income losses, wage losses and rental of temporary space. Relocation expenses include the cost of shifting and transferring, and the rental of temporary space. Capital related income losses, wage losses and rental income losses are estimated depending on the building recovery time (calculated on the basis of the time for physical restoration of the building, for clean-up, and for inspections, permits and the approval process, and the delays due to contractor availability). All these components are estimated in dependency of water depth and business branch. The thus derived flood and sector specific building recovery time is used to estimate monetary costs per day and area, which are defined for various economic sectors. As for the wind model, it considers the damage as a function of the wind speed (fig. 1).

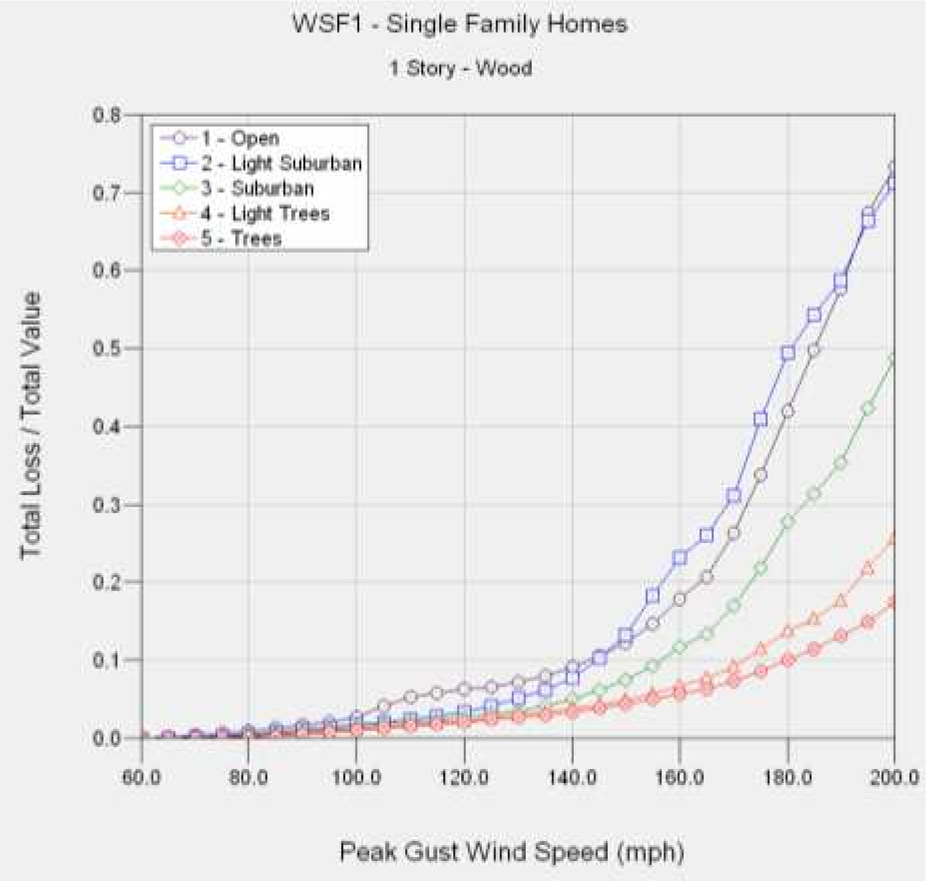

Fig. 1. Example of possible wind damage functions for single family homes (as used in the HAZUS-MH Wind software). Types of terrain include: open, light suburban, suburban, light trees and trees. Source: HAZUS-MH Wind Loss Functions.

More precisely, estimated building or contents damage are, for example, expressed as a percent of building replacement value or total contents value.

Example:
Vickery, P. J., Skerlj, P. F., Lin, J., Twisdale, L. A., Young, M.A., Lavelle, F. M. (2006). HAZUS-MH Hurricane Model Methodology II: Damage and Loss Estimation. Natural Hazards Review, May 2006, pp. 94-103.

• *Explanation*: The HAZUS-MH Hurricane Model estimates economic loss associated with damage to buildings (by using empirical cost estimation techniques). The estimated losses include the losses associated with buildings, contents, inventory losses and the costs associated with the loss of use of the buildings, and the examination of insurance company claims determines what values are at risk. In the damage model, explicit cost functions are used to estimate the replacement costs of the exterior components of the buildings. These cost functions are based on the relationship between a damage and a hazard parameter. For example, damages to roofs, windows and walls are determined as a function of wind speed. Other parameters such as building orientation and storm duration are also used. On the other hand, implicit cost functions, based on a combination of engineering judgment and insurance loss data, are used to estimate the cost of repairing the interior of the buildings. A hurricane simulation modeling is then used to predict potential losses.
• *Cost types addressed*: Direct tangible costs (e.g. costs of building repair and replacement, loss of use); in the case of the HAZUS-MH Hurricane Model, the assessed damages are determined for wind-related hazards.
• *Objective of the approach*: The method provides a loss estimation model with software application, to estimate hurricane winds and potential damage and loss to buildings. A hurricane simulation modeling is used to predict potential losses.
• *Impacted sectors*: Residential, commercial, and industrial buildings.
• *Scale*: Hurricane damaged areas (city, county, or U.S. state); Time scale: long-term: the wind speed and direction are obtained from long-term hurricane wind field simulation model.
• *Effort and resources required*: High. Many engineering and insurance data are required to use this model as a tool. Its development requires much more efforts and skills.
• *Expected precision (validity)*: Good. Hurricane loss studies served as validation for the model by comparing modeled losses (from loss functions) and actual losses (from insurance loss data collected after storm events).
• *Parameters used for determining costs*: Loss functions, insurance loss data.
• *Results and result precision*: Prediction and evaluation of damage and loss to buildings subjected to hurricanes.
• *Is the method able to deal with the dynamics of risk?* Yes. The model predicts damage and loss to buildings subjected to hurricanes. The models statistically assess losses on the basis of event return periods.
• *Skills required*: Engineering, scientific, computer and technical knowledge; hazard knowledge and risk perception, econometrics.
• *Types of data needed*: Insurance loss data and building costs and characteristics (cost of roof cover, roof frame, windows, structural framing, interior walls, foundation, etc.), hurricane data, engineering and land-use data.
• *Data sources*: General building stock (census office), hurricane data (national weather service), land-use data (USGS, water management office), and insurance loss data (insurance companies).
• *Who collects the data*: Engineers, insurers, and scientists.
• *How is the data collected*: In the field, from various databases, from post-storm damage surveys.

• *Is data derived ex ante or ex post*: Ex post (empirical cost estimation) and ex ante (simulation models).
• *Data quality*: Not standardized, since such a model is specially developed by FEMA. On the other hand, data on hurricanes come from many sources; the quality of data can vary widely between local communities and organizations within communities.

3.3 Zone-based Damage Estimation

In coastal areas, damages and losses of built capital are very much related to the location of the buildings, and especially to their distance to the shoreline. Based on this precept, i.e. in order to link the notion of vulnerability with distance to the shoreline, the FEMA developed a model based on damage zones for loss estimations. This model defined into two different zones inside a coastal areas: first, V-zones along the water's edge and which are subject to damage from both inundation and breaking wave heights greater than approx 1 m (3 feet); second, A-zones further inland and which are subject to damage from inundation and breaking wave heights lower than 3 feet (FEMA, 2009). Within V-zones, residential depth-damage functions using water depth and wave height parameters are taken into account in damage modeling. Applicable to areas subject to 3-foot wave action, i.e. subject to "critical waves" or "waves possessing sufficient energy to cause major damage on contact with conventional structures" (USACE, 1975), these water-level damage functions are used for estimating structure and contents damage (FEMA, 2006). Other studies developed similar approaches by classifying coastal areas into different vulnerability zones. For example, instead of using a depth parameter, West et al. (2001) implemented the distance dependent damage concept in a probabilistic approach, by which the probability of damage decreases linearly with the distance of the structure from the shoreline. In the context of coastal management and storm surge damage reduction (but outside the development of any methodology for cost assessment), the Government of New Brunswick defined specific sensitivity zones: (1) coastal lands core area (zone A), (2) coastal lands buffer area (zone B), and (3) coastal transition area (zone C). This zoning approach is used for different management and development acceptability within coastal zones. In terms of sensitivity to impacts and storm damage, zone A is characterized by a very high risk, and few development activities would be acceptable in this zone; in zone B, direct impacts may affect coastal features and development activities would expose people to storm damage; at last, the sensitivity to impact varies a lot in zone C (an area further inland), it mainly depends on topography, elevation and erodibility of the land (New Brunswick Department of the Environment and Local Government, 2005).

Example:
Hondula, D.M. and Dolan, R. (2010). Predicting severe winter coastal storm damage. Environmental Research Letters, volume 5, number 3, 1-7.

• *Explanation*: By comparing post-storm damage zones and their evolution in time (on the basis of aerial photographs) and by considering (1) the rate of coastal erosion, (2) the rate of development, as well as (3) the increase in property values, the financial risk for coastal communities changes over time and can be estimated for different coastal zones. Three damage zones are identified from the ocean towards the land: (1) a zone of destruction, (2) a zone of structural damage, and (3) a zone of extensive flooding. From that, the defined damage zones can be attributed further specific characteristics. As an example, during major storms, buildings in zones of destruction are considered as being constantly impacted by breaking waves and storm surge.
• *Cost types addressed*: Direct tangible costs (Dollar value of storm damage); the assessed damage results from wind storms in coastal areas.
• *Objective of the approach*: To produce a model allowing the encoding of known damage data from a past storm event, and the prediction of present-decade damage from a storm of similar magnitude.
• *Impacted sectors*: Water systems, campsite areas, dunes, buildings, fishing piers, highway pavements and removal of sand deposits.
• *Scale*: Three geographic zones along the North Carolina barrier island (USA). Time scale: Mid-term effects, depending on the storm of reference, in the past, enabling the prediction of damage from a storm of similar magnitude or more exactly on the period of observation (in the case study, observations were made over four decades).
• *Effort and resources required*: Low. The risk model mainly requires specific financial data from former storms, and requires the observation of coastal changes through aerial photographs for different coastal zones.
• *Expected precision (validity)*: Low. Although the validity of the model highly depends on validity of data on previous storm records taken as a reference to determine the risks related to an equivalent storm, the method is mainly based on approximate extrapolations.
• *Parameters used for determining costs*: Property values, number of structures exposed to storms. In order to estimate potential property losses, wind and wave information, as well as property loss information from previous storms are used and combined with land use change information determined by the analysis of aerial photographs. Depending on wave height and energy, the impacts on coastal structures will be different, and potential financial losses are defined accordingly. For example, the zone of destruction is considered as the zone of highest kinetic energy, where approximately 50% of the total financial losses occur. Wave heights are also defined according to the different storm categories.
• *Results and result precision*: Estimated financial values for damage resulting from a present-decade storm. The result precision can be delicate given that geographic variations of coastal development or property values can be important.
• *Is the method able to deal with the dynamics of risk?* Yes. The financial risk for coastal communities can be determined from observed changes over time in coastal areas (such as changes in coastal erosion and development, and property values), and can be assessed by considering anticipating losses from specific storms.
• *Skills required*: Environmental sciences, natural disasters.

• *Types of data needed*: Four main factors are needed: the defined damage zones (from aerial photographs), the change in property values, the rate of coastal erosion, and the rate of coastal development.

• *Data sources*: Categorized and historical damages, detailed reports of structural damage, census of housing.
• *Who collects the data*: Engineers, scientists, meteorological institutes, census office.
• *How is the data collected*: From census, previous reports, archives and aerial photographs.
• *Is data derived ex ante or ex post*: Ex post (empirical historical storm data and observations over time).
• *Data quality*: Not standardized to our knowledge. Specifically to this study, the data quality especially comes from previous scientific reports in which data on identified damage to structures resulting from specific coastal storms have been collected.

3.4 Probable Maximum Loss

Probable Maximum Loss (PML) is statistical loss estimation, generally used in the insurance industry, to estimate the expected value of the largest loss resulting from a natural disaster i.e. the "maximum credible event". The PML is actually defined as the loss associated with a natural hazard of a certain magnitude or a certain probability of occurrence. As an example, the Natural Disaster Coalition (a group of insurers and emergency managers dedicated to reducing property losses from natural disasters in United States) defines the PML as the loss associated with a 500-year return period. In the context of hurricanes, the calculation of the PML in infrastructures generally requires the use of wind-speed damage functions, building structural characteristics, as well as economic parameters such as replacement or repair costs of buildings exposed to hurricane winds. A specific approach using the concept of building damage bands has also been developed for predicting the probable maximum damage degree to individual buildings or groups of buildings for different hurricane scenarios (Unanwa, 1997). This approach is a weighting technique that uses cost data, failure probabilities, and location parameters to obtain building damage thresholds.

Example:
Dominey-Howes, D., Dunbar, P., Varner, J., Papathoma-Köhle, M., 2009. Estimating probable maximum loss from a Cascadia tsunami. Natural Hazards (2010), 53, 43-61
• *Explanation*: A tsunami hazard flood layer is used as input to study the vulnerability of residential and commercial buildings in seaside. Building exposure is mapped and a Tsunami Vulnerability Assessment model (PTVA model) enables the calculation of building vulnerability. Vulnerability of buildings and their market value (or replacement costs) are used to estimate the Probable Maximum Loss (PML) associated with a tsunami flood return period (PML associated with the tsunami do not take account of earthquake-related damage to structures prior to the arrival of the tsunami).
• *Cost types addressed*: Direct tangible costs of tsunami; the assessed damage results from coastal flooding.

• *Objective of the approach*: (1) to map and quantify the exposure of one-story residential and commercial buildings within the 1:500 year tsunami flood hazard zone in Seaside; (2) to use the PTVA model to quantify the vulnerability of these structures; (3) and to provide a preliminary estimate of PML in USD for the buildings in the 1:500 year tsunami flood zone.
• *Impacted sectors*: Residential and commercial buildings.
• *Scale*: Local level: seaside study location, northwest coast of Oregon, USA. Time scale: 1:500 year tsunami flood.
• *Effort and resources required*: Medium. The effort is needed because of many required data to be used; on the other hand, the study requires the identification and quantification of one-story residential and commercial building vulnerability, and the use of specific vulnerability models.
• *Expected precision (validity)*: Medium. Examples of limitations are: (1) the quantification of exposure, vulnerability and PML which was based upon a probabilistic map that does not directly equate to an actual event: the use of a credible worst case scenario would increase confidence in estimates of exposure and PML; (2) the use of a simplified tsunami inundation to a single wave running across the region parallel with the shoreline; (3) there is no estimation regarding human vulnerability.
• *Parameters used for determining costs*: Replacement cost calculated from market value of residential buildings. The PTVA model is dynamic model that incorporates multiple data (physical, environmental, and socio-economic data). The vulnerability of a building structure is calculated on the basis of its carrying capacity associated with the horizontal hydrodynamic force of water flow, and on the basis of the vulnerability of building elements due to their contact with water.
• *Results and result precision*: Total Probable Maximum Loss calculated for a specific tsunami event. In the case study, total PML was calculated for a Cascadia type tsunami (northwest coast of Oregon). With a 1:500 year tsunami flood, 95% of single story residential and 23% of commercial buildings would be destroyed, and total PML would exceed USD116 million.
• *Is the method able to deal with the dynamics of risk?* Yes. By using available estimations of future tsunami occurrence, Probable Maximum Loss (PML) for a particular event is calculated. The results have important implications for tsunami disaster risk management.
• *Skills required*: Scientific, engineering.
• *Types of data needed*: Extent and severity of the hazard (i.e. inundation distance and flow depth); asset exposure (e.g. buildings located within the expected flood zone); vulnerability of those buildings and their market value (or replacement cost); attributes within the PTVA model which are relevant to the study (e.g. water depth above ground surface, building material, number of floors, orientation of building, land cover, etc.) for determining the vulnerability of buildings.
• *Data sources*: PTHA (probabilistic tsunami hazard assessment) tsunami flood map, hazard loss estimation database (e.g. HAZUS-MH data), County Tax Assessor Taxlot Database, and building stock survey.
• *Who collects the data*: Engineers and scientists.
• *How is the data collected*: from previous field surveys for data on individual buildings, from structural data (e.g. from the HAZUS-MH database), from expert judgment from tsunami damage assessment surveys and engineering reports.

• *Is data derived ex ante or ex post*: Ex post (empirical historical data, risk assessment based on return periods).
• *Data quality*: Medium. There may be uncertainties regarding the data used in the PTVA model.

3.5 Input-Output Model

Input-Output Models (or I-O models) are models used to evaluate the economic impacts associated with changes in industry output or demands. Such models can be applied to valuate economic losses due to business interruption resulting from a shock such as a natural disaster. An input-output model enables the evaluation of how the disturbance (e.g. after a hurricane event) affects the economic system through changes in consumption and demand, as well as through changes in supply and prices, generally at a national or regional level. More precisely, the model assesses how the natural disaster indirectly affects the economy of a country or a region, i.e. the changes in the interrelations between different economic actors such as industries and consumers. The data can directly be obtained from input-output tables. The model is actually based on the principle that an industry (or economic sector) uses inputs that are produced by other industries, while the production of this industry will serve as input to other economic sectors. The methodology, consisting in determining the flows of goods and services between the different economic sectors, is applied for determining the economic response over a certain period of time, usually for yearly-based economic calculations. Although the methodology is generally simple, the use and calibration of data sources can require many efforts, especially because the standard framework of the model can be modified (e.g. by including specific variables in order to improve the model), or even extended (Jonkman et al. 2008a). For example, input-output relationships between industries may also be incorporated in Computational General Equilibrium (CGE) models, which consist in very sophisticated models that precisely enable the integration of those flows of goods and services in the economic system.

Example:

Hallegatte, S. (2008). An Adaptive Regional Input-Output Model and Its Application to the Assessment of the Economic Cost of Katrina. Risk Analysis 28, pp. 779‑799.

• *Explanation*: Using an adaptive regional input-output (ARIO) model, i.e. a model based on input-output tables, the applied methodology assesses indirect losses resulting from a hurricane, through production and job losses and reconstruction phase (duration and cost). The main particularity of the model is that it considers (1) changes in sector production capacities and both forward and backward propagations in the economic system (i.e. indirect effects resulting respectively from modifications in supply and demand capacities); and (2) adaptive behaviors in the aftermath of the hurricane.
• *Cost types addressed*: Indirect tangible costs (also expressed as a function or percentage of direct costs); resulting from hurricanes. There is no distinction between wind and flood-related damage to assess total indirect losses.

• *Objective of the approach*: The approach proposes a new model (adapted IO model) to examine the consequences of natural disasters and the subsequent reconstruction phase. The model provides a simulation of the response of the economy in the aftermath of the hurricane.

• *Impacted sectors*: There are many impacted sectors such as agriculture, forestry, fishing and hunting; mining; utilities; construction; manufacturing; wholesale trade; retail trade; transportation and warehousing; information; finance; insurance, real estate, rental, and leasing; professional and business services; educational services, health care, and social assistance; arts, entertainment, recreation, accommodation, and food services; other services, except government; and government.

• *Scale*: Regional: landfall of Katrina, Louisiana. Time scale: From the time of the shock to full recovery.

• *Effort and resources required*: Medium. Input-output tables are usually easily accessible. However, collecting parameters and data may require efforts, and this for several reasons: (1) even though national input-output tables are readily available, transforming them into regional ones is difficult, especially when one wants to distinguish between locally produced inputs and imported inputs; (2) the behavioral equations of the model, needed to model adaptation and price responses, introduce numerous parameters that are difficult to calibrate; (3) at last, data on disaster damages are not easy to collect and are often of poor quality [sic].

• *Expected precision (validity)*: Good. However, some I-O models, as traditionally used in several studies of economics of disasters, only consider the propagation of indirect effects through modified demand, i.e. by neglecting the effects resulting from changes in supply processes (that would modify production capacities). On the other hand, limitations in other classic I-O models may arise from the impossibility, for example, to consider the influence of alternative suppliers in the economic system that would not be affected by the disaster (Hallegatte, 2008).

• *Parameters used for determining costs*: Input-output tables, behavioral parameters, and disaster data.

• *Results and result precision*: Economic response of Louisiana to the damages caused by the hurricane; mainly the sectoral and total production losses (relative to the initial production).

• *Is the method able to deal with the dynamics of risk?* Yes.

• *Skills required*: Mathematics, econometrics.

• *Types of data needed*: Input-output tables, pre-event values of economic variables, production capacity data, adaptation and demand data, disaster data.

• *Data sources*: Input-output tables (structure of the economy and industries), economic analysis office, bureau of statistics, bureau of census.

• *Who collects the data*: Economists, statisticians.

• *How is the data collected*: Survey samples to people and businesses through scientific processes, data from a variety of private and public sources.

• *Is data derived ex ante or ex post*: Ex post (in the aftermath of extreme events).

• *Data quality*: Depending on quality of input-output tables (however, often poor data quality for disaster damages). Classic input-output models are commonly used by following a standardized method.

3.6 Contingent Valuation Method

The premise of the Contingent Valuation Method (CVM) is that people have preferences in relation to all kinds of goods, including goods and services that are not traded in the market, and therefore have no market value. Based on this premise and through surveys, a CVM study can estimate 'intangible values' such as economic values of ecosystem services and environmental goods. By using questionnaires, the surveys consist in asking people the maximum amount of money they would be willing to pay for a specific environmental service (or change in the availability of a good). This technique is also referred to as a stated preference method, because survey respondents are asked to directly state their values, rather than deducing values from actual choices (such as in revealed preference methods). The preferences can also be expressed as willingness to pay (WTP) to prevent environmental degradation and/or willingness to accept (WTA) compensation to suffer degradation (Environment Agency/DEFRA, 2004), or to give up an environmental service. One of the main advantages of contingent valuation method resides in its capacity to valuate non-use values (through artificial market prices), while one of its main disadvantages is that expressed preferences methods traditionally inspire economists with less confidence than, for example, revealed preferences methods which use observable behaviour of individuals (Messner et al., 2007).

Example:

Environment Agency/DEFRA, 2004. The appraisal of human-related intangible impacts of flooding. Technical Report FD2005/TR Joint DEFRA/ Environment Agency Flood and Coastal Erosion Risk Management R&D Programme.

• *Explanation*: The report consists in giving guidance for the valuation of the health impacts of fluvial (or coastal) flooding on residents in England and Wales. "Intangible" effects resulting from flooding are, by definition, difficult to valuate. By using contingent valuation surveys, the methodology enables the estimation of the willingness to pay of respondents to avoid negative effects (such as intangible health-related damages) associated with different types of floods (in terms of attributes and impacts). In this way, intangible impacts of flooding, such as e.g. hassle and stress, can be estimated. Alternatively, the study also presents a method called *choice modeling* (also based on questionnaires, this method explores the WTP of respondents to mitigate the attributes of floods over a large number of scenarios).

• *Cost types addressed*: Direct intangible costs (health-related damages due to flood events); the assessed damage results from coastal flooding.

• *Objective of the approach*: The main objective of this contingent valuation approach is to provide an estimation of intangible effects of floods, as a complement to conventional cost analysis using actual market values that include tangible health impacts (such as the value of lost earnings because of the illness). The study mainly aims at (1) measuring the extent of intangible health impacts of flooding by using WTP questionnaires; (2) examining how the health impacts vary according to the flood characteristics.

• *Impacted sectors*: intangible health-related damages.

• *Scale*: Survey locations in England and Wales. Time scale: N/A.

• *Effort and resources required*: High (design of questionnaires and survey).

• *Expected precision (validity)*: Reasonable. The main imprecision resides in the fact the WTP estimates non market values, what is obviously much less accurate than actual economic values, as inferred in revealed preference methods. Indeed, in the case of a CVM, people often act differently from what they state. And yet, the problem may arise from the difference between what people actually do and what they state. However, in order to measure health effects, different standardized scales of measurement have also been used in the method: a first scale can measure the general health or well-being, and a second scale measures the level of stress experienced. This provides a good quantitative measure of different levels of well-being and health states.
• *Parameters used for determining costs*: WTP (£/household/year) of both flooded and at risk respondents, through different attributes of floods. Questionnaires cover health impacts of flooding as well as the WTP to avoid such impacts. The degree of health impact was associated with a wide range of factors including socio-demographic factors, flood characteristics (especially flood depth) and post flood events.
• *Is the method able to deal with the dynamics of risk?* Yes.
• *Skills required*: Social and economic science.
• *Types of data needed*: Flood characteristics (depth, duration, etc.), survey data from respondents: socio-demographic questions (age, income, etc.), property questions (types, household members, etc.), questions on flood experience and awareness (flood warnings), health effects, valuation questions (WTP).
• *Data sources*: Mainly from survey data set (data from respondents).
• *Who collects the data*: Scientists, environment agency, flood hazard research center.
• *How is the data collected*: Through survey and questionnaires.
• *Is data derived ex ante or ex post*: Depending on the questioning of flooded or at risk respondents (ex ante in this case, if flood scenarios are used).
• *Data quality*: Only few scales for measuring health effects have been used in the context of flood impacts and damages. However, the use of scales of measurements enables a certain standardization of health states.

3.7 Hedonic Pricing Method

The Hedonic Pricing Method (HPM) is related to the variation in property prices (land or house prices) in relation to the surrounding environment. The fundamental principle of the methodology resides in the fact that property prices depend on the characteristics of a particular environmental effect (Coastal Wiki, 2008). Conversely, this environmental effect can be given a price on the basis of house prices. As the price of a house also reflects its specific characteristics (e.g. number of rooms, size, etc.), the environmental effects (or resources) are considered as marginal additional factors influencing house prices. This method is generally applied for the valuation of the environmental goods or services. Contrary to stated preference methods (such as the contingent valuation method), the hedonic pricing method is based on revealed preferences, since it relies on actual transactions. In the context of natural hazards, this method is also applicable. For example, Chao et al. (1998) reviewed academic literature on the effects of flood risks on house prices, notably by measuring discounts in property values according to flood damages or floodplain location. In the context of environmental changes in coastal areas, the hedonic pricing method was also applied. The role that coastal and other landscape features have on the attractiveness to tourists has been studied by Hamilton (2007). This study evaluated, among other things, the impact on revenue caused by changes in the attractiveness of the coast, such as changes due to adaptation measures to sea-level rise (e.g. from the conversion of open coast to dikes).

Example:
Bin, O., Kruse, J. B. and Landry, C. E. (2008). Flood Hazards, Insurance Rates, and Amenities: Evidence from the Coastal Housing Market. Journal of Risk & Insurance, The American Risk and Insurance Association, vol. 75(1), 63-82.
• *Explanation*: By using the hedonic property price method, this study examines the effects of flood hazards on coastal residential property values. The observed marginal willingness to pay from the coastal housing market is used to be correlated with the risk of flooding. For example, the study observes how discounts on properties in an area with a high flood risk reflect households' willingness to pay to avoid such a risk. In addition to the housing market, variations in insurance premium rates are also examined. The study revealed that estimated sales price differentials associated with location in a floodplain are closely related to the capitalized value of flood insurance for different levels of risk.
• *Cost types addressed*: Direct intangible costs (costs of flood risks as perceived by coastal homeowners); the assessed damage results from coastal flooding.
• *Objective of the approach*: Examining the effects of flood hazard on coastal property values.
• *Impacted sectors*: Coastal residential properties.
• *Scale*: Carteret County, North Carolina, USA. Time scale: N/A.
• *Effort and resources required*: High. The methodology requires important data collections and statistical calculations. Particularly to this case study, GIS applications were used.
• *Expected precision (validity)*: Good, insofar as losses related to flood risks are revealed through coastal property values arising from actual transactions, i.e. from householder preferences revealed through the housing market.
• *Parameters used for determining costs*: Hedonic prices, estimated sales price differentials associated with location in a floodplain.
• *Results and result precision*: Sales price differentials on coastal residential properties located within different flood zones; marginal effects related to flood risks; and comparative analysis of flood insurance premiums and house price differentials.
• *Is the method able to deal with the dynamics of risk?* Yes. Percentage annual chance of flooding is used to estimate discounts on properties from a low to a high risk of flooding.
• *Skills required*: Econometrics, statistics.
• *Types of data needed*: Residential property sales records and transactions, amenities (water frontage, distance to coastal water) and structural attributes influencing the coastal housing market (such as the number of bathrooms, age of the house, square footage of the house, the lot size), flood zone data and, particularly to the case study, GIS-based data sets (e.g. property parcel data, digital flood maps).
• *Data sources*: Flood hazard maps and data, center for geographic information, national flood insurances programs, previous studies.
• *Who collects the data*: Insurers, scientists.
• *How is the data collected*: Census bureau.

• *Is data derived ex ante or ex post*: Ex post (based on the empirical data).
• *Data quality*: Good as regards mapping and meteorological data, but probably depends more on the quality of insurance and housing census data.

As alternatives, stated preferences methods (i.e. mainly based on WTP) also include Choice Modeling Methods (CMM) which is specifically applied in the domain of health economics. This method is mainly based on discrete choice econometric models. In fact, it is slightly different from traditional CVM, because the technique avoids asking direct questions on people's WTP for certain activities (van Beukering et al., 2011): instead, a small set of choices are given with different attributes: In this way, choice modelling tends to capture non-market lifestyle values better than traditional contingent valuation [SIC]. The Life Satisfaction Analysis (LSA), which is applied to evaluate public non-market goods such as health and environmental assets affected by natural hazards, is also a method based on revealed preferences. It correlates the degree of public goods with the subjective well-being of individuals and evaluates them directly in terms of life satisfaction.

As for revealed preference methods (i.e. based on observed data relating to individuals' actual behaviour), in addition to HPM, other methods exist. These include Travel Cost Methods (TCM) which measures the recreational value that visitors put on particular recreational sites: the basic principle supposes that the costs in terms of time and transportation paid by an individual reflect the person's appreciation of that site; therefore the method can be used to estimate the economic costs or benefits resulting from changes in access costs for a recreational site. In this context, a TCM can be used to value the intangible costs of coastal hazards, by correlating environmental impacts of coastal hazards to losses in travel expenditures. As an example, Hartje et al. (2001) used a TCM to estimate the economic impacts of climate change to the island of Sylt (Germany), in the context of increasing frequency of storm surges. The replacement cost (or restoration cost) method (RCM) is a methodology based on the estimation of the cost of a man-made substitute providing the same service as the ecosystem, in order to evaluate this ecosystem service. The Production Function approach (PFA) is another revealed preferences method which can be used to value non-market goods and services that serve as an input to the production of market goods. The cost of illness approach (COI), which can estimate the health costs for treating the illness caused by natural hazards, is also an example of revealed preference methods. This method is based on medical costs and lost of income due to illness (income being lost while recovering from illness) caused by the natural hazard (McDonald, 2001). At last, it has to be noted that methods for evaluating the intangible effects of natural hazards can be used in complementary way.

The cost assessment methods estimating the intangible costs of natural hazards can be summarized as follows:

Table 5. Loss estimation methods for estimating the intangible costs of natural hazards

Stated preferences methods	Revealed preferences methods

Contingent Valuation Method (CVM) Choice Modelling Method (CMM) Life Satisfaction Analysis (LSA)	Hedonoic Pricing Method (HPM) Travel Cost Method (TCM) Cost of Illness Approach (COI) Replacement Cost Method (RCM) Production Function Approach (PFA)
Benefit Transfer Method (BTM)	

When surveys and reporting processes require an important amount of time, and especially when data collection is too expensive, Benefit Transfer Methods (BTM) may be used. These methods consist in environmental benefit estimates based on other case studies which are spatially and/or temporally transferred to the policy case study. Researchers simply obtain a benefit estimate from a similar study conducted elsewhere and use it for the current case study.

Methods used to valuate intangible effects of natural hazards are further developed in the ConHaz WP3 report on the intangible effects of natural hazards. In addition, this report describes the advantages and disadvantages of these economic valuation methods. The benefits from managing coastal areas in order to preserve the natural ecosystem have also been studied - see for example Bower and Turner (1997) who describe the benefits from ICZM, notably by presenting different methods for valuing use and non-use values -.

3.8 Key characteristics of the cost assessment methods

Table 6 presents a comparative overview of some key characteristics of different methods for assessing the costs of coastal hazards.

Table 6. Coastal hazards: overview of the main characteristics of cost assessment methods

Method	Type of assessed costs	Main hazard	Expected precision	Ability to deal with the dynamics of risk	Main types of data needed	Main data sources	Effort and resources
Multivariate model	Direct and indirect costs	Hurricane	Reasonable	Yes, but through probabilistic risk analysis	Historical disaster data, public expenditures, meteorological data, physical and socio-economic variables	Statistics (land planning agencies, weather services, previous research)	Low
Damage Function Approach	Direct costs	Hurricane	Good	Yes	Natural hazard data (e.g. wind speed), general building stock, land-use data, insurance loss data	Census offices, weather services, land-use offices, insurance companies	High
Zone-based damage estimation	Direct costs	Storm	Medium	Yes, through predictive methods	Aerial photographs, structural damage property values, erosion data, coastal development over time	Remote sensing centers, census offices, meteorological institutes, previous reports	Low
Probable Maximum Loss	Direct costs	Tsunami	Medium	Yes	Flow depth, asset exposure, buildings characteristics and location, flood zone, replacement cost, water depth	Flood map, hazard loss estimation database, county tax assessor’s office, building stock surveys	High
Input-output models	Indirect costs	Hurricane	Good	Yes	Input-output tables; production capacity; adaptation and demand parameters, disaster data	Economic analysis, statistical and census offices	Medium

Contingent valuation method	Intangible costs	Flood	Reasonable	Yes	Coastal flood characteristics, stated willingness to pay, environmental conditions, socio-economic data	Surveys, environment agencies, flood hazard research center	High
Hedonic pricing method	Intangible costs	Flood	Good	Yes, through the determination of flood risks	Coastal flood characteristics, revealed willingness to pay from environmental conditions, insurance and housing market data	Housing market data services, national flood insurances programs, previous research	High

4 Mitigation and adaptation policies of coastal hazards

4.1 Coastal vulnerability

The present paragraph briefly introduces facts and observations regarding the vulnerability of coastal areas to sea-level rise and storm surges in Europe. This introduction may be necessary to better apprehend the next steps dedicated to adaptation and mitigation strategies in Europe, as well as some considerations regarding the costs of their implementation.

Vulnerability to storm surges in Europe

ESPON (the European Spatial Planning Observation Network) has provided approximate probabilities of having storm surge events in Europe. A vulnerability map (Fig 2) for storm surges in Europe gives a good overview of the spatial distribution of the occurrence of such events.

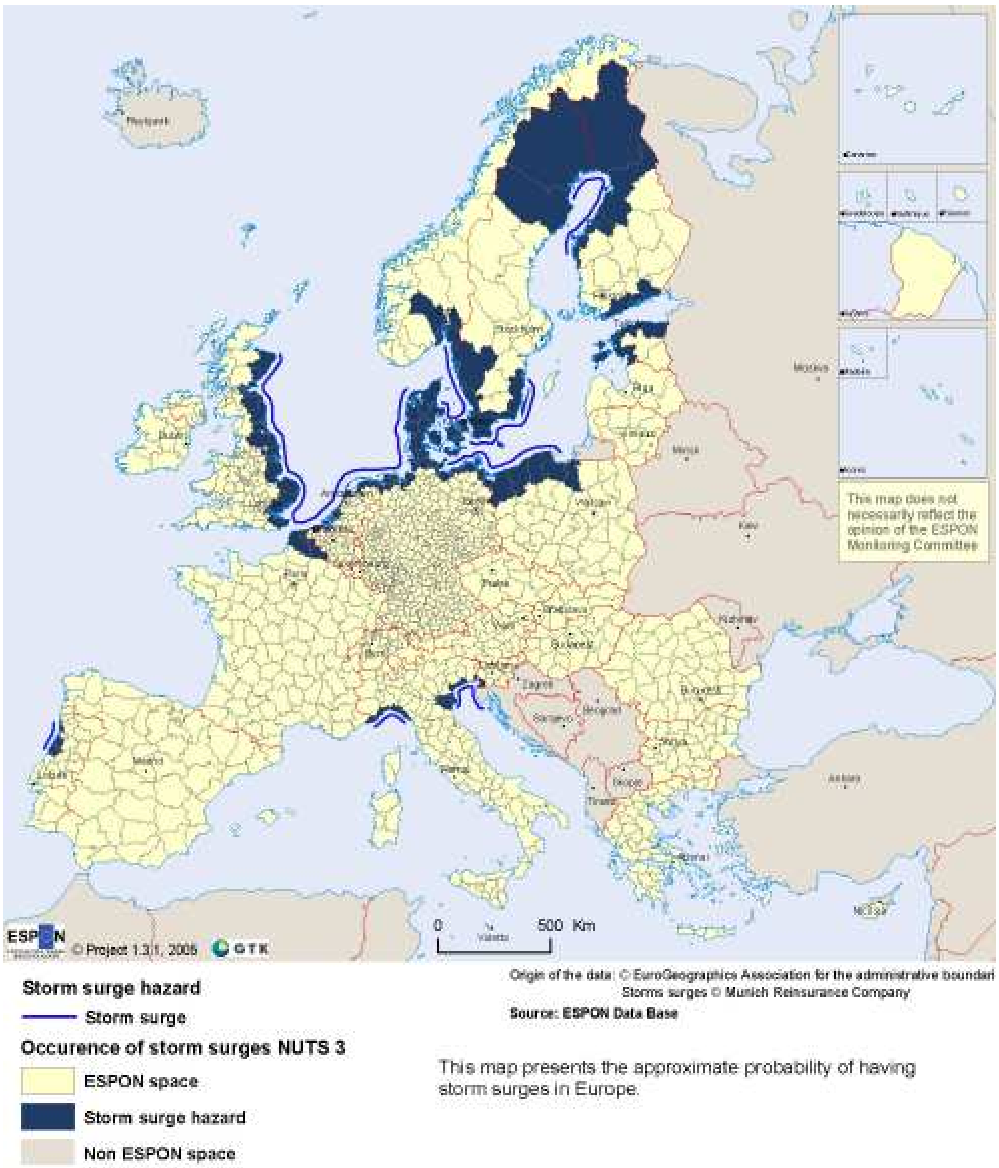

Fig. 2. Approximate probability of having storm surges in Europe (Source: ESPON, 2006)

It shows that the probability of occurrence of storm surges is the highest in northern Europe. The reason is that in northern Europe many coastal areas are just above or even under the mean sea level and the danger from storm tides is very high. Actually storm surges can appear in many European areas, but due to the high storm probability, the North Sea shoreline is especially exposed to this hazard (ESPON, 2006). In southern Europe, the probability of having storm surges in southern Europe is high in some coastal areas in Portugal and Italy.

Vulnerability to sea-level rise

In the context of sea-level rise, communities living in lowlands are particularly threatened by the risk of flooding. By way of an example, 20.6% of the world's population lives within 30 km of the coast (Gommes et al., 1997). Climate change and sea-level rise are likely to threat many coastal environment and communities in Europe, and many coastal systems will experience disasters in the coming decades. In this context, increased levels of inundation and storm floods, accelerated coastal erosion, and seawater intrusion into fresh groundwater, are examples of increased disaster risks in coastal environments and ecosystems. Figure 3 shows the location of European lowlands particularly vulnerable to a rise in sea level and therefore particularly exposed to coastal flooding.

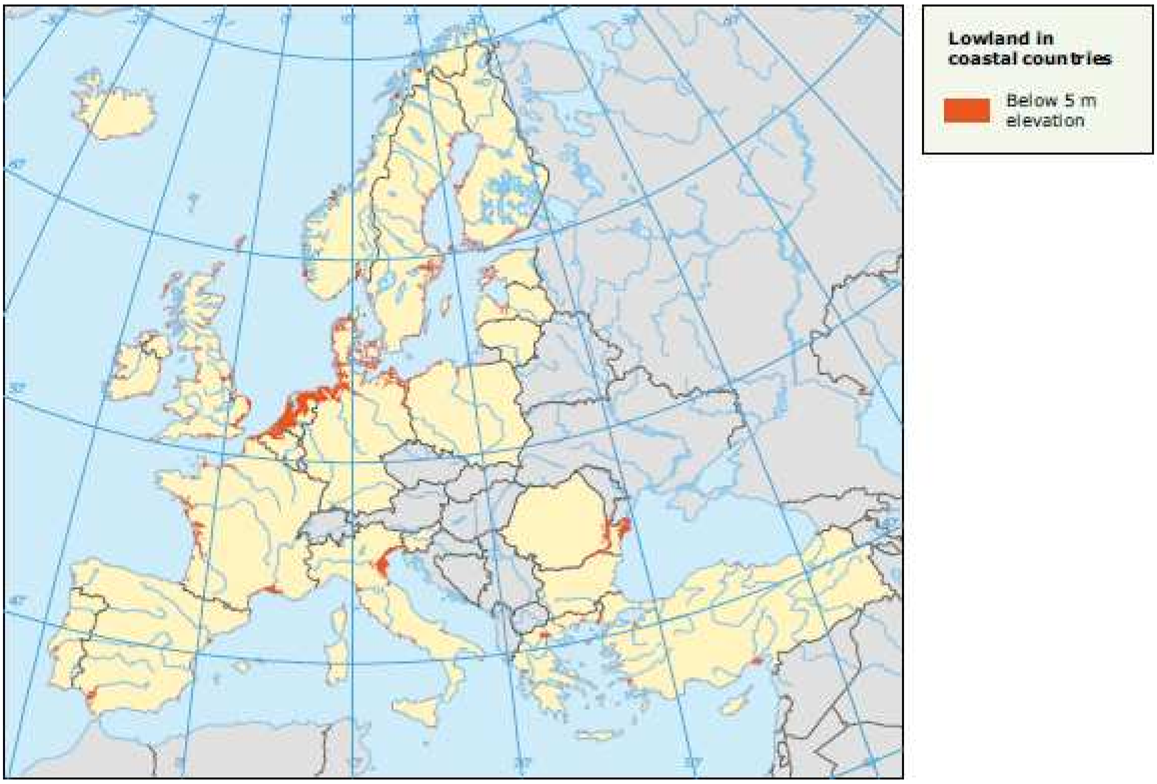

Fig. 3. European coastal lowlands most vulnerable to sea level rise (Source: EEA, 2006)

Accordingly, and in the context of climate change and coastal risk management, particular attention has to be given to several countries: the Netherlands and Belgium, where coastal lowlands are the most vulnerable (more than 85 % of coast is under a 5 m elevation). Other countries particularly vulnerable to sea-level rise also include: Germany and Romania (where 50 % of the coastline is below 5 m), Poland (30 %) and Denmark (22 %). Less vulnerable countries are France, the United Kingdom and Estonia (where lowlands cover 10 to 15 % of the country). Severe storm surges make the vulnerability of these coastal lowlands even more important, especially in Northern Europe, for the reasons mentioned previously.

Sea-level rise predictions

Climate change and global sea-level rise are expected to intensify coastal and weather-related hazards in the 21st century. According to predicting scenarios of the 2007 IPCC report (IPCC, 2007), the global average sea level will rise from 18 cm to 59 cm by 2100. However, Cazenave and Llovel (2010) proposed a new estimation with a rise in global sea level of between 60 cm and 120 cm by the end of the century. The reason advanced is that IPCC models did not account for the accelerated melting of ice sheets in Greenland and Antarctica (UNEP/GRID-Arendal, 2010). By considering the IPCC sea-level rise predictions, or by supposing a higher rise in sea level such as predicted by Cazenave and Llovel, coastal storm surges are, in both cases, expected to become much more frequent and severe in the next coming decades. Therefore different sea-level rise scenarios have to be considered for preparedness planning; and they have to be taken into account when estimating present and future costs and benefits of different mitigation and adaptation policies. On this condition, coastal areas may be preserved in their integrity and in a sustainable way.

Measuring coastal vulnerability

Coastal vulnerability may be measured in different ways. Many studies have evaluated the risks of coastal flooding by taking into account different socio-economic and physical parameters, and by considering sea-level rise. As en example, ABI (2006) defined four major factors that can influence the risks of coastal flooding along the East Coast of England: (1) rises in relative sea level; (2) North Sea storm surges; (3) local tidal conditions and shoreline configuration; and (4) coastal defences and flood management measures. The impacts of sea-level rise are among the major threats to coastal environment and communities. Therefore, many studies attempted to measure the vulnerability of coastal areas to sea-level rise. In this context, a Coastal Vulnerability Index (CVI) has been developed, and applied in many cases (e.g. Hegde and Reju, 2007 for the Indian coast). The CVI has been based on different parameters of which: geomorphology, regional coastal slope, rate of relative sea-level rise, historical shoreline change rates, mean tidal range, and mean significant wave height (Pendleton et al., 2005). It is one of the most common methods and standards for assessing coastal vulnerability. On the contrary, there exist other specific coastal vulnerability assessment methods. As an example, Meur-Ferec et al. (2008) analyzed coastal vulnerability in France by taking into account the exposure to risk, the management of risk, the remembrance of risk, and the perception of risk by those endangered. In the context of vulnerability to climate extremes, Nicholls et al. (2008) performed a study aiming at estimating the exposure of large port cities to coastal flooding due to storm surge and damage due to high winds. In addition, they studied how climate change is likely to impact the exposure of each city in the future. The methodology is very interesting in that sense that it takes into account both wind- and flood related risks. For example, used parameters for measuring the exposure to flooding are mainly population parameters, i.e. the number of people who are exposed to extreme water levels. In addition, calculation of population distribution by elevation is performed in the exposure analysis. As for the relative exposure to wind damage of the cities, the exposure is mainly calculated on the basis of wind characteristics such as the historical and the present-day wind activity. At last, exposure to sea-level rise is based on the calculation of future water levels and on extreme sea levels calculated on the basis of coastal characteristics data obtained from the DIVA model (Dynamic Interactive Vulnerability Assessment), “a global analytical database which is based on a vector model of linear coastal segments determined by variations in population density, administration boundaries, geomorphic structure of the coast, and expected coastal morphological change given sea-level rise" (McFadden et al., 2007).

Measuring the magnitude of hazards

Only few international standards exist for measuring the magnitude of hazards in coastal areas. Different systems to rate the intensity of hurricanes and other severe storms exist. The Beaufort scale classifies storms based on wind speed: storm severity varies from 0 (calm) to 12 (hurricane-force). Another example is the Saffir-Simpson scale which is designed to measure hurricanes: the severity of hurricanes varies from the category 1 (with no significant structural damage to building structures) to category 5 (with complete building failures). As for the magnitude of floods, no international standards exist. However, the magnitude of floods has been determined by different quantitative methods in the scientific literature.

4.2 Management plans, land-use planning and climate adaptation

Examples of measures taken into account into management plans are the definition of building codes and zoning, regulation and flood risk mapping, etc. In Europe, climate change and coastal adaptation plans are designed at different responsibility levels. At the same time, some European countries do not examine potential impacts of climate change for their country in particular. Research is, for example, very limited for some countries, while for other countries, especially those that have suffered from severe weather events in the past have invested more research for possible national impacts of climate change (European Commission, 2010). Strategic climate change adaptation plans (including the coast) or coastal adaptation plans are available, for example, for the following European countries: Belgium (integrated master plan for coastal protection), Denmark (general strategy for climate change adaptation); Finland (national adaptation strategy to climate change); France (national adaptation plan to climate change); Germany (master plan for coastal defence and a climate change adaptation strategy); Ireland (national adaptation strategy and local coastal management strategies); Italy (general plan of interventions); and the Netherlands, where there exists a long tradition in water management, and which has a national water plan, Delta commission recommendations, and a national adaptation agenda spatial planning (European Commission, 2010); etc. In some countries, legal safety standards are defined. Safety standards are generally defined as the maximum admissible annual failure probability or minimum required return period. For example, legal safety standards in Denmark range from 50 to 1,000 years, while in the Netherlands legal standards (based on CBA) range from 2000 to 10,000 years (Safecoast, 2008). In Belgium, the minimum safety standard for the coastal protection defined by the Flemish government is 1:1000 year event (Ferreira et al., 2009). However all the countries do not have strategies in their national plans for reducing the impacts of sea-level rise in coastal areas. At the international level, there also exist international cooperation mechanisms for risk reduction, for example the Intergovernmental Oceanographic Commission (IOC) of UNESCO which gives recommendations to policy makers for reducing the risks to coastal communities.

Costs related to the definition and enforcement of building codes are direct tangible costs that can be subdivided into R&D, engineering and investment costs. However, in risk adaptation plans, costs of adaptation can also be viewed as relative costs. Indeed, in the context of adaptation to coastal hazards and to climate change, there exist different options for coastal management, each one having its advantages and disadvantages, as well as specific financial costs and benefits. Cost and benefit analysis (CBA) thus has a fundamental role in decision making and risk prevention since it is usually used for estimating the efficiency of projects, i.e. by giving an overview of the advantages and disadvantages of protection project alternatives. Costs and benefits are expressed in monetary terms in order to make different risk mitigation project options as comparable as possible. However, project effects are first described in quantity and quality before being expressed in economic terms. As an example, the question is, among other things, to know whether the net social benefits are positive (Persson et al. 2006). The analysis can be used to explore different climate change adaptation projects. For coastal zones, this evaluation method can, for example, support decision-making as regards the best protection project to implement in order to cope with erosion or sea-level rise. The quantification of different ecological and socio-economic effects require data and parameters such as damage to property, loss of infrastructure, loss of biodiversity and ecosystems, quality of life, etc. The following sections describe two examples of cost and benefit analysis for project feasibility between different options of adaptation to coastal hazards. These are about decision making methods and therefore they cannot be considered on the same level as costing methods which have been previously compiled and evaluated. In other words, CBA is not a cost assessment method in itself, but may actually require inputs on the basis of previous studied methods. Even though these two examples are closely related, the latter model - called life-cycle simulation model - is designed to assess the physical performance and economic costs and benefits of coastal protection projects, in particular for beach nourishment along sandy shores.

Example: Cost-Benefit Analysis, Case Study in Maine (USA)

Marine Law Institute of the University of Maine School of Law, the Maine Geological Survey, and the Maine State Planning Office, 1995. Anticipatory Planning for Sea-Level Rise along the Coast of Maine. EPA-230-R-95-900. U.S. Environmental Protection Agency, Office of Policy, Planning, and Evaluation.

• *Explanation*: This report proposes an assessment of Maine's vulnerability to projected changes in shoreline position due to accelerated sea-level rise. Several options for anticipatory response strategies are possible, and highly depend on sea-level rise scenarios. A cost/benefit analysis of possible adaptive response strategies is applied for one specific case study area. Four different response strategies are evaluated (two using protection and two using rolling easements).

• *Cost types addressed*: Costs and benefits of adaptation to accelerated sea-level rise, increased coastal erosion, and storm surges.

• *Objective of the approach*: Determining costs and benefits of four possible adaptive response strategies to cope with different scenarios of sea-level rise. The aim is to reduce future losses resulting from accelerated coastal erosion and storm surges.

• *Impacted sectors*: Beach, public and private properties, infrastructures, natural environment.

• *Scale*: Camp Ellis/Ferry Beach, city of Saco, Maine (USA). Time scale: N/A.

• *Effort and resources required*: Medium. Efforts are mainly due to data collection, definition of sea-level scenarios and adaptation strategies.

• *Expected precision (validity)*: Reasonable precision. Several issues prevent an accurate valuation of costs and benefits of different response strategies. For example, it is difficult to predict how people will respond to impacts over time, with and without governmental intervention.
• *Parameters used for determining costs*: Value of land and buildings, sea-level rise scenarios, aggregate social costs. The method requires preliminary cost assessment methods to estimate the costs of different adaptation projects, and to be able to compare them.
• *Results and result precision*: The cost-benefit analysis determines the most cost-effective strategy to maintain the shoreline in its current position.
• *Is the method able to deal with the dynamics of risk?* Yes (risk from accelerated sea-level rise).
• *Skills required*: scientific, economics, politics.
• *Types of data needed*: Change in shoreline position, impacts on buildings (property values) and infrastructures, accelerated erosion/inundation of dunes and beaches, inundation of wetlands and lowlands, and loss of natural coastal protection systems.
• *Data sources*: Intergovernmental Panel on Climate Change (IPCC), historical maps and aerial photographs, previous studies, assessor records.
• *Who collects the data*: Scientists, local town offices.
• *How is the data collected*: From previous report, by scientists, administrators.
• *Is data derived ex ante or ex post*: Ex ante (data required for predictions of changes in shoreline position for different scenarios of sea-level rise and strategies).
• *Data quality*: Unknown.

As mentioned previously, in response to extreme coastal storm events, stakeholders and decision makers need to examine how to efficiently implement coastal defence systems. Evaluating the long-term economic efficiency of any shore protection project is therefore important, and can also be done by using a life-cycle simulation model. Life-cycle simulation techniques and related research methods may be relatively complex insofar as they may use sophisticated models requiring many resources and efforts. However they represent useful technical tools. Such a life-cycle simulation model was developed for coastal storm damage reduction planning. In this context, it enables the evaluation of costs and benefits of shore protection projects. In that capacity - as for multi-criteria analysis (MCA) -, this approach is part of integrative decision-making methods. The method does not attempt to ultimately evaluate direct or indirect costs of coastal storms, but rather uses in the model, direct costs of potential damages as input parameters (from damage functions based on the type of construction, foundation type, etc.). In addition, life-cycle costs are associated with project maintenance and implementation. In order to properly evaluate costs and benefits of reducing risk from coastal storms, future storm event scenarios are also determined on the basis of historical storms.

Example: Life-cycle simulation model, Case Study in Florida (USA)
Gravens, M.B., Males, R.M., Moser, D.A., 2007. Beach-fx: Monte Carlo Life-Cycle Simulation Model for Estimating Shore Protection Project Evolution and Cost Benefit Analyses, Journal of the American, Shore and Beach Preservation Association, 75(1), 12-19

Gravens, M.B., 2007. Walton County, Florida Hurricane and Storm Damage Reduction Feasibility Study. U.S. Army Corps of Engineers Research and Development Center, Coastal and Hydraulics Laboratory.

• *Explanation*: Beach-fx (based on a Monte-Carlo simulation) was developed to evaluate the physical performance and economic costs and benefits of shore-protection projects, in particular beach nourishment along sandy shores. It incorporates the best current practical knowledge on coastal engineering methods in order to perform economic evaluations of hurricane and storm damage reduction projects in a risk and uncertainty framework.

• *Cost types addressed*: Costs and benefits of different shore-protection alternatives (over a life cycle evaluation period), related to storm impacts.

• *Objective of the approach*: The model investigates, analyzes and recommends solutions to provide for hurricane and storm damage protection along the coastline. It enables the establishment of a planning model and decision support with development of a new framework for performing engineering and economic analysis associated with storm damage reduction studies.

• *Impacted sectors*: Infrastructures (defined as damage elements): residential, commercial and recreational structures and their contents.

• *Scale*: Walton County, Florida; Time scale: life-cycle evaluation period of 50 years.

• *Effort and resources required*: High. Many meteorological and coastal morphology data, as well as economic and management measures data and processes are required to develop the model, as well as to use the model as a tool.

• *Expected precision (validity)*: Good, insofar as the model considers uncertainties involved in predicting future scenarios.

• *Parameters used for determining costs*: Cost associated with armor construction (per foot of armor length), mobilization cost per beach nourishment, unit placement cost (estimated cost of constructing an emergency nourishment project expressed as a cost per cubic yard of fill material).

• *Results and result precision*: Emergency nourishment mobilization and placement costs; planned nourishment mobilization and placement costs (expressed in monetary values).

• *Is the method able to deal with the dynamics of risk?* Yes, Beach-fx enables quantification of risk with respect to shore-protection project evolution and economic costs and benefits of its implementation.

• *Skills required*: Ideally engineers, economists and planners (and other disciplines) work together to set-up, calibrate and run the model; as well as to interpret the outputs.

• *Types of data needed*: GIS data, historically-based plausible storm events, specific beach morphology responses, inventory of structures that can be damaged, damage function data.

• *Data sources*: Meteorological offices, pre-computed data (storm-induced beach change model), previous scientific research, data from numerous fields and disciplines.

• *Who collects the data*: Meteorological office, scientists, engineers, economists, and planners.

• *How is the data collected*: In the field, through observation and experiments (aerial and georeferenced images, storm-induced beach change model); by the meteorological office and multidisciplinary specialists.

• *Is data derived ex ante or ex post*: Ex ante (simulation model estimating future storm events and beach profile changes).
• *Data quality*: While life-cycle simulation techniques are traditionally used, this method applied in the context of hurricane events is particularly specific, and could therefore not be considered as standardized. In this specific model, data quality can be assured, insofar as tests on the availability of the model to detect input that may result from user errors in sourced data can be performed.

In addition to CBA which are used for adaptation strategies, the use of Multi-Criteria Analysis (MCA) also facilitates the decision-making in adaptation management. This method consists in considering a number of positive or negative effects for each project alternative. Each effect is given a weight. Based on overall scores, the outcomes enable to rank the project alternatives in order of preference.

4.3 Hazard modification

Coastal configuration such as the presence of wetlands and dunes may protect the coastal areas. Indeed, they can constitute a buffer zone to protect against storm surges. This effect is also well-known in tropical coastal areas where mangroves provide good protection against tsunami, cyclones and other coastal storms. Conserving the integrity of these natural environments is therefore essential. In this context, two types of hazard modification have been distinguished (Tonkin & Taylor Consultants, 2006): structural hazard modification and non-structural hazard modification. Non-structural hazard modification is precisely related to those natural barriers which enable the reduction of the adverse effects of coastal hazards. Thus, the decision of restoring dune systems in order to maintain a buffer zone that protects against wave actions and reduces coastal erosion may be considered as non-structural hazard modification. While building sea walls or offshore breakwaters are examples of structural modification.

Determining the costs of modifying coastal hazards does not seem having been reported in many studies. However, natural ecosystems, such as wetlands which are able to have significant impacts on hazard reduction, have been economically estimated. For example, their positive effects such as protection against coastal storms and shoreline stabilization can be used as indirect use values (through reducing property damages) to be considered in the calculation of total economic value of wetlands (Barbier et al., 1997). Total valuation including benefit estimates from different positive effects of wetlands, including protection against coastal storms, has also been carried out by Costanza et al. (1989) for Louisiana’s coastal wetlands. By considering parameters such as estimates of property damages resulting from hurricanes (including both wind and flooding damages), distance of the center of a county from the coast, population, hurricane strength, distance from the path of the hurricane, and probability of hurricane incidence, they estimated how much expected damage losses would increase in case of wetland recession, as well as their total value. As an example, their estimates of the total present value of an average acre of natural wetlands in Louisiana are 2429 USD per acre (assuming an 8% discount rate), of which 1915 USD is the present value per acre due to the sole effect of protection against storms (Costanza et al., 1989).

As regards to the costs of structural hazard modification, they may mainly be related to the costs of coastal defence structures. For example, in the context of climate change, Hillen et al. (2010) attempted, for three specific case studies (the Netherlands, New Orleans, and Vietnam), to estimate the costs of coastal defence structures on the basis of unit costs of coastal defence (from different sources). As an example, because of safety standards and sea-level rise in the Netherlands, dikes need to be raised. Thus, coastal defence costs have been estimated in euro per km of raised dikes, for different places and situations. In the same idea, but for non-structural modifications, costs estimates have been applied for unit costs of sand nourishments (in euro per m3 of material). These depend on the type of nourishment (foreshore or beach nourishment), and vary over time depending on the market situation. In the Netherlands, the main authority dealing with these coastal defence works is the Public Works and Water Management (RWS).

As non-structural modifications are closely related to the natural environment, contingent valuations may be appropriate methods to estimate the values associated with coastal dunes or wetlands. However, other methods enable the quantification of the value of coastal environments. For example, Farber (1985) developed a model to place a value on wetlands for their role in reducing wind damage to property because of diminished storm intensities (for the Louisiana gulf coast). As property damages from high winds depend on wind velocity and property at risk, a structural equation system is used, and integrates different wind parameters such as: the wind velocity at location, the distance of location inland, the distance from the path of the storm, the intensity of the storm at landfall, etc. In addition, expected damages per unit of property at risk are evaluated (on the basis of the annual probability of a specific hurricane).

4.4 Infrastructure

There exist many measures to protect the coastal areas against sea-level rise and risks of flooding and coastal erosion. Examples of coastal infrastructures to protect the coast are: dikes, dams, seawalls, breakwaters, groynes, storm surge barriers, dune building, building on pilings, adapting drainage. Physical infrastructures and mitigation/adaptation measures are often classified into *hard* and *soft* options (Table 7).

Table 7. Hard and soft options against SLR and increased risks of flooding and coastal erosion

Option	Protect (effort to continue use of vulnerable areas)	Accommodate (effort to continue living in vulnerable areas by adjusting living and working habits)	Retreat (effort to abandon vulnerable areas)
Hard	Dykes, seawalls, groins, breakwaters, salt water intrusion barriers.	Building on pilings, adapting drainage, emergency flood shelters.	Relocation threatened buildings.
Soft	Sand nourishment, dune building, wetland restoration or creation.	New building codes, growing flood or salt tolerant corps, early warning and evacuation systems, risk-base hazard insurance.	Land use restriction, setback zones.

Source: OSPAR, 2009

In Europe, coastal defence structures and measures implemented may vary from one country to another. As an example, in Denmark and the United Kingdom, beach nourishment and dike foreland management are common practices; while in the Netherlands, coastal protection usually includes large scale beach nourishment, dams, storm surge barrier design, or land reclamation and coastal defence structure (Hodgson, 2009).

As hard structures to protect the coast are very much related to structural hazard modification, and soft options to non-structural hazard modification, the methodology developed on the basis of unit costs of coastal defence previously mentioned remains valid and could be applied in this context. Apart from these structural and non-structural protection measures, accommodate and retreat options in Table 7 may be considered as adaptation or mitigation measures.

For structural protection options, implementation and maintenance may represent important costs to consider in total costs and benefits of shoreline protection. As infrastructures can have negative impacts on social welfare due to their impacts on land fragmentation and aesthetics, revealed preference methods such as hedonic pricing methods should be used to measure these negative impacts. As a counterpart they are also a potential source of benefits by bringing additional recreational activities or tourism; even though they also may have negative impacts on landscape and tourism, for example, because of the replacement of natural environments with hard structures. The study carried out by Hamilton (2007) mentioned previously also refers to the impacts of changes in attractiveness of the coast.

4.5 Mitigation measures

Mitigation measures are meant to reduce the physical costs of the coastal hazards. They can be very diverse and have different scale of implementation. Therefore, different measures can be decided and implemented at different levels such as the state, the regions, the local communities or the private households. These measures enable the limitation of damage and life losses caused by coastal hazards, and do not require the construction of large-scale infrastructures. Examples of mitigation measures may be cutting the trees close to houses and roads, the protection of electrical and phone lines by putting them underground, and the creation of refuge zones under buildings for the protection of people. Against other coastal hazards such as salt floods on agricultural lands or erosion, it is possible to grow flood or salt resistant crops, or to grow plants meant to stabilize the beaches and the dikes.

One way to measure the costs and benefits related to mitigation measures is the use of a cost-effectiveness analysis (CEA). The aim of a cost-effectiveness analysis is to determine for which measure (project alternative) an objective can be reached at the lowest cost possible, or to determine which project alternative will contribute most to the achievement of the objective (Coastal Wiki, 2008). For example, McKenzie et al. (2005) described the cost effectiveness of the relocation of a hospital after the Cyclone Heta in Niue Island. After having been demolished during the cyclone, and according to the methodology, direct, indirect and intangible impacts of a major cyclone similar to the Cyclone Heta were estimated with and without hospital relocation to a safer location, away from the vulnerable coastal zone.

4.6 Communication (in advance of events)

Communication in advance of storm surge events is important insofar as it contributes to increase public awareness of coastal risks; it may provide incentives for the implementation of protective measures by communities, households and businesses, or incentives for change in coastal settlements in the long-term. In this context, flood mapping is for example a good instrument for communication in advance of events. Different forms of communication are used by the EU Member States and the regions in order to increase the awareness and preparedness of the populations at risk of coastal hazards. These include legislation enforcements, assistance programs, websites providing information to the population and industries, etc. For example, the websites of the French government (www.prim.net) provide information on coastal floods and other hazards, as well as advices to protect businesses, communities and households against the risk. However, communication campaigns on coastal hazards are relatively rare. They mainly provide advices to the population to protect against erosion and floods, as well as coastal properties and lives in case of flood or storm. They may also give information to coastal farmers to protect their crops and their lands.

4.7 Monitoring and early warning systems (just before events)

Monitoring evolution of shorelines is important to assess beach changes. Coastal monitoring is, for example, important to assess general trends in shoreline movement such as coastal erosion. In the shorter term, coastal monitoring may also qualitatively and quantitatively predict characteristics (occurrence, intensity, duration, etc.) and impacts of storm surges, as well as determine when beach-nourishment will be required. In reality, when a coastal hazard is occurring, beach monitoring has an important role since it enables the provision of real-time information about the upcoming event (e.g. by collecting meteorological parameters) that can then be relayed by early warning systems. This relayed information is crucial to alert population and relevant authorities, as well as to make adequate decisions regarding emergency responses and therefore minimize social and human losses. As an example, video-based monitoring systems (such as the ARGUS video system) collect data continuously, and often at low cost. These systems are notably used in the European Project MICORE (Morphological Impacts and COastal Risks induced by Extreme storm events), which is currently developing early-warning systems for storms in coastal areas, notably through operational predictive tools in support of emergency response to extreme storm events. One of its objectives is to set-up these real-time warning systems and to implement their use within civil protection agencies. Thus, monitoring is an important means of providing a basis for early warning and preparedness, and enables the reduction of social and human impacts of storm surges. In addition, their associated losses as well as the costs associated with emergency response procedures can be minimized when efficient warning systems exist.

In Europe, operational warning systems may differ from one country to another, or may be non-existent. In this context, there exist needs for coastal information and warning systems, particularly by providing on-line predictions of storm impacts for both frequent and more extreme events, as well as to have access to standardized methods for post-event damage quantification (Ciavola et al., 2011). To have better idea about risk management and how warning systems are implemented in Europe, Ferreira et al. (2009) compared - for nine study sites in Europe - coastal storm risks, coastal management plans, as well as civil protection schemes. They concluded, among other things, that operational approaches used for major event prediction and responses are actually poorly developed. Indeed, for the study areas of Belgium, Bulgaria, France, Italy, Portugal and Spain, there are no implemented operational approaches. For these sites, real time warnings and alerts exist, but they mainly aim at navigational safety (Ferreira et al., 2009). In Italy, there exist operational early warning systems for sea water flooding. This is the case, for example, in Venice where people are alerted when high floods are occurring. At least four hours before the event, alert systems are set off, and local population is alerted about the event by sirens, short message services, or Internet. Emergency measures can then be taken accordingly. In Belgium, there exists a warning system for storm surges. These are based on water level records but not on forecasts. When the water level is high, an official alert is released; while for very high water levels, an official storm tide alarm is set off. However, the alerts are not connected with any warning plan or intervention. The exceptions are Poland, the Netherlands, and the United Kingdom where operational approaches linked to warning systems exist. As an example, in Poland, where warnings are based on meteorological and hydrodynamic models that predict wind speed and sea level elevation, actions are taken if observed conditions are above defined thresholds. In the Netherlands, an operational surge forecast model is used as a warning tool for authorities. At last, in the United Kingdom, tide-surge models are used to forecast storm surges and run in real-time: this service provides the warnings needed to protect coastal communities from flooding, as well as aiding in operational decisions (Ferreira et al., 2009).

At the international level, the Intergovernmental Oceanographic Commission (IOC) of UNESCO is aiming, among other things, at providing efforts for scientific and technical support for storm surge warnings. Its role is important insofar as it promotes international cooperation and serves as a liaison between the marine scientific research community and the government of Member States. It also focuses on the extension of the systems for all sea-level related hazards, such as tsunamis, storm surges, sea-level rise, etc. Depending the type of coastal hazard, the estimated time required before being able to predict and alert anyone on the occurrence of the hazard in question is different. Indeed, the predicting time generally varies from minutes to hours for tsunamis, from 12 houres to 2 days for storm surge, and from 1 to 3 days for wind-driven waves. In the case of sea-level rise and coastal erosion, this time can be spread over decades. For storm surges, efficient dissemination of warnings normally supposes good data transmission of observation in real time and, if possible, wave propagation modelling. Actually, four components are fundamental for effective early warning systems (WMO, 2011): (1) the detection, monitoring and forecasting the hazards; (2) the analysis of risks involved; (3) the dissemination of timely warnings; and (4) the activation of emergency plans to prepare and respond.

Several international organizations or systems contribute in developing observing systems and dissemination of information. For example, the Global Sea Level Observing System (GLOSS) coordinates sea level networks, and play a predominant role in implementing warning systems. Another example is the Global Ocean Observing System (GOOS) which, implemented by Member States via their government agencies and research institutions, aims at monitoring and predicting weather and climate, as well as mitigating damage from natural hazards. At last, the World Meteorological Organization (WMO) which, through a telecommunication system and global data processing and forecasting system, facilitates the sharing of data, analysis and forecasts across the State Members (through their national meteorological and services).

As regards to financial aspects, there does not seem to be many estimates available for the costs and benefits of early-warning systems. Indeed, such estimations are relatively complex to carry out. In this context, Teisberg and Weiher (2009) defined six factors likely to determine the benefits of early warning systems. Two of them are related to the very nature of the hazard: (1) the frequency and (2) the severity of the hazard; while the four other factors determine the most appropriate response when a warning is issued: (3) the lead-time (between a warning and the actual occurrence of a disaster), (4) the accuracy of the warning, (5) the response costs (the costs of possible responses to the warning), and (6) the loss reduction (the expected costs of the disaster reduced, given the public response to the warning). In any case, it should be noted that "the improvement of early warning systems is clearly an investment in sustainable development, as demonstrated in many countries where benefits exceed costs many times over" (Michel Jarraud, Secretary General of the WMO in World Bank, 2010); hence the importance of developing early warning systems also for the long-term, and in parallel to operational warning plan or intervention.

4.8 Emergency response and evacuation

During or after natural disasters in coastal areas, emergency responses can be implemented. Generally, if emergency responses are required and operated at the place of the disaster, the actions undertaken are in line with preliminary guidelines which are often set by regional or national crisis management plans. As an example, in United Kingdom, local authorities (i.e. local councils) are responsible for providing emergency aid during floods; while the Department for Environmental Food and Rural Affairs (DEFRA) has responsibility for national level flood emergency planning and for ensuring policy coordination to local emergency responders. Most of the time, the civil protection is operative in warning, in protecting communities when coastal disasters occur (e.g. evacuation of populations), and in rescue operations (rescue and relief operations, medical assistance, etc.). After coastal storms, responses can also be in the form of beach restoration and sand nourishments, debris removal, etc. Although emergency measures are generally carried out under national, regional, or local civil protection schemes, there also exists a civil protection scheme at the European level. Indeed, a European Union Civil Protection Mechanism aims to better protect people, their environment, property and cultural heritage, in the event of major natural disasters which occur both inside and outside the European Union. As an example, all countries participating in this EU Civil Protection Mechanism offered assistance when Hurricane Katrina and Rita struck the United States in 2005. This assistance is provided when the affected country's preparedness for a disaster is not sufficient to provide an adequate response in terms of available resources (European Commission, 2011).

In the context of risk reduction strategies in particularly for emergency measures, only few methodologies for cost assessment exist. In reality, when emergency measures are efficiently implemented, these highly contribute to the reduction of losses of human capital (cf. Gaddis et al., 2007). As for the evaluation of the benefits associated with these emergency measures, a Cost-Effectiveness Analysis (CEA) can be appropriate for measuring the benefits of risk reduction strategies, especially because human losses and health effects are intangibles. The basic principle of the method, which is an economic approach, is to estimate the cost of an intervention to its effectiveness. Indeed, it compares the gain in health from a measure and the cost associated with the health gain. In other words, the approach relates the investments in safety measures to the reduction of the expected number of fatalities (Jonkman et al., 2008b). Actually CEA is a commonly used alternative to cost-benefit analysis. However, CEA differs from CBA, notably because it expresses outcomes in natural units: for example, the cost effectiveness of measures can be related to the reduction of loss of life, by evaluating the cost of saving an extra statistical life year. This method can be recommended because intangible costs and benefits of emergency measures cannot be accurately measured. Unfortunately, to our knowledge, no CEA has been applied for estimating benefits of risk reduction strategies in the context of coastal storm disasters.

4.9 Financial incentives

Financial incentives are private or public interventions - e.g. through premiums from insurance services or through taxes and subsidies provided by authorities - to encourage hazards loss reduction or, in the context of sea-level rise, to encourage adaptation strategies. Financial incentives can, for example, support long-term changes in coastal land-use, encourage the elevation of existing shoreline protection structures in areas at risk of sea-level rise, or encourage home or business owners to adopt adaptive measures to reduce the vulnerability of properties to storm surge flooding. These incentives may be implemented by different entities and at different levels. For example, in its 2009 final report (PRC, 2009), the Policy Research Corporation recommended to encourage the involvement of national authorities in climate change adaptation and coastal protection through the creation of an incentive scheme that would be implemented at the European level. This support would be in the form of a financial contribution for which national authorities could apply for when preparing their national adaptation or coastal protection strategy (PRC, 2009). It has to be said that, with respect to the increasing number of natural hazards caused by climate change in Europe (such as in the Netherlands because of high risk of submersion), the level of catastrophic risk financing is unfortunately far below optimum levels (CEA, 2007). In the market, although incentives generally exist for wind storms in Europe, only few incentives are implemented for storm surges and associated flooding. Hence the need for concerted efforts towards a legal framework in each European country, precisely to implement incentive schemes to adapt to sea-level rise and to reduce the risk of coastal flooding. In reality, national governments bear responsibility for providing a legal framework to guide effective adaptation by individuals and businesses - which require local solutions - especially if market forces alone are unable to deliver the full response necessary to deal with the serious risks from climate change (CEA, 2007).

4.10 Risk transfer

Despite financial incentives or coastal management plans which tend to minimize loss of life and property in coastal areas, there exists the possibility to “transfer” the risks of storms and floods to which coastal communities are exposed. More precisely, in the context of risk reduction and management, a risk transfer enables the management of risks that would be too large for people and companies to bear on their own (Warner et al., 2009). As the effects of climate change can affect the probability of flooding (because of higher water and storm surge levels), they will lead to an increase of consequences if flooding occurs (Maaskant et al., 2009). Sea-level rise and increasing strength of storm surges will affect European countries, like the Netherlands where current potential losses in the coastal areas are estimated at €300 billion (Consorcio de Compensación de Seguros, 2008), or other countries where large cities are close to the sea. To efficiently protect households and companies, different risk transfer mechanisms exist across Europe. The insurance market is one of the most common risk transfer strategy. On the other hand, as for financial incentives in risk management, wind storms are generally covered by the insurance industry (CEA, 2005), while storm surge and flood insurance coverage is less common. However, because of climate change and increasing risk of flooding in coastal areas, the continued availability of cover for flooding as a standard component of household and business policies will certainly come under increasing pressure (ABI, 2006).

Financial risks of climate change and/or natural disasters may imply insurance or even reinsurance mechanisms, i.e. insurance companies are themselves insured by other private insurance companies, by governmental agencies, or by the State. This is the case for example in the United Kingdom, where insurers purchase reinsurance for windstorm and coastal flooding (ABI, 2006). The financial risk to which people or companies are exposed can therefore be transferred to different levels of competence or authority; and natural hazards can therefore be covered by a cooperation between e.g. the state and the insurance sector, namely by a mixed public/private insurance system. In Europe, natural disaster coverage (through insurance and reinsurance systems) varies widely from one country to another. The European insurance and reinsurance federation or *Comité Européen des Assurances* (CEA) listed different insurance coverage systems currently applied in different EU countries by both the insurance industry and the state, and for different types of natural disasters. It appears, for example, that insurance coverage for storm, hurricane or flood events may be either compulsory by law (e.g. in France), pooled by insurers (e.g. in Spain), optional (e.g. in the United Kingdom), proposed (e.g. in Greece), non-existent. More generally, i.e. for the whole range of natural hazards in Europe, four main categories of disaster coverage are apparent (CEA, 2007, p.25):

- In countries such as the Netherlands or Denmark, insurers play a minimal or optional role in the provision of cover against natural hazards. The state organizes the insurance scheme through the government annual budget or through tax levied on fire damage policies which are managed by a specific fund.
- In Switzerland, the State does not intervene in the provision of insurance but makes the insurance of certain risks compulsory, most of the time by means of fire contracts.
- In countries such as Belgium, France or Norway, the solution is a mix of compulsory insurance and of state intervention in case of damage. Similar schemes are currently considered by the public authorities in Italy and Romania. In most of the countries, the inclusion of such coverage in certain branches' policies is compulsory whereas underwriting by policyholders is made on a voluntary basis.
- Finally, the solution, which is the most widespread, is the case in which the state's intervention is totally absent and most of the covers relating to natural hazards are optional. The rate of penetration of these covers varies according to the risk perception and to the effective risk exposure [sic].

As for coastal areas, there also exist multiple compensation schemes for damage caused by coastal disasters such as storms and floods. For example, there exists in Denmark a national Storm Flood Fund for the compensation of property damage for floods caused by coastal storms. This compensation is administered by the Danish Storm Council, benefits to all sectors (private, commercial, industrial, agricultural), and is applicable when specific conditions are met: for example, flooding must be caused by seawater, and the invasion of seawater must be caused by a manifest rise in sea level as the result of a storm event. In Norway, compensation for property damage resulting from storm surges is either paid by the State through the Norwegian National Fund for Natural Damage Assistance (Statens Naturskadefond), and/or by insurance companies through the Norwegian Natural Perils Pool (Norsk Naturskadepool) which comprises, among others, a committee of insurers responsible for the management of losses and claims. In the Netherlands, the Calamities Compensation Act (WTS) published in 1998 enables the State to pay compensation (under certain circumstances) for flood damage which is not to be insured. Although the compensation terms actually make no mention of loss from flooding in coastal zones, the scope of the Act would be enlarged in a Royal Decree in case of national-scale catastrophe caused by seawater flood (Consorcio de Compensación de Seguros, 2008). These few examples of risk transfer mechanisms at the national level show, for natural disasters in coastal areas, several types of risk management actions, as well as the importance of having mechanisms enabling the transfer of risk from householders or businesses to the competence of the state (i.e. under legal schemes) or, for example, to the competence of a committee made of an association of insurance companies, when the risk cannot totally be transferred to the single insurance market.

5 Analysis of cost assessment methods

This section mainly refers to chapter 3 as well as Table 6 which gives a comparative overview of main key characteristics of different methods for assessing the costs of coastal hazards.

5.1 Direct costs

Economic methods for evaluating direct costs are relatively well-established. For example, multivariate models, mainly based on multiple regressions, are notably designed to evaluate total direct costs of natural hazards. Although a regression analysis is in itself a basic technique which is a priori not related to any cost assessment, such a technique may be useful and very accessible to easily provide correlations between different physical, social or economic variables, and correlate them the total costs related to the natural hazard. Regression techniques do not require many efforts, and the multivariate model also constitutes a good method to understand the damaging processes. In addition, using such regression techniques may require only few data sets and parameters related to a storm (compared to other methods for direct costs). The limitation is often a question of data availability. Regarding the validity of the methodology, one has to be careful when choosing appropriate independent variables representative of specific characteristics of the coast. An example was given in the methodology where proxies such as population and population density are used to measure the intensity of coastal development, whereas other variables could better measure accurate socio-economic characteristics. As for the results, these may unfortunately be very approximate. Indeed, there exist relative uncertainties, and the method is acceptable for providing regional estimates of potential storm losses, but does not seem capable of providing a level of precision sufficient to local governments for estimating with precision potential losses related to local infrastructures and coastal properties.

Direct costs due to damages to public and private properties, commercial and industrial buildings or infrastructures, are generally primarily estimated on the basis of depreciate values, replacement costs or costs of reconstruction calculated from market values and by insurance companies after the disaster. Contrarily to the multivariate model, the estimation modeling based on damage functions which has been developed for hurricanes by the FEMA precisely includes these factors and seems to be a very good and precise methodology to obtain very accurate results and good cost estimations. This is notably due to the number of detailed parameters taken into account (especially engineering parameters for buildings). The model includes different damage categories such as physical damages to structures and contents, loss of use, and damages to building repair and replacement, which enables the full estimation of total potential losses. Although the HAZUS-MH model can be applied for different types of hazards (through different model applications), in the case of coastal hazards, its applicability ranges over storm and flood. This cost assessment method is probably one of the most appropriate tools to precisely assess the direct damage resulting from coastal hazard events because it uses damage functions, i.e. flood- or wind-damage functions (depending on the use of different HAZUS-MH models), that we consider as a very good approach in evaluating direct losses to infrastructures. Indeed, these take into account water parameters such as water depth, flood duration and water velocity (for the flood model) or wind characteristics such as wind speed in calculation of damages for the Hurricane Model (cf. fig.1). However, some uncertainty exists in the model and may be related, for example, to the HAZUS-MH modeled peak gust wind speeds, since micro-bursts are likely to occur, and yet these are not represented in the curve. On the other hand, the location of large buildings in an area could reduce wind speeds in a given area. These wind speed anomalies may cause some uncertainties in modeling the losses due to the hazard. The HAZUS flood and hurricane models are mainly based on physical damages to building and infrastructures. By only considering the HAZUS-MH model as a given tool to assess direct costs due to storm damages to buildings, its use requires many parameters, which represents many efforts in collecting data, but may be relatively simple when data are easily available. However, developing such a model requires much more skills and efforts.

The zone-based damage estimation, from our point of view, is a simple way to approach the estimation of direct costs of coastal storms. Indeed, this methodology may be relatively accessible in terms of data collection and efforts because data on damages are collected from past events, on the basis of existing damage reports, and by using aerial photographs which enable the representation of different vulnerability zones in a spatial dimension. At the same time, as losses and damages to buildings and infrastructures are highly dependent from their location on the shoreline or behind, this approach enables to take into account this specific requirement. The validity of results, ensured by previous damage costs used for determining the risks related to future storms of similar magnitude, is relatively low as it mainly extrapolates the coastal damages resulting from a past event to the potential losses resulting from a future storm event. However, the validity also mainly depends on the use of reliable parameters of change over time in property values, population or number of structures exposed. Although this makes the model able to deal with shoreline dynamics and the evolution of risk, there exist relatively high uncertainties in the estimation of future storm damage-related losses, notably because we cannot completely rely on extrapolations from one specific past storm event to another future storm event. The main advantage of the method is that it does not require many data and is therefore more accessible.

At last, the probable maximum loss (PML) estimates potential losses resulting from tsunami and resulting coastal waves and flooding. As for statistical methods such as zone-based damage estimations, the estimation of PML has the advantage of predicting damage losses from expected events, but provides instead information on the extent of the maximum risk involved. Indeed, it predicts the potential maximum losses resulting from severe coastal wave events, and thus enables the use of worst case scenarios in decision making and risk management in coastal areas. However, there may be significant statistical uncertainty, particularly regarding the severity of loss that might occur. Indeed, the method may require some validation, notably when using the PTVA model to determine the PML, because specific factors such as variation in bathymetry, angle of wave approach, shape of the coastline, etc. may actually influence the magnitude and severity of the tsunami within different locations, as well as the variation in degree of associated damages which is not considered in the model (Dominey-Howes and Papathoma, 2006). Despite these few limitations, we recommend this method when assessing the worst scenarios related to coastal disasters - specifically to coastal flooding - may be necessary.

From these four approaches estimating direct costs (multivariate model, damage function approach, zone-based damage estimation, and probable maximum loss), the models based on damage functions, such as those developed by the FEMA, are certainly the best in terms of precision in results for direct losses. Wind speed (for storm events) and water depth parameters (for coastal flooding events) are probably among the most important factors to consider when assessing direct physical damages (e.g. damage to buildings and infrastructures), even though damages resulting from coastal disasters frequently results in business disruption and tourism. And yet it is important to take these factors into consideration. Unfortunately, except within the HAZUS-MH MR5 model or from multivariate models, these effects cannot fully be taken into account. Multivariate models are much more flexible than models requiring specific and detailed data - e.g. related to buildings and infrastructures - and may probably be more appropriate for easily estimating not only direct but also indirect losses due to disruption processes, unless accurate results are needed.

Although direct costs can be precisely determined for damages resulting separately from wind and flood events, it remains difficult to evaluate the combined effects of wind storms and storm surge flood. And yet no one from these four methodologies, primarily designed for direct costs, is able to provide full consideration of combined effects rather than separate effects due to wind or flood hazard. In order to improve the understanding of the interaction of storm surge with the built environment, and more precisely to consider damage costs resulting from both hazards, Friedland (2009) proposed the use of a combined scaling method which would enable the valuation of direct losses resulting from the combined effects of wind and flood. Indeed, instead of quantifying the economic loss resulting from flooding as a function of water depth (for example), economic losses are determined on the basis of levels of physical damage (Friedland, 2009). For this, general scales for physical damage have been determined on the basis of a combination of existing damage scales respectively designed for wind and flood damage. The effects of flooding can be correlated with existing wind metric systems (e.g. the Saffir-Simpson Scale). Thus, a resulting Wind and Flood Damage Scale can serve as a basis for determining wind and flood combined damages and associated economic costs. Considering both hazards in one single model for building damage may certainly contribute to better results in cost assessment.

All these methodologies are very much related to structural direct physical damages; and yet, coastal storms and flooding may cause significant losses in terms of human lives. For estimating these human losses, Jonkman et al. (2009) provided a methodology able to estimate the loss of life in Louisiana, caused by the flooding following the Hurricane Katrina. The methodology focuses on loss of life and mainly consists in providing an analysis of the relationship between (simulated) flood characteristics and mortality (number of fatalities divided by the number of people exposed to the flooding). The number of fatalities due to a flood event is determined by factors such as the characteristics of the flood (depth, velocity, rise rate), the possibilities for warning, evacuation, and shelter, and the loss of shelter due to the collapse of buildings (Jonkman et al., 2009). An estimate of loss of life due to a flood event can therefore be given based on information on flood characteristics (example in figure 4), an analysis of the exposed population and evacuation, and an estimation of the mortality among the exposed population. The approach applied for flood simulations notably consists in using a digital elevation model and a terrain model. These simulations provide important results on water depth, flow velocity, rise rate, or arrival time.

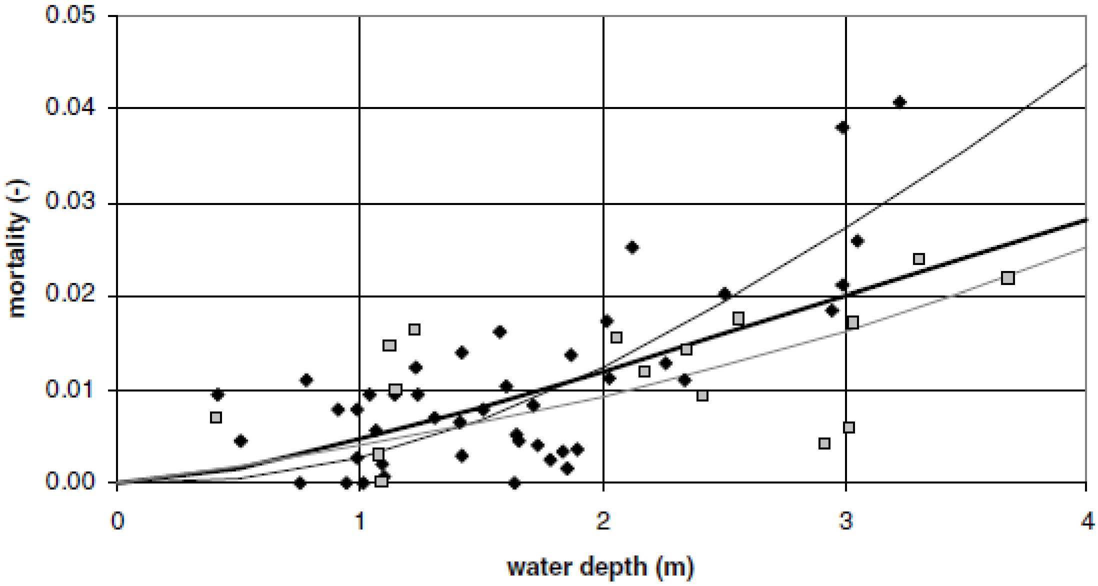

Fig. 4. Loss of life caused by the flooding after Hurricane Katrina: relationship between water depth and mortality for the Orleans and St. Bernard areas, Louisiana, USA (black squares are observations for Orleans; grey squares are observations for St. Bernard; the bold curve is the best trend line for all the observations). Source: Jonkman et al., 2009.

From our point of view, this method gives a very good approach to assess the loss of life resulting from hurricane-associated flooding. In the same way as the assessment of building damage developed in HAZUS flood model, the method developed by Jonkman et al. (2009) describes the loss of lives as function of water-depth. Again, this precisely links the amount of loss with the intensity of the flood event. However, given the intangible nature of losses, the method does not enable the economic valuation related to the human losses. In order to further investigate their economic valuation, this method should be coupled with other cost assessment methods such as contingent valuation methods.

5.2 Indirect costs

Methodologies for assessing indirect costs of natural hazards may be developed on the basis of multivariate models and econometric approaches. Two main methodologies enabling the valuation of indirect costs have been investigated. The first methodology concerns the multivariate model already evaluated in the previous section for direct costs (cf. paragraph 5.1.1). This method, based on regression analysis, has the main advantage of being very flexible in the choice of parameters that can be taken into account to valuate damages due to coastal hazards; namely, the methodology does not necessary require predetermined data sets, but rather the development of a set of available and independent variables that can be correlated with total damage costs. The second methodology concerns an adaptive regional input-output model. Although input-output models are usually useful tools for analyzing hypothetical scenarios such as effects on the economy of a change in policy, it can be applied to evaluate indirect costs of disasters. Here the costs due to disruption of production processes has to be referred as “primary indirect damages”, contrarily to direct damages which occur due to the immediate impact of the disaster; even though there exist some exceptions, e.g. business interruption losses are sometimes considered as direct costs, and evaluated in terms of stocks instead of flows. This is the case, for example, in the ANUFLOOD model which estimates direct costs, but also business interruption due to floods (NR&M, 2002). The particularity of the adaptive regional input-output model resides in the fact that forward and backward propagations in the economic system, as well as adaptive behaviors, are fully taken into account. The model is therefore particularly interesting insofar as it enables the valuation of indirect costs in the aftermath of a shock for the whole economy of a region by taking into account the effects of changes in demand and supply in many sectors of activity. It differs in this way from other input-output models which do not consider productive capacity which enables the assessment of the consequences of a shock on the supply-side (Hallegatte, 2008). Secondly, and as mentioned earlier, input-output models may not take into account price and responses elasticity related, for example, to alternative suppliers that would not be affected by the shock. As well as the adaptive regional input-output model, Computable General Equilibrium (CGE) models precisely enable these price responses and demand elasticity (Hallegatte, 2008). These models are more complex, but also less rigid than classic input-output models. They may be defined as a “multi-market simulation model based on the simultaneous optimizing behavior of individual consumers and firms in response to price signals, subject to economic account balances and resource constraints” (FEMA, 2006). These models may therefore be considered as an alternative to input-output models. At last, in its flood model technical manual, the FEMA (2006) also listed some disadvantages of basic input-output models of which: their linearity, the lack of behavioral context, the lack of interdependence between price and output, the lack of explicit resource constraints, and the lack of input and import substitution possibilities [sic].

Generally, input-output models are good approaches to assess indirect impacts in the aftermath of natural disasters such as hurricanes, even though the method may present some limitations, especially due to lack of flexibility in economic systems, and also because the method is not very suitable for local scales. Depending on the type of input-output model, efforts in data collection may be relatively high, as input-output tables often need to be adjusted to the spatial scale and the period of the hazard event. Computable general equilibrium is able to deal with more flexibility in economic processes. As an alternative to input-output models, possible applications of such a method for the case of indirect costs of coastal storms could be further investigated, and its relevance and significance in results evaluated. However, this latter method may require high efforts given its complexity.

5.3 Intangible costs

Intangible costs are, by definition, difficult to quantify in monetary terms. The main reason of the difficulty of valuation resides in the fact that these effects are not traded in a market. Contingent valuation methods (CVM) or hedonic pricing methods (HPM) enable the valuation of such effects. The main difference between these two methodologies resides in the fact that the first one is based on stated preferences, while the second is based on revealed preferences. Both of the methods are applied in the context of coastal flood impacts and risks.

The first case study, which is based on a contingent valuation (CVM), uses survey questionnaires in order to determine flood impacts on human health, well-being and stress experienced. Although this method requires important efforts in order to design the questionnaires and make the survey results as representative as possible, the case study proposes a good approach for evaluating intangible flood effects. From our point of view, one of the main strengths of the methodology came, among other things, from the definition of specific health-related scales used in the questionnaires: these scales enable the scoring of health effects resulting from floods, and the health effects can therefore be used in multivariate regression analysis. One of the main weaknesses, as reported in the description of the methodology, concerns the risk of identifying symptoms unrelated to the flood event (Environment Agency/DEFRA, 2004). Despite very complete and well-designed questionnaires that may bring relatively accurate results, the main weakness may also be inherent in the very methodology which is based on non market values.

The second case study, which is based on a hedonic pricing method (HPM), is on the contrary much closer to reality in that sense that it is based on actual market values. The notion of flood risk was directly translated into monetary values by looking at actual economic values or transactions. Indeed, the method determined economic from the coastal housing market, i.e. from revealed preferences of householders.

In order to have a better overview on methodologies, we also looked at the main characteristics of these economic valuation methods, as defined, for example, by The Commission on Geosciences, Environment and Resources (CGER) which provides an overview of their different advantages and disadvantages (Table 8).

Table 8. Advantages and disadvantages of the economic valuation methods

Method	Advantages	Disadvantages
Contingent valuation method (CVM)	▪ It can be used to measure the value of anything without need for observable behavior (data). ▪ It can measure non-use values. ▪ Technique is not generally difficult to understand. ▪ Enables ex ante and ex post valuation.	▪ Subject to various biases (e.g., interviewing bias, starting point bias, non-response bias, strategic bias, yea-saying bias, insensitivity to scope or embedding bias, payment vehicle bias, information bias, hypothetical bias). ▪ Expensive due to the need for thorough survey development and pre-testing. Controversial for non-use value applications.
Hedonic pricing method (HPM)	▪ Based on observable and readily available data from actual behavior and choices.	▪ Difficulty in detecting small effects of environmental quality factors on property prices. ▪ Connection between implicit prices and value measures is technically complex and sometimes empirically unobtainable. ▪ Ex post valuation. (i.e. conducted after the change in environmental quality or quantity has occurred). ▪ Does not measure non-use values.

Source: adapted from CGER, 1997

As mentioned in the table, one of the advantages of a contingent valuation method is its ability to estimate non-use values. In this context, this method may be useful when assessing coastal natural environments, or maybe when only few data on any actual economic transactions in a given region are available or usable. The main disadvantage is that this method may also be source of many biases. On the contrary, a hedonic pricing method is able to deal with actual behavior and choices, but is unable to measure non-use values, and yet non-use values in coastal areas may be important to valuate natural environments at risk of flooding, especially in the context of sea-level rise (e.g. for coastal lowlands and wetlands).

Health effects and the housing market effects both enable the valuation of intangible effects related to floods or flood risks. Although intangible valuation in the context of coastal hazards is much less common in literature than the valuation of tangible effects, similar valuation studies for measuring intangible effects in the context of coastal hazards have been carried out. As an example, Turner et al. (1993) used a CVM to estimate recreation and amenity values of the ecosystem of Broadland (United Kingdom); while Hamilton (2007) used a HPM in order to valuate coastal landscapes.

The Hedonic Pricing Method and Contingent Valuation Method have been chosen for several reasons: first because they seem to be part of the best methodologies to measure intangible effects related to coastal disasters, and secondly because they are representatives of available methods that were applied for measuring such intangible effects. Contingent Valuation Method is also the most commonly applied technique for the estimation of the intangible costs. At the same time, these two methodologies give very good examples of evaluations based on either stated values (stated preference methods) or real values (revealed preference methods), what is important to distinguish to better understand the reliability or validity of methods assessing intangible losses.

More generally, regarding the methods for evaluating intangible costs of coastal hazards, some recommendations have been made by the stakeholder community. These showed, among other things, that there is a need for ex-post assessment (e.g. based on historical storms) and comparison to ex-ante estimations (i.e. by using scenarios or simulations) in order to achieve more efficient cost assessment. In addition, there is also a need for wider use of intangible cost attributes in models, in order to properly quantify the costs related to the human capital as well as the costs of environmental assets and services.

5.4 Mitigation and adaptation

In the context of climate change and sea-level rise, managing and choosing the best adaptation measures for protecting coastal areas is essential. Adaptation measures require being able to minimize the costs of coastal protection measures. In order to fulfill these special requirements, we consider methodologies that use cost and benefit analysis as being appropriate. Indeed, its main advantage is the possibility to integrate the risk related to sea-level rise. The method is generally based on different IPCC scenarios, and constitutes in that sense a very good approach to compare different policy response strategies. One difficulty when using this approach probably resides in the economic valuation of each effect, which requires the application of various costing methods. On the other hand, the complexity in CBA of accounting for non-market values may make ethical decisions difficult (Mechler, 2005); and their determination usually has to rely on contingent valuation techniques. The CBA based on life-cycle simulations, such as in the model previously studied (cf. Gravens et al., 2007), is also a good approach to evaluate costs and benefits of shore protection projects, especially in the case of beaches threatened by hurricanes.

However the model is primarily based on coastal storm damage reduction projects rather than sea-level rise scenarios and related risks of flooding. CBA and other methods such as multi-criteria analysis (MCA) or cost effectiveness analysis (CEA) which enable the measurement of cost and benefit of different beach protection options are appropriate to measure the efficiency of different projects, notably in the perspective of climate change. We have also mentioned the use of CEA for assessing the benefits of emergency response in case of coastal disaster, the use of choice experiment methods for comparing different adaptation measures. As for risk transfer and financial incentives for reducing the risks to which coastal communities are exposed, more recommendations on methodologies would be necessary even though the sector of public and private insurance may provide useful data and information a to evaluating their costs and benefits.

5.5 Data sources

The main data sources for measuring direct costs of coastal hazards may be regional or national weather services or meteorological institutes, land planning agencies, insurance companies or census offices. Most of the time, data are available within from the local, regional or national level, and yet it may be useful to have access to more standardized data at the international scale. For example, regarding historical data, the impact of storms that have historically affected the European coastlines was evaluated in different ways in different countries, often using as criteria the socio-economic impact, e.g. loss of lives and damage to properties (https://www.micore.eu). However, there exist available databases at smaller scale. As an example, the DINAS-COAST project (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise) - that conducts a top-down, integrated modeling effort to improve our understanding on potential impacts of, and adaptation to accelerated sea-level rise at national, regional and global scale -, is a global coastal database which is an important source of physical and socio-economic data and parameters; at last, it also provides sea-level rise data. The project EUROSION may facilitate the access to relevant coastal data and information such as elevation and bathymetry, infrastructure, hydrographical features, littoral geo-morphological aspects, sea level rise, etc. (http://www.eurosion.org). There exist other general coastal database; however, further general data sources may be needed, notably providing relevant economic data. As an example, for measuring indirect costs, it is recommended to easily obtain information on flows of goods and services. In this context, Eurostat has developed a manual to assist statistical institutes in the production process of input-output tables, which may also serve as a source of information for data users (Eurostat, 2008). As regards to general databases on intangible effects, there is a clear lack of data sources, as they are closely related to socio-economic surveys which require much effort and are often carried out on local levels.

6 Recommendations and knowledge gaps

Direct costs

Generally, except maybe for statistical methods, there exist relatively few cost assessment methodologies for estimating the direct costs of coastal hazards which combine flood and wind effects related to storm surges. Accurate methods and models for direct costs are typically based on one form of the hazard, i.e. taking into account either wind or flood damages for loss assessment. And yet, these two forms of hazard should be better associated when evaluating total direct losses and damages. As a result, the methods applied to assess direct costs due to coastal flooding are generally the same for riverine flooding or for inland storms. In the Netherlands, for example, with its long shoreline and large parts of the country being located below sea level, potential damages from riverine and coastal flooding are assessed using the same method, namely the HIS-SSM (Kok et al., 2005). For Belgium, the UK and France, no differences between cost assessment methods for riverine and coastal flooding have been identified. As for the damage functions, a problem may arise from the question whether damage functions for riverine and coastal floods are interchangeable or not. Indeed, wave action and flow velocities in coastal areas may lead to different damage patterns compared to river flooding (FEMA, 2011).

Another important aspect in direct cost assessment is the use of replacement costs instead of depreciated asset values. Most of the cost assessment methods are based on replacement values because these are more accessible (e.g. from insurance industry) compared to depreciated values; in reality, the choice of one or the other also depends on the type and objectives of the study (purpose of the cost assessment), as well as on the needs of end-users. Independently from this, it is important to use water and/or wind parameters or characteristics as a basis for accurately evaluate direct damages to coastal properties and infrastructures. Actually, this requires general wind and flood data (e.g. data on wind speed and water depth). In this context, a specific gap is precisely the need for more damage data that should be collected in a systematic way, and maybe the need for more transparency. The data availability and quality for cost assessment methods could then be improved. Data quality and availability highly depend on the type of data needed (real or estimated; physical, social, economical or environmental data), on the type of data sources (e.g. official census offices, insurance industry, surveys, meteorological centers), etc. More standardization coming from similar types of data sources would probably enhance data quality and would facilitate their use in cost assessment methods. Another gap is related to the validity of cost methodologies as uncertainty analyses are not always clearly defined; hence the difficulty to determine the best cost methodologies, as well as their degree of precision.

In the context of climate change, several studies have attempted to put an economic value on the effects of sea-level rise in coastal areas (see e.g. Brooks et al., 2006). Although the methods studied in the report are usually able to take into account the dynamics of risk, further research remains important to learn about how accurately evaluate the economic impacts of sea-level rise and about how to integrate them in methods and models for full cost assessments of future hazards in coastal areas.

Indirect costs

End-users need relatively simple model and data for estimating indirect costs of coastal hazards, and yet the cost assessment methods which were mentioned as examples in the report are more accessible compared to sophisticated models such as computational general equilibrium models. These latter models enable more precision notably because they further consider elasticities in the economic systems, and may therefore further reflect the reality compared to the input-output models. More generally, it is also important to consider the indirect costs on long scale perspectives, and at different scales. Difficulties may arise from the fact that there exist many different indirect effects such as income losses, tourism decline, and other business disruptions; hence the importance of considering them by having full access to economic and sectoral data, at the scale of the disaster, and for a given period. In this context, statistical data or data of national accounts - e.g. input-output tables - should be easily accessible. A last point concerns the determination of the costs for recovery time which is not easy. In fact, this highly depends on the non-disaster baseline scenario which is often particularly difficult to estimate. To sum up, there exist different needs and priorities for indirect cost assessment of coastal hazards, of which the need for data accessibility, the development of simple and reliable models, but also the need for more knowledge about possible losses.

Intangible costs

Contingent valuation methods (CVM) and hedonic pricing methods (HPM) have been presented in chapter 3 and analyzed in chapter 5. Although these two methods enable the evaluation of the intangible effects resulting from coastal hazards, there is generally a need for more accurate estimations of environment assets and services, ecological values, health costs, and other effects related to the human capital. More attention is also required on psychological effects and specifically post-traumatic stress that are not easy to quantify. In reality, there exist theoretical methods for estimating the valuation of intangible effects related to the natural environment or to the human capital (e.g. choice modeling methods, travel cost methods, etc.) but they are relatively limited and not sufficiently applicable in the context of coastal hazards. At the same time, the valuation of intangible effects is sometimes subjective, and therefore more standards for the valuation of effects such as loss of life or health effects should be defined. It is also relatively difficult to apply models for estimating intangible effects, as these often require many efforts given that most of the time a variety of surveys necessary. At last, there is an apparent lack of data sources, and a need for elaborating more social science surveys and dissemination of results.

Adaptation and mitigation planning

The best practices for risk reduction planning probably include the mapping of areas at risk from coastal erosion and storm surges that can serve for present and future land planning. For example, this can be used to restrict coastal development in areas that may require protection measures. Maps of flooded areas are also important for combined risk of storm waves and surges according to probability of occurrence for given return periods. Although the determination of good or bad practices in coastal management depends primarily on population density and risk probabilities in coastal areas, another good practice which is important especially in high-risk and high populated areas is the development of quasi-real time warning systems for competent authorities. This enables the implementation of appropriate emergency measures in case of disasters. The implementation and maintenance of coastal infrastructures is also, in many cases, an example of good practice. On the contrary, if the hazard frequency is high or in case no protective structures are in place, examples of bad practices for risk reduction include the presence of permanent structure occupying the coastal zone as close as possible to the water line. Artificial change in beach profile to increase width for occupation during the tourist season, as well as beach replenishment demanded by users to have larger beach may be problematic since the beach width should be enhanced only in areas subject to storm surges. Generally, users often prefer hard structures to soft engineering because they feel safer behind the structures. And yet, appropriate protection measures have to be implemented, because when infrastructures are located within the acting zone of a storm, the beach is usually subject to important erosion, coastal retreat and damages (Ferreira et al., 2010). Risk reduction planning could also be improved by implementing further measures, especially because some areas do not have a regional characterization of sea-level rise; because they do not have a probabilistic dataset for waves and surges; and because they do not have locally measured waves and tides. At last, there is no systematic collection of information of damages following significant storm events, neither standardized method for economic valuation of costs.

In addition, different problems have been pointed out by the stakeholder community, notably because it is difficult to consider and demonstrate the ecological value of coastal ecosystems which is necessary to be integrated in risk mitigation strategies, as well as to carry out cost and benefit analysis. In addition, during the cost assessments, some cost categories are currently neglected due to a division of responsibilities among different public agencies (e.g. coastal protection is separated from emergency management or risk communication).

Other recommendations regarding the valuation of adaptation costs have also been highlighted within the stakeholder community. For example, the costs on the macro level (State, national, or federal level) and on the micro level (individuals) should be distinguished. Adaptation on the micro level might evolve because the macro level is not fully involved in adaptation, and there actually could be a combination of measures implemented on both the macro and the micro level. Unfortunately, there exists only little knowledge about optimal combination of measures. At last, there is a clear need for clear risk governance to better implement public adaptation measures; while more incentives are needed to strengthen adaptation of individuals.

Further recommendations

In general, although economic methods for estimating the direct costs of coastal hazards are relatively numerous (even though they generally do not consider both wind and flood hazards for total cost accounting), further research for estimating indirect and intangible costs of coastal hazards is necessary. The reason is that there less practice and few applications related to the estimation of these cost categories. There is also a clear need to have more available databases, and at different levels. This would facilitate the use of methods or models when coastal data and information on socio-economic, environmental or physical specific characteristics are missing. In the context of adaptation and mitigation measures, there is a general need for data about operation and maintenance costs, as well as data about emergency response. As the expert community also pointed out the need to have better access to data, it would be interesting to have access to data sources such as official statistics or data archive collections at the European scale, as well as national guidelines about how to collect damage data.

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