Mireille Escudero Castillo[1]
Edgar Mendoza Baldwin[1]
Rodolfo Silva Casarin[1]
Gregorio Posada Vanegas[2]
Maritza Arganis Juaréz[1]

[1]Instituto de Ingeniería, Universidad Nacional Autónoma de México, Mexico
[2]Instituto EPOMEX, Universidad Autónoma de Campeche, México, Mexico

Review

Characterization of Risks in Coastal Zones: A Review

Interest in sustainable development for the natural, socio-economic, and cultural resources of coastal zones is growing worldwide. On the other hand, the range of threats to coastal zones increasingly posed by hydro-meteorological natural phenomena has led to a trend in the analysis and assessment of risks to these areas. The available literature dealing with coastal risk assessment is quite wide, focusing mainly on the risk evaluation of coastal flooding and erosion resulting directly from the occurrence of extreme natural events. The risk assessment methodologies are usually specific to the conditions and available data of each country, society or location, though most have evolved to assess the risk concept more precisely and rigorously. However, there are still very few studies that present feasible and effective methodologies, which lead to the effective integration of risk analysis at all levels. In Mexico coastal risk analysis has barely begun despite our extensive coastline, which is highly vulnerable to the threat of tropical cyclones. This paper aims to give a broad view of the risk assessment methodologies which already exist, in order to provide a starting point for future efforts in Mexico and elsewhere.

Keywords: Coastal risks; Hydro-meteorological hazards; Risk assessment

Received: December 6, 2011; *revised:* February 1, 2012; *accepted:* March 14, 2012

DOI: 10.1002/clen.201100679

1 Introduction

Among the most important and dynamic natural environments worldwide, the approximately 440 000 km long coastal area is one of a small group of systems where several human, animal, vegetal and geomorphologic activities interact. Its invaluable landscape and ecological richness make it a very desirable zone to develop social, industrial, and recreational infrastructure.

On the other hand, coastal zones are attacked by different natural phenomena, mostly from hydro-meteorological origin, such as waves, wind, tides, and rainfall which can reach extraordinary magnitudes during the occurrence of events like hurricanes and tsunamis. The direct consequences of these extreme events are flooding (derived from mean sea level rise) and beach erosion (as a result of the increase in current velocities and wave energy), a combination of both of these causes land loss, damage to infrastructure and natural habitats, ecological imbalance, health problems in the population and instability in economic activities [1–4].

The phenomena mentioned above are commonly grouped under the generic term of "dangers", and the combination of these with the vulnerability of the natural and/or artificial elements found at the coast gives the risk of a specific coastal area. In the last decade, the interest shown in the assessment of risks comes from the evidence of an increase in the magnitude of natural dangers, added to the expansion of human activities in coastal zones which results in a higher level of risk [5–8]. In turn, while not arguing against it nor agreeing on the causes of it, the fact that there is a changing climate represents an increase in the risks to coastal areas [9–14].

With this scenario, the concept of sustainable development for the natural, socio-economic and cultural resources in coastal zones becomes much more relevant. To achieve that kind of development several recommendations exist in Integrated Coastal Zone Management (ICZM), which define the principles of sound coastal planning and management. These include the need to base planning on reliable and shared knowledge, the need to take a long-term and cross-sector perspective, to pro-actively involve stakeholders and the need to take into account both the terrestrial and the marine components of the coastal zone [15]. An important component of ICZM planning is the analysis and assessment of coastal risks, i.e., to characterize the behavior and potential damage caused by natural phenomena in the long-term, in order to optimize decision-making, planning and management in areas susceptible to hydro-meteorological hazards and climate change. ICZM also discusses the design of anticipated measures to preview possible risks, in order to minimize loss and damage and avoid disasters.

The available literature dealing with analysis and evaluation of risks in coastal zones is quite wide; it includes laws and regulations, guidelines and manuals, research projects and studies published at coastal conferences and workshops. Nevertheless, very few studies really present feasible and effective methodologies for coastal risk assessment. Some of these studies can be found in Jha et al. [4], Papathoma and Dominey-Howes [16], DEFRA/EA [17], Werritty et al.

Correspondence: Dr. R. Silva Casarin, Instituto de Ingeniería, Universidad Nacional Autónoma de México, Circuito Escolar s/n, Edificio 5, Cub. 407, Cd. Universitaria, Coyoacan, 04510, México D.F., México
E-mail: rsilvac@ii.unam.mx

Abbreviations: **CBA**, cost-benefit analysis; **CVI**, coastal vulnerability index; **GIS**, geographical information system; **HDRI**, hurricane disaster risk index; **ICZM**, Integrated Coastal Zone Management; **MCA**, multi-criteria analysis; **SPRC**, source-pathway-receptor-consequences

[18], Kazmierczak and Handley [19], Narayan et al. [20], FLOODsite [21], THESEUS [22].

The Republic of Mexico has one of the longest coastlines relative to its total surface area and the coastal areas contain very valuable, diverse ecological systems. Unfortunately, available works and studies on risk assessment for our coastal zones are still very poorly developed, resulting in great uncertainty about the dangers and vulnerability on Mexican coasts.

For this reason, the aim of the work presented here is to give an overview of existing methodologies for risk assessment, in order to provide a starting point for future work in Mexico and other countries.

2 The risk concept

In the specialized literature the term "risk" has been analyzed from very diverse points of view; sometimes its definition is stated by the needs of particular decision-makers, which has led to several meanings of risk attending different safety, economic, environmental, and social issues. Some examples of these are:

Risk involves an "exposure to a chance injury or loss" [23].

Expected losses (of lives, persons injured, property damaged, and economic activity disrupted), due to a particular hazard, for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability [24].

Risk is a compound measure combining the probability and magnitude of an adverse effect [25].

risk = impact of hazard × elements at risk × vulnerability of elements at risk [26].

risk = hazard × vulnerability × value of the threatened area/preparedness [27].

Risk is the actual exposure of something of human value to a hazard, and is often regarded as the combination of probability and loss [28].

Risk might be defined simply as the probability of the occurrence of an undesired event [but] be better described as the probability of a hazard contributing to a potential disaster. Importantly, it involves consideration of vulnerability to the hazard [29].

Risk means the expected number of lives lost, persons injured, damage to property, and disruption of economic activity due to a particular natural phenomenon, and is consequently the product of specific risk and elements at risk. Total risk can be expressed in pseudo-mathematical form as:

risk (total) = hazard × elements at risk × vulnerability [30].

Risk is the combination of the probability of occurrence of harm and the severity of that harm [31].

Risk is the probability of a loss, and depends on three elements, hazard, vulnerability, and exposure [32].

Risk is defined as a function of the probability of the hazard, of exposure to the hazard, and the vulnerability of receptors to the hazard [33].

Risk is the probability of hazard occurrence, where hazard = potential threat to humans and their welfare [34].

Risk is function of probability and magnitude of different impacts [35].

Risk is the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted, or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions [36].

Risk is a combination of the chance of a particular event, with the impact that the event would cause if it occurred. Risk therefore has two components: the chance (or probability) of an event occurring and the impact (or consequence) associated with that event [37].

risk = probability × consequence [38–41].

Risk is the function of the probability that a risk event occur and the consequence associated with that event. Practically, risk is made up of four major building blocks: the probability of flooding, the exposure of the elements-at-risk to a flood with certain characteristics, the value of these elements-at-risk, and the vulnerability of these elements-at-risk [42].

3 Risk analysis and assessment approaches

Although risk analysis and risk assessment terms are often confused, some sources separate them. FLOODsite [43] defines risk analysis as a methodology to determine risk by combining probabilities and consequences; while risk assessment comprises understanding, evaluating, and interpreting the perceptions of risk and societal tolerances of it to inform decisions and actions in the risk management process. The objective of risk assessment methodologies is to come up with an estimate of the probable future risk and to provide an insight into the distribution of risk and its related causes. The review presented here examines both of these perspectives, because the evolution of risk approaches is a story of adapting knowledge to the conditions and available data in each country, society, and location.

In general, the methodologies found define risk in qualitative and/or quantitative terms, of which the quantitative approaches usually lead to a more precise risk determination. Among the approaches presented in this section, "analysis of revealed preferences" and the "analysis of expressed preferences" can be classified into purely qualitative methodologies; and the "cost-benefit analysis" (CBA), the "multi-criteria analysis" (MCA), the "prior, posterior and pre-posterior analysis", the "coastal vulnerability index" (CVI), the "source-pathway-receptor-consequences model" (SPRC) and the "flood risk triangle" into quantitative risk group. On the other hand, the "generic representation of risk analysis" presented, the "risk matrix", the "multiple coastal hazard risk", and the "multiple hazard (seismic-hydrologic)" methodologies can be included in the qualitative or quantitative classification depending on the specific needs for each risk assessment.

3.1 Analysis of revealed preferences

This approach assumes that society has reached equilibrium between the risks and the benefits of a specific activity. The knowledge gathered to get there, allows authorities to set or "reveal" acceptable risk levels according to the economic and social relevance of the activity. This model is quite limited as it neglects the context and power relations defining people's decisions and as it assumes that risk acceptance is similar in different realms of life; it is well known that acceptable risk levels are different for each type of risk and for each danger [43].

3.2 Analysis of expressed preferences

This method is focused on considering what society "expresses" as their preferred security levels, recorded by means of public consultation. This preference is used to determine the acceptable risk for each danger and location. The main advantage of this approach over the revealed preferences is that the uncertainty related to the different scenarios is minimized if the consultation undertaken is sufficiently deep. However, this approach can be criticized for its assumption that laypeople can handle appropriately rather complex questions concerning risk activities. Other limitations of this methodology are the difficulty in choosing a suitable design of investigation that reduces complexity and uncertainty, and to consider the context of questioning people on their preferences [43].

3.3 Cost-benefit analysis (CBA)

This approach has been utilized for more than 50 years to quantify in monetary terms as many of the costs and benefits of a feasible proposal, including items for which the market does not provide a satisfactory measure of economic value. CBA examines whether the total benefits of a risk reducing activity, evaluated in terms of money, exceed the costs involved in utilizing resources. It has undergone continuous refinement and expansion due to the increasing importance of social and environmental concerns in development projects in recent years, by applying monetary values to social and environmental issues.

This approach is unable to take into account the factors and issues that cannot be expressed in monetarily terms, such as moral issues, distributional equity, etc. As a result, this kind of risk management often manages only certain parts of risk. Moreover, the spatial distribution of risks as well as the benefits of risk mitigation measures is rarely considered, and the evaluation and selection of appropriate mitigation measures is mostly based on their overall net benefit. This methodology has been analyzed by several authors in the frame of research projects such as: ADAPT [42], FLOODsite [43], and ASFPM (Association of State Flood Plain Managers) [44].

3.4 Multi-criteria analysis (MCA)

The MCA is usually considered as a decision making tool more than a risk assessment approach; however, it has been included as a methodology to assess risk by using the same information as risk analysis.

The MCA methodology is based on economic, social, and environmental criteria, which are joined together into a single risk estimation. Each criterion is weighted to allow the representation of the relative importance of each risk type. The possibility of this approach for evaluating monetary and non-monetary risk in an integrated way, as well as showing their spatial distribution provides a better supported technique for the comparison of project alternatives. There are various approaches that suggest multi-criteria procedures to map, manage and assess the economic, social and ecological dimension of risk in an integrated manner such as: Tkach and Simonovic [45], Bana et al. [46], Brouwer and van Ek [47], RPA [48], and FLOODsite [49].

Some decision frameworks combining cost-benefit and multi-criteria have been developed; monetary issues are often given more importance but an MCA-based framework is used to involve non-monetary items. This combined methodology has been used for guiding decisions about adaptation measures to climate change induced flooding, as part of the ADAPT Project work [42].

The multi-criteria approach is often supported on geographical information systems (GISs) technology to evaluate and map damage and risks [46, 49].

3.5 Generic representation of risk analysis

The flow chart presented by Faber and Stewart [50] is a representation of risk analysis independent of its application, which is based on the Australia/New Zealand code on risk management and composed of the several steps shown in Fig. 1.

3.6 Risk matrix approach

An example of this approach is the risk matrix developed by Arthur D. Little in collaboration with the Federal Emergency Management Agency to anticipate losses and to evaluate potential impacts [51]. This consists of the seven steps shown in Fig. 2.

Depending on the needs for risk assessment and associated costs, the risk assessment can range from cursory risk screenings to full-scale quantitative risk assessments. An example of a qualitative risk matrix is presented in Fig. 3.

The hazard is classified in four severity categories: minor, serious, extensive, and catastrophic, which includes an examination of the potential fatalities, injuries, property damage, business interruption, and environmental and economic impacts.

The frequency of occurrence of a hazard is ranged in four other categories, from high to very low frequency.

The combination between the frequency and severity determine the risk level, which is ranked in four qualitative categories: high-risk (class A), moderate to high risk (class B), risk condition suffi-

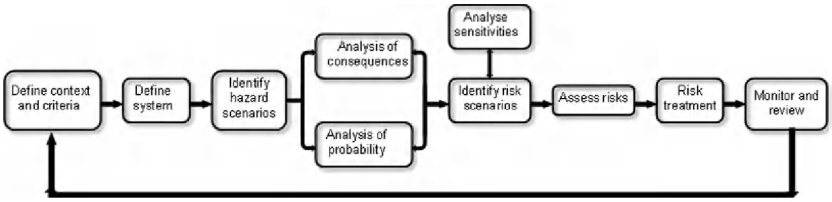


Figure 1. Generic representation of risk analysis (modified from [50]).

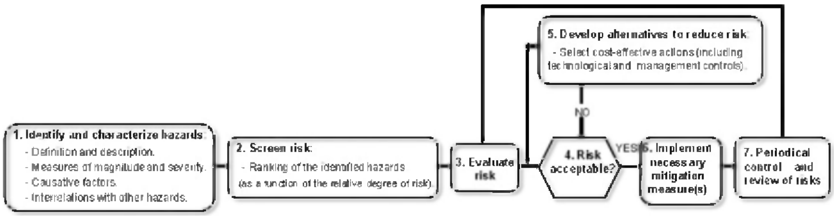
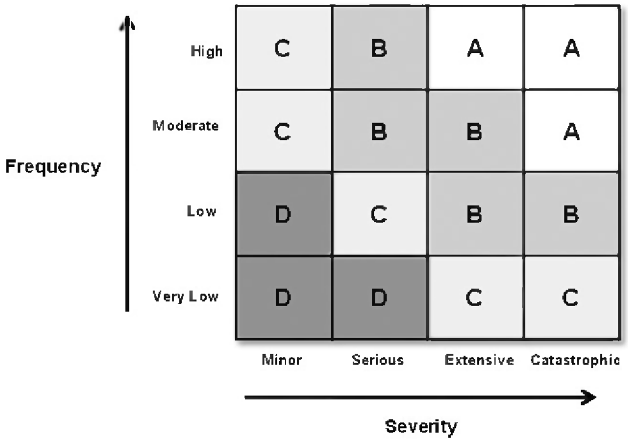


Figure 2. The risk matrix approach (modified from [51]).



Severity

Frequency	Minor	Serious	Extensive	Catastrophic
High	C	B	A	A
Moderate	C	B	B	A
Low	D	C	B	B
Very Low	D	D	C	C

Figure 3. Example of risk matrix (modified from [51]).

ciently high to give consideration for further mitigation and planning (class C), low risk (class D).

3.7 Prior, posterior, and pre-posterior analysis

Faber and Stewart [50] describe the prior-analysis as the simplest form of risk analysis, where the risk is defined as the expected utility and is evaluated prior to any decision and/or activity as:

$$R = E[U] = \sum_{i=1}^{n} P_i C_i \tag{1}$$

where R is the risk for each possible activity/option, U the utility, P_i the ith branching probability, and C_i is the consequence of the event of branch i.

The posterior analysis allows the evaluation of the risk of the new problem obtained as a result of the effect of risk reducing measures, risk mitigating measures and/or collection of additional information. These changes are reflected in the branching probabilities and/or the consequences of a decision tree.

The prior and posterior analysis can be illustrated by the simple decision tree represented in Fig. 4.

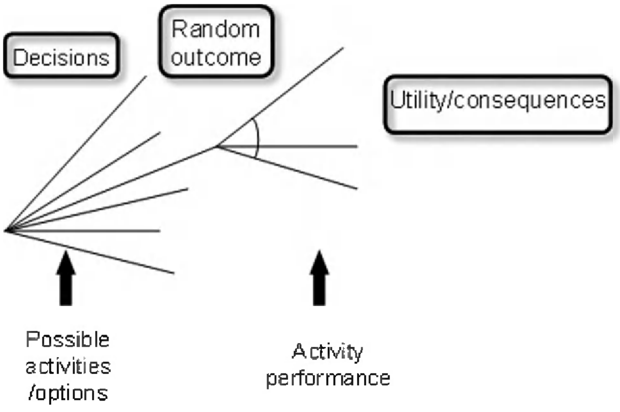


Figure 4. Decision tree for prior and posterior analysis (modified from [50]).

Lastly, the application of pre-posterior analysis is focused on the risk appraisal of activities that may be performed in the future. This is represented as a decision tree in Fig. 5.

3.8 Multiple coastal hazard risk

This approach uses a qualitative and/or quantitative evaluation of risk caused by diverse coastal factors. An example of these studies was carried out by the Coastal Engineering Research Center and the University of Virginia to evaluate risk and exposure to coastal hazards in several stretches of U.S. coastline [52]. Coastal factors that are used to identify coastal hazards are: shoreline change, overwash distance, storm surge, storm and wave damage, earth movements, and stabilization. The results are mapped and represent qualitative and quantitative risk assessments.

This methodology uses a simple definition of risk, easily accessible to potential users, in the form of risk indexes; e.g., the hurricane disaster risk index (HDRI), which has been developed to compare the risk of hurricane disaster for coastal counties in the USA [53]. The HDRI comprises two sub-indexes: the economic HDRI and the life HDRI, which are focused on the economic impacts of hurricanes and bodily harm, respectively. The final value of each index ranges in a scale from 0 to 10; this value is computed as a combination of scalar indicators with weights to describe the relative importance of the associated indicators to the concept being measured.

A similar development is the Hyogo Framework for Action (HFA) 2005–2015 [54] which aims to make the world safer from natural hazards (United Nations, 2005).

3.9 Multiple hazard (seismic-hydrologic) approaches

These approaches are focused on the assessment of multiple seismic-hydrologic hazards of risk and vulnerability. Preuss and Hebenstreit [55] carried out the evaluation of the multiple hazard impacts involved in the earthquake occurrence and associated tsunami flood event for a coastal community on Washington's Pacific coast. Other study is the realized by Toppozada and others [56], which describes a methodology to assess the coastal vulnerability in a Cascadia subduction zone characterized by a high seismic activity. The hazards assessed include tsunami waves, inundations, ground failure and motion, liquefaction, subsidence, landslides, and other secondary hazards such as release of toxic and hazardous chemicals.

3.10 Coastal vulnerability index (CVI)

The CVI is based on a complex set of coastal factors which identify the risk from a specific coastal hazard. The definition of the vulnerability indices can be determined as a function of coastal erosion [57, 58], a variation of sea level [59–63], or an ecological and cultural context [64].

The Oak Ridge National Laboratory developed a CVI to identify the risk from permanent and episodic sea level rise events on the U.S. East and Southeast coast [61–63]. The CVI value was composed of seven marine and land variables, and six climatological variables; where the degree of risk for each of them was weighted based on the relative importance to the inundation or erosion risk

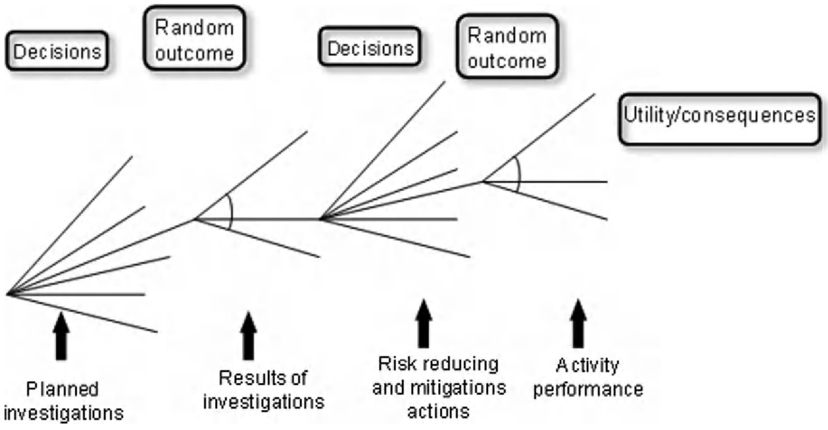


Figure 5. Decision tree for pre-posterior analysis (modified from [50]).

determination. The CVI was ranked for each risk classification on a scale of increasing vulnerability, from 1 (very low risk) to 5 (very high risk).

CVIs have also been used to estimate the vulnerability to erosion of the Aegean Hellenic coastal zone in relation to a future sea level rise [65]. The CVI includes six variables: (i) coastal geomorphology; (ii) shoreline erosion and accretion rates; (iii) regional coastal slope; (iv) relative sea-level change; (v) mean significant wave; and (vi) tidal range. The CVI is calculated as the square root of the product of the ranked variables divided by the total number of variables, that is:

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

The CVI values obtained from Eq. (2) are ranked into five categories to highlight the different levels of vulnerability, from very low (<3%) to very high (>12%).

The CVI index has been applied to assess the vulnerability to the erosion and flood process impacts in relation to sea level rise impacts on the northeast of the state of Pará, Brazil [66]. In this particular case the CVI is integrated in a GIS (GIS-based composite vulnerability index) and combines more than 20 natural and socio-economic variables. Table 1 shows some examples of socio-economic and natural variables, and Fig. 6 states the mathematical definition of the corresponding indices.

Approaches like those by El-Raey [67] and Hughes and Brundrit [68], are examples of CVI applied at local scale, which are intended for application over small coastal stretches. In these studies the

Table 1. Variable classification considering their relevance in the construction of the CVI, expressed by their dependency degree and factor of weight [66]

	Variables	Dependence degree (a)	Weight
Socio-economic vulnerability	Total population affected (flood); non-local population affected (flood), children affected (flood), and elderly affected (flood)	1	1
	Population density	2	0.5
	Non-local population, children, elderly	3	0.25
	Total population 2000, municipal budget 2000, poverty	5	0.125
Natural vulnerability	Coastline length, flooding area, protection measures, emergency relief history cases, total length of fluvial system	1	1
	Coastal features	2	0.5
	Continentality, coastline complexity, proportion of flooding area, drainage density, split ratio	3	0.25

$$\text{Total Vulnerability Index} = \frac{\text{Natural Vulnerability Index} + \text{S}ocio - economic\ \text{Vulnerability Index}}{2}$$

$$\text{Natural Vulnerability Index} = \frac{\sum \text{Natural Vulnerability Variables}}{\text{Number of Variables}}$$

$$\sum \text{NaturalVulnerabity Variables} = 1(a1)_{xy} + 0.5(a2)_{xy} + 0.25(a3)_{xy}$$

$$\text{Socio - economic Vulnerability Index} = \frac{\sum \text{Socio - economic Vulnerability Variables}}{\text{Number of Variables}}$$

$$\sum \text{Socio- economicVulnerabilty Variables} = 1(a1)_{xy} + 0.5(a2)_{xy} + 0.25(a3)_{xy} + 0.125(a4)_{xy}$$

Figure 6. Definitions of natural, socioeconomic, and total vulnerability indices [66].

effects of macro-scale climatic variability and hydrodynamic force are reduced or negligible.

Other approaches use vulnerability indicators or develop integrated vulnerability indices for different kinds of natural hazards, with an emphasis on social vulnerability indicators [69–71].

The CVI is best used in smaller scale studies with detailed geomorphologic, sedimentologic, and coastal oceanographic data, which includes characteristics that may play an important role in the evolution of a specific coastal region.

3.11 Source-pathway-receptor-consequences (SPRC) model

The SPRC model is a conceptual model that represents in a simple way the processes and systems involved in risk occurrence which is expressed as a particular consequence. This is one of the most recently developed methodologies for risk assessment and its application allows the social and environmental risk components to be taken into account. Some studies where this approach has been used are Jha et al. [4], DEFRA [17], Narayan et al. [20], FLOODsite [21], Evans et al. [72], Oumeraci et al. [73], Naulin et al. [74], Sayers and Meadowcroft [75], and Burzel et al. [76].The factor grouping of the SPRC model is defined as follows:

Source of risk (S): is defined as climatic factors inducing flooding, erosion and any other threat to the safety or stability of the land-water fringe, e.g., tsunamis, storm surges, waves, or wind.

Pathway (P): describes the main variables and processes controlling the coastal risk in its way from the source to the receptor. It includes natural and artificial elements such as morphologic processes of flooding, and those related to the behavior and failure mechanisms of defense (overtopping, overflow, breaching, or flood plain inundation).

Receptor (R): are all physical entities exposed to the threat, such as people, buildings, possessions, property, infrastructure, or environment.

Consequence (C): represents all the physical, social, institutional, economic, and environmental adverse effects derived from the occurrence of any hazard. To evaluate the full consequences, direct and indirect losses, social and ecologic resilience as well as acceptance and perception of risk should be considered.

Sources, pathways, receptors, and consequences are spatially and temporally overlaid, thus the division between sources, pathways, and receptors is not strict and depends upon the scale and context of the research [77]. An example of the scope of this model is shown in Fig. 7, where the damage to the coastal zone of Isla del Carmen is evaluated for the passage of hurricane Isidore, September 2002.

3.12 The flood risk triangle

Risk is defined by the commonly accepted definition of risk as being a function of the probability of the hazard, of exposure to the hazard, and the vulnerability of receptors to the hazard [33]. In the flood context, this definition of risk is formalized into the risk triangle shown in Fig. 8 [78–81].

3.13 Other methodologies for coastal erosion risk assessment

Various methods have been proposed over the years for shoreline-change prediction, such as the Bruun rule, extrapolation of historic shoreline change rates, and simple inundation of a static topography. These methods are based on assumptions that are either difficult to validate or too simplistic to account for the complex processes driving coastal change to be reliable for many real applications;

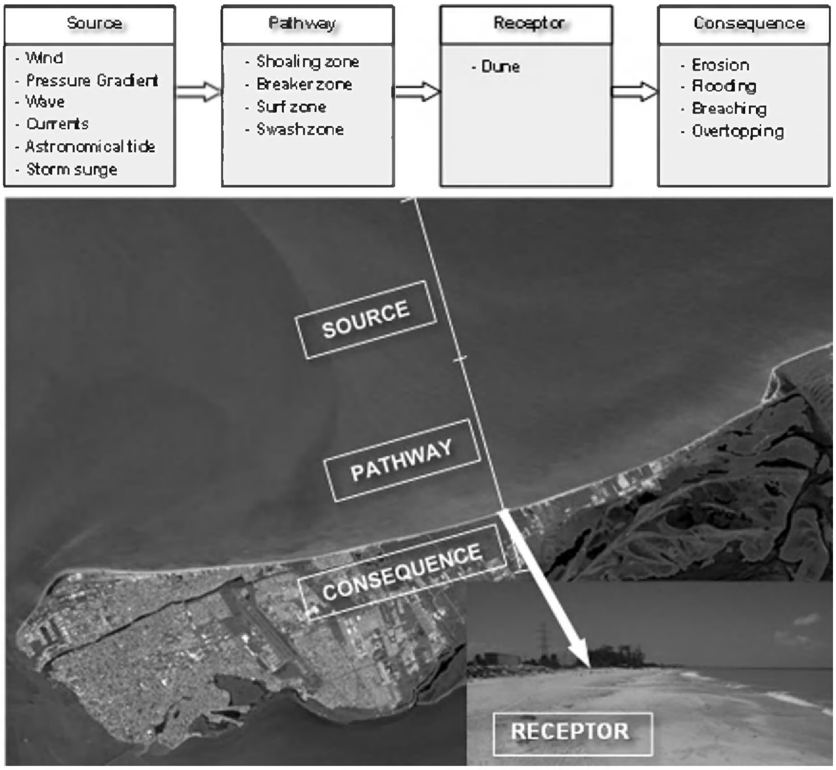


Figure 7. Scope of SPRC model in the coastal zone of Isla del Carmen (Mexico).

Figure 8. The risk triangle (modified from [80]).

thus, the ability of these methods to quantify the link between sea-level rise and shoreline change has been questioned by various authors [65].

It is worthwhile to mention the work developed by Felix et al. [82] that includes a risk analysis as a fundamental component of the general methodology proposed for the optimum management of a coastal stretch. The risk analysis is based on the appraisal of the consequences of hazardous events by using of a hedonic price method.

4 Numerical models involved in risk assessment

All the risk assessment approaches use numerical methods to reproduce and simulate the most possible processes involved in a risk scenario.The SPRC approach uses different models at each stage of the process, e.g.:

(i) Source: rainfall-runoff, climate models.
(ii) Pathway: hydrological and hydraulic models, failure models, morphological models.
(iii) Receptor: exposure data models.
(iv) Consequence: damage and other vulnerability models.

The research on coastal morphology has led to a number of new developments [21], these include:

(i) Stochastic model of beach plan shape variability.
(ii) Regional model for regional scale changes.
(iii) Rapid coastal evolution model.
(iv) Beach overwash and dune erosion models.

Shore zone evolution models have been developed during the past decades: nearshore hydrodynamics and sediment dynamics, coastal zone sediment budget, like the advanced circulation model (ADCIRC), the regional ocean modeling system (ROMS), and the shoreface translation (GEOMBEST) [65].

Examples of numerical models to predict wave induced breach initiation processes are BRES, Deich_P, SIMBA, Fire_bird, and HR BREACh models [83]. Flood inundation models combined with digital terrain models (e.g., digital elevation model) are used to describe the processes taking place in the flood plain.

The results of a flooding model are the water depth, the flow velocity and the increase in water depth variables; and are commonly presented in maps. Some examples of prominent flooding models are:

(i) "Integrated hydrodynamic and economic modeling of flood damage in The Netherlands" [84]: this is a model developed for the estimation of damage caused by floods. The model attempts to fill the gap in the international literature about integrated flood damage modeling and an integrated framework for the assessment of both direct hazard-induced damage and indirect economic damage, such as the interruption of production flows outside the flood affected area, as well as loss of life due to flooding.
(ii) Flood risk modeling to sea level rise scenarios related to climate change [42]: this model comprises three complementary flood risk assessment modules, respectively, focusing on the effects of flooding to economic, social, and ecological systems. The outputs of each module can be combined and integrated to arrive at an overall flood risk (see Fig. 9).
(iii) Flood inundation model developed as part of the TRAIT (tsunami risks, vulnerability, and resilience in the Phang Nga and Phuket Provinces, Thailand) project work, for the assessment of the local tsunami risk at the Andaman Sea Coast of Thailand [85]. The model includes a hazard analysis and a vulnerability analysis, which is integrated in an SPRC risk model as can be seen in Fig. 10.
The model comprises simulating tsunami generation, propagation, and inundation including the interaction of the tsunami with vegetation and buildings, and provides results for the inundation depth, velocity (flow dynamics), and expansion (the maximum inundation area). The model includes social, economic, and ecological vulnerability.

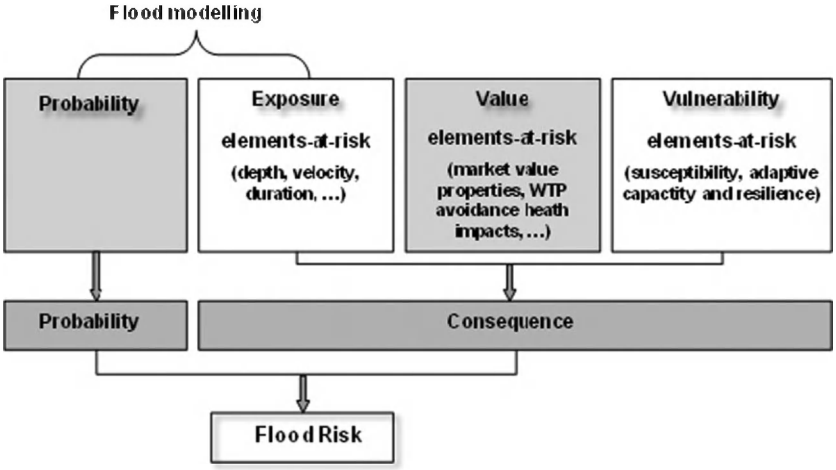


Figure 9. Components of the flood risk assessment framework (modified from [42]).

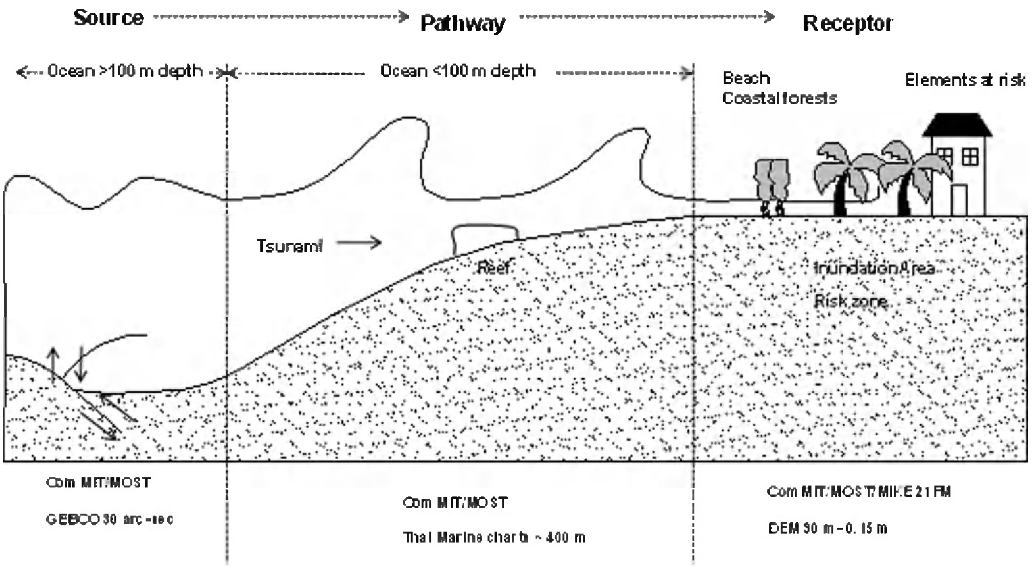


Figure 10. Sketch of flood inundation model for tsunami risk assessment (modified from [85]).

(iv) The dynamic interactive vulnerability assessment (DIVA) model version 2.0.2 is a global model developed to evaluate the potential risks, impacts, and costs of climate change. The DIVA model was run for Germany, The Netherlands, and the United Kingdom to identify the potential costs of sea-level rise under different climatic and socio-economic scenarios (IPCC SRES scenarios) from 2000 to 2100. CBAs were applied to decide upon based adaptation, full adaptation and no adaptation for the different scenarios modeled [86].

A model used as a support to the numerical estimation of coastal erosion hazards/risks is the CoSTAT GIS model. An example of its application is the quantitative assessment of coastal erosion susceptibility for emerged hazard/risks in Italy, which is expressed as the ratio between the value of sea-land boundary shift in the analyzed period (from time t_0 to t_1) and the beach emerged at time t_1 [87]. The application of this model is limited to sandy beaches.

Baquerizo and Losada [88] and Losada et al. [89] presented a methodology to predict the morphological evolution driven by wave action over the coastline, in a decadal scale; and the evaluation of the associated uncertainty. The methodology is based on the application of a one-line model with time dependent boundary conditions combined with a 1-D river model for non-permanent flux that allows to considering the sediments coming from river.

5 Particular case: Coastal risk studies developed in Mexico

The most relevant contribution for risk assessment in Mexico has been developed by the National Center for Disaster Prevention (CENAPRED) [90]. Since 2000 CENAPRED has been working on the Mexican Atlas of risk and hazard areas which aims to establish a national methodology to evaluate hydro-meteorological risks at coastal zones. The most recent publication on the topic is the basic guide for the Elaboration of State and Municipal Atlas of Risks and Hazards in 2006, where a methodology for the construction of flooding risk maps is described. This methodology can be summarized as follows:

(i) Identify coastal flooding hazards: this step is mostly focused on evaluating storm surge numerically.
(ii) Evaluate the vulnerability to flooding of dwellings: the physical vulnerability is set considering the material of construction of the walls and roofs; and the potential damage related to the flooding levels.
(iii) Draw the map of risk. CENAPRED [90] defines risk as the probability of occurrence of damage to people, communities or their goods as a consequence of the impact of natural phenomena, while the probability of occurrence of those phenomena is the threat. In a simple relation, risk can be represented as:

$$R = f(P, V, E) \tag{3}$$

where R is the risk, P the hazard, V the vulnerability, and E is the exposure.

Hazards are defined as the probability of occurrence of a potentially harmful phenomenon. Exposure is the number of persons, goods, and systems that could be damaged. Vulnerability refers to the strength or weakness of the exposed systems. Considering a specific return period, T, the risk can be expressed as:

$$R = CV_\mathrm{T}P_\mathrm{T}$$

where V_T is the vulnerability related to the return period, P_T the probability of occurrence of a certain event in the return period, and C is the value of the exposed goods. If several events are to be considered, the risk is:

$$R_\mathrm{j} = \sum_{i=1}^{n} C_\mathrm{j} P(i) \cdot V_\mathrm{j}(Y_\mathrm{i}) \tag{4}$$

where the subindex i stands for each return period considered and j refers to each system of interest; $P(i)$ and $V_\mathrm{i}(Y_\mathrm{i})$ are the hazard and vulnerability functions, respectively. From Eq. (4) each exposed system has a risk index defined as:

$$I_{R_j} = \frac{R_j}{C_{MAX}}$$

C_{MAX} is the highest value of the exposed systems.

I_{R_j} is high if $0.67 < I_{R_j} < 1.0$

I_{R_j} is medium if $0.33 < I_{R_j} < 0.67$

I_{R_j} is low if $0 < I_{R_j} < 0.33$

CENAPRED [90] defines two other indices one to evaluate the damage possibility of low cost dwellings due to wind and the second to evaluate social vulnerability to natural disasters.

Two recent studies were published regarding risk evaluation in climate change scenario:

González Turrubiates [91] defines flood risk as a function of physical risk and existing vulnerability, i.e.:

$$\mathrm{IRI_x} = \mathrm{IRFI}(1 + \mathrm{IVP}) \tag{5}$$

$\mathrm{IRFI_x}$, stands for physical risk index and it is obtained through descriptors of the territory and social damage; $\mathrm{IVP_x}$ is the existing vulnerability index which includes the exposure and susceptibility as well as socio-economic fragility and lack of resilience.

Based on a model of the OCDE, Seingier et al. [92] use indices to describe the risk to Mexican coasts in the case of an increase of sea level. The risk index is defined by a combination of a vulnerability index and the natural hazardness of coastal plains. This model includes demographic and socio-economic vulnerability. The coastal risk index, IRC, is expressed as:

$$\mathrm{IRC} = \sum(\mathrm{IPC}, \mathrm{IVC})$$

where the coastal hazardness, IPC, index is:

$$\mathrm{IPC} = \sum(\mathrm{SIPF}, \mathrm{SIPC});\ \mathrm{SIPF} = \sum(l, p, a);\ \mathrm{SIPC} = \sum(\mathrm{em})$$

SIPF is the index of physical hazardness, SIPC the index of climatologic hazardness, l the coastline length, p the percentage of the municipality corresponding to coastal plain, a the number of interior marine water bodies, and em is the frequency of meteorological events.

The application of the model by Seingier et al. [92], gives risk maps similar to the one shown in Fig. 11.

There are some on going studies in Mexico in relation to coastal risk among which it is worth to mention the following:

(i) "Flooding risk diagnosis for Campeche City" sponsored by Mexican body: Sedesol and the municipality of Campeche. This is mainly an analysis of the most relevant damage and the causes of it; the results are maps of registered flooding since 1769.
(ii) Hydro-meteorological hazards map, which is part of the Itsmo de Tehuantepec Regional Atlas [93].
(iii) Map of zones susceptible to flooding, which is part of the New Mexican Atlas [94].
(iv) Map of zones susceptible to natural disasters [95].

Finally, the importance of the advances already achieved regarding the characterization of hydro-meteorological hazards on the coast of Mexico must be highlighted. Some of these studies are:

(i) "Natural Hazard Atlas of the State of Campeche" [96].
(ii) "Storm surge induced by tropical cyclones" [97].
(iii) "Analysis of the storm surge hazard in the Gulf of Mexico" [98].
(iv) "Wave re-analysis in Mexico: 1948–2007" [99].

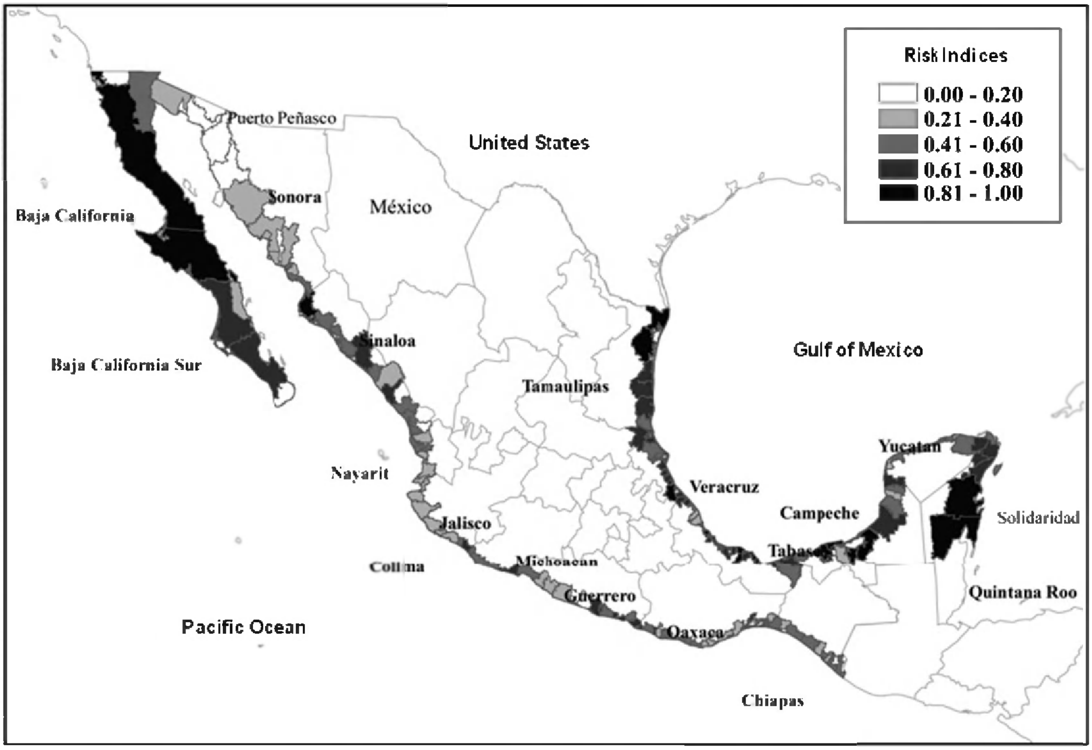


Figure 11. Risk index by municipality (modified from [92]).

6 Conclusions

Increasing public awareness of the devastating damage that natural phenomena can produce in coastal zones, the threat of climate change and the recognition of disaster prevention as a means to ensure social safety and welfare have led to the development of initiatives, tools, and models for hydro-meteorological risk assessment worldwide.

Risk assessment methodologies have been adapted to the needs of a wide range of decision makers, and the concept of risk has evolved to become more precise as methodologies are developed. Moreover, technological advances have made it possible to reduce the uncertainty involved in the risk evaluation process and, therefore, to improve the ability to take appropriate measures for the prevention and mitigation of risk.

Among the methodologies known as "traditional methodologies" are those purely qualitative that establish acceptable risk levels for society, according to the optimal balance between the risks and benefits associated with an activity (analysis of revealed preferences); those which set the preferred safety levels of society for each risk situation (analysis of expressed preferences); or those that focus on the factors that can be easily expressed in monetary terms (CBA). Those methodologies have been adapted to MCA to consider the increasing importance of social and environmental factors over time. A recent, innovative risk assessment approach is the SPRC model, which allows a better integration of social and environmental factors, and understanding of the physical processes taking place in the propagation and consequences of coastal flooding.

The interest in improving the precision of the results of a risk assessment approach has led to quantitative risk and vulnerability indices, being developed; a combination of the relevant economic, social, and environmental factors in each analysis area. However, at the moment, relatively few studies have obtained quantitative indices, and the application of these indices has often been limited to the unit of analysis for which they were obtained. Despite progress on the issue of hydro-meteorological risk assessment, a common methodology, with unified relevant criteria and parameters that allows the effective integration of risk analysis at all levels (municipal, local, state, national, and international) has not yet been obtained.

In México, the first steps in prevention have barely been taken, despite its extensive coastline and its vulnerability to tropical cyclones. The most important contribution to hydro-meteorological risk assessment has been conducted by the National Center of Disaster (CENAPRED), with the publication in 2006 of the "basic guidelines for the construction of a State and Municipal Atlas of Hazards and Risks". In that guide, still under construction, a methodology for risk assessment by storm surge is presented as well as the definition of several social and physical indices that have not yet been applied. In addition some studies related to climate change effects have been carried out, which define risk and vulnerability indices for the analysis of coastal flooding resulting from the predicted sea level rise. However, the validity of those indices is still being questioned because of the large number of descriptors used in some of them and the lack of consideration of relevant factors in others.

Acknowledgments

This publication is one of the results of the Regional Network Latin America of the global collaborative project "EXCEED – Excellence Center for Development Cooperation – Sustainable Water Management in Developing Countries" consisting of 35 universities and research centres from 18 countries on 4 continents. The authors highly acknowledge the support of German Academic Exchange Service DAAD for taking part in this EXCEED project.

The authors have declared no conflict of interest.

References

[1] J. van der Weide, A Systems View of Integrated Coastal Management, *Ocean Coastal Manage.* **1993**, *21*, 129–148.

[2] P. Tran, R. Shaw, Towards an Integrated Approach of Disaster and Environment Management: A Case Study of Thua Thien Hue Province, Central Viet Nam, *Environ. Hazards* **2007**, *7*, 271–282.

[3] J. E. Lamond, *PhD Thesis*, University of Wolverhampton, West Midlands, UK **2008**.

[4] A. Jha, J. Lamond, R. Bloch, N. Bhattacharya, A. López, N. Papachristodoulou, A. Bird, et al., *Five Feet High and Rising Cities and Flooding in the 21st Century*, World Bank Policy Research Working Paper 5648, The World Bank Group, Washington, DC **2011**.

[5] P. Vellinga, R. J. T. Klein, Climate Change, Sea Level Rise and Integrated Coastal Zone Management: An IPCC Approach, *Ocean Coastal Manage.* **1993**, *21*, 245–268.

[6] R. C. Ballinger, H. D. Smith, L. M. Warren, The Management of the Coastal Zone of Europe, *Ocean Coastal Manage.* **1994**, *22*, 45–85.

[7] A. Zerger, D. I. Smith, G. J. Hunter, S. D. Jones, Riding the Storm: A Comparison of Uncertainty Modelling Techniques for Storm Surge Risk Management, *Appl. Geogr.* **2002**, *22*, 307–330.

[8] J. Duxbury, S. Dickinson, Principles for Sustainable Governance of the Coastal Zone: In the Context of Coastal Disasters, *Ecol. Econ.* **2007**, *63*, 319–330.

[9] AU IPCC, *Workshop Report of the Intergovernmental Panel on Climate Change Workshop on Sea Level Rise and Ice Sheet Instabilities* (Eds.: T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. Allen, P. M. Midgley), IPCC Working Group I Technical Support Unit, Bern **2007**.

[10] M. El-Raey, Vulnerability Assessment of the Coastal Zone of the Nile Delta of Egypt, to the Impacts of Sea Level Rise, *Ocean Coastal Manage.* **1997**, *37 (1)*, 29–40.

[11] R. J. Nicholls, F. M. J. Hoozemans, M. Marchand, Increasing Flood Risk and Wetland Losses due to Global Sea-level Rise: Regional and Global Analyses, *Global Environ. Change* **1999**, *9*, 69–87.

[12] A. Magnan, B. Garnaud, R. Billé, F. Germenne, I. S. Hallegatte, *The Future of the Mediterranean from Impacts of Climate Change to Adaptation Issues*, IDDRI, Paris, France **2009**.

[13] J. Hofstede, Climate Change and the Need for Integrated Coastal Risk Management in the Baltic Sea, in *Global Change and Baltic Coastal Zones* (Eds.: G. Schernewski, J. Hofstede), Coastal Research Library Series, Springer, Heidelberg **2011**, pp. 93–102.

[14] The Government Office for Science, *Foresight International Dimensions of Climate Change, Final Project Report*, The Government Office for Science, London **2011**.

[15] Environmental European Commission, Recommendation of the European Parliament and of the Council of 30 May 2002 Concerning the Implementation of Integrated Coastal Zone Management in Europe, *Off. J. Eur. Commun.* **2002**, *148*, 22–27.

[16] M. Papathoma, D. Dominey-Howes, Tsunami Vulnerability Assessment and Its Implications for Coastal Hazard Analysis and Disaster Management Planning, Gulf of Corinth, Greece, *Nat. Hazards Earth Syst. Sci.* **2003**, *3*, 733–747.

[17] Defra/Environment Agency, *Best Practice in Coastal Flood Forecasting*, R&D Technical Report FD2206/TR1; HR Wallingford Report TR 132, DEFRA, London, UK **2004**.

[18] A. Werritty, D. Houston, T. Ball, A. Tavendale, A. Black, *Exploring the Social Impacts of Flood Risk and Flooding in Scotland*, Scottish Executive, Edinburgh **2007**.

[19] A. Kazmierczak, J. Handley, *The Vulnerability Concept: Use Within GRaBs*, School of Environment and Development, University of Manchester, Manchester, UK **2011**.

[20] S. Narayan, S. Hanson, R. Nicholls, D. Clarke, Use of the Source–Pathway–Receptor-Consequence Model in Coastal Flood Risk Assessment, in *European Geosciences Union General Assembly*, Copernicus Publisher, Vienna **2011**.

[21] FLOODsite, *Integrated Flood Risk Analysis and Management Methodologies*, FLOODsite EU Integrated Project, Sixth Framework Programme, European Community, Brussels **2004–2009**.

[22] THESEUS, Flood and erosion maps at present conditions, *THESEUS Deliverable ID1.3*, European Commission, Bologna, Italy **2011**.

[23] M. G. Morgan, M. Henrion, in *Vulnerability, Risk and Adaptation: A Conceptual Framework* (Ed.: N. Brooks), Working Paper 38, Tyndall Centre for Climate Change Research, Norwich **2003**.

[24] Department N of Humanitarian Affairs, *Internationally Agreed Glossary of Basic Terms Related to Disaster Management*, Relief Web Report, UN Department of Humanitarian Affairs, Geneva **1992**.

[25] J. Adams, in *Vulnerability, risk and adaptation: A conceptual framework* (Ed.: N. Brooks), Working Paper 38, Tyndall Centre for Climate Change Research, Norwich **2003**.

[26] I. Kelman, *Defining Risk*, FloodRiskNet Newsletter **2003**, *2*, 6–8.

[27] S. de La Cruz-Reyna, in *Defining Risk* (Ed.: I. Kelman), FloodRiskNet Newsletter 2003, 2, 6–8.

[28] K. Smith, in *Defining Risk* (Ed.: I. Kelman), FloodRiskNet Newsletter 2003, 2, 6–8.

[29] P. Stenchion, *Defining Risk* (Ed.: I. Kelman), FloodRiskNet Newsletter 2003, 2, 6–8.

[30] K. Granger, T. Jones, M. Leiba, G. Scott, in *Defining Risk* (Ed.: I. Kelman), FloodRiskNet Newsletter 2003, 2, 6–8.

[31] SO/EC, in *Language of Risk – Project Definitions*, FLOODsite EU Integrated Project, Research Report T32-04-01, European Community, Brussels **2005**.

[32] D. Crichton, *Urban Flood Risk Management – A Tool for Integrated Flood Management*, (WMO/GWP Associated Programme on Flood Management), Flood Management Tools Series, World Meteorological Organisation, Geneva **2008**.

[33] K. Thywissen, *Components of Risk, A Comparative Glossary*, UNU Institute for Environment and Human Security, Bonn, Germany **2006**.

[34] N. Brooks, *Vulnerability, Risk and Adaptation: A Conceptual Framework*, Working Paper 38, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich **2003**.

[35] PCC, in *Vulnerability, Risk and Adaptation: A Conceptual Framework* (Ed.: N. Brooks), Working Paper 38, Tyndall Centre for Climate Change Research, Norwich **2003**.

[36] B. Gouldby, P. Samuels, *Language of Risk – Project Definitions*, Floodsite Project Report T32-04-01, FLOODsite Consortium, Oxfordshire, UK **2005**.

[37] R. Wallingford, in *Language of Risk – Project Definitions*, FLOODsite EU Integrated Project, Research Report T32-04-01, European Community, Brussels **2005**.

[38] B. Gouldby, P. Samuels, in *Language of Risk – Project Definitions*, FLOODsite EU Integrated Project, Research Report T32-04-01, European Community, Brussels **2005**.

[39] Helm, in *Defining Risk* (Ed.: I. Kelman), FloodRiskNet Newsletter 2003, 2, 6–8.

[40] Safecoast, *Coastal Flood Risk and Trends for the Future in the North Sea Region, Synthesis Report*, Safecoast, The Hague **2008**.

[41] D. Bellomo, *Flood Map Modernization and FEMA Levee Policy*, FEMA – U.S. Department of Homeland Security, Hyattsville, MD **2008**.

[42] ADAPT, *Towards an Integrated Decision Tool for Adaptation Measures – Case Study: Floods*, Final Report (Phase I), Belgian Science Policy, ADAPT, Brussels Belgium **2008**.

[43] FLOODsite, in *Language of Risk – Project Definitions*, FLOODsite EU Integrated Project, Research Report T32-04-01, European Community, Brussels 2005.

[44] Association of State Flood Plain Managers, *Use of Benefit/Cost Analysis for FEMA Programs*, Association of State Flood Plain Managers, Madison, WI **2007**.

[45] R. J. Tkach, S. P. Simonovic, A New Approach to Multi-criteria Decision Making in Water Resources, *J. Geogr. Inf Decis. Anal.* **1997**, *1 (1)*, 25–43.

[46] C. A. Bana, P. A. da Silva, F. N. Correia, Multicriteria Evaluation of Flood Control Measures: The Case of Ribeira do Livramento, *Water Resources Management*, Kluwer Academic Publishers, Netherlands **2004**, 18, 263–283.

[47] R. Brouwer, R. van Ek, Integrated Ecological, Economic and Social Impact Assessment of Alternative Flood Control Policies in The Netherlands, *Ecol. Econ.* **2004**, *50*, 1–21.

[48] RPA – Risk and Policy Analysts Ltd., *Evaluating a Multi-criteria Analysis (MCA) Methodology for Application to Flood Management and Coastal Defense Appraisals*, R&D Technical Report, DEFRA, London **2004**.

[49] FLOODsite, *GIS-based Multicriteria Analysis as Decision Support in Flood Risk Management*, FLOODsite EU Integrated Project, Research Report T10-07-07, European Community, Brussels **2007**.

[50] M. H. Faber, M. G. Stewart, Risk Assessment for Civil Engineering Facilities: Critical Overview and Discussion, Reliab, *Eng. Syst. Saf.* **2003**, *80*, 173–184.

[51] FEMA, *Multi Hazard – Identification and Risk Assessment, The Cornerstone of the National Mitigation Strategy*, Federal Emergency Management Agency, New York **1997**.

[52] F. Anders, S. Kimball, R. Dolan, *Multi Hazard – Identification and Risk Assessment, The Cornerstone of the National Mitigation Strategy*, Federal Emergency Management Agency, New York **1997**.

[53] R. A. Davidson, K. B. Lambert, Comparing the Hurricane Disaster Risk of U.S. Coastal Counties, *Nat. Hazards Rev.* **2001**, *2 (3)*, 132–142.

[54] Hyogo Framework for Action (HFA) 2005-2015, *Building The Resilience of Nations and Communities to Disasters, International Strategy for Disaster Reduction*, United Nations – Mid-Term Review, UNISDR, Geneva **2011**.

[55] J. Preuss, G. T. Hebenstreit, Integrated Tsunami-hazard Assessment for a Coastal Community, Grays Harbor, Washington, in *Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest*, Vol. 2 (Eds.: A. Rogers, T. Walsh, W. Kockelman, G. Priest), U.S. Government Printing Office, Washington **1998**, pp. 517–536.

[56] T. Toppozada, G. Borchardt, W. Haydon, M. Peterson, R. Olson, H. Lagorio, T. Anvik, *Multi Hazard – Identification and Risk Assessment, The Cornerstone of the National Mitigation Strategy*, Federal Emergency Management Agency, New York **1997**.

[57] P. Ricketts, National Policy and Management Responses to the Hazard of Coastal Erosion in Britain and the United States, *Appl. Geogr.* **1986**, *6*, 197–221.

[58] A. V. Hedge, V. R. Reju, Development of Coastal Vulnerability Index for Mangalore Coast, India, *J. Coastal Res.* **2007**, *23 (5)*, 1106–1111.

[59] V. Gornitz, P. Kanciruk, Assessment of Global Coastal Hazards from Sea-level Rise, *Proceedings of the Sixth Symposium on Coastal and Ocean Management*, ASCE, Charleston **1989**, pp. 1345–1359.

[60] E. A. Pendleton, J. A. Barras, S. J. Williams, D. C. Twichell, *Coastal Vulnerability Assessment of the Northern Gulf of Mexico to Sea-Level Rise and Coastal Change*, U.S. Geological Survey, Reston, VA **2010**.

[61] R. C. Daniels, V. N. Gornitz, A. J. Mehta, S. C. Lee, R. M. Cushman, *Multi Hazard – Identification and Risk Assessment, The Cornerstone of the National Mitigation Strategy*, Federal Emergency Management Agency, New York **1997**.

[62] V. M. Gornitz, T. W. White, *Multi Hazard – Identification and Risk Assessment, The Cornerstone of the National Mitigation Strategy*, Federal Emergency Management Agency, New York **1997**.

[63] V. M. Gornitz, R. C. Daniels, T. W. White, K. R. Birdwell, *Multi Hazard – Identification and Risk Assessment, The Cornerstone of the National Mitigation Strategy*, Federal Emergency Management Agency, New York **1997**.

[64] R. Dal-Cin, U. Simeoni, A Model for Determining the Classification, Vulnerability and Risk in the Southern Coastal Zone of the Marche (Italy), *J. Coastal Res.* **1994**, *10*, 18–29.

[65] G. Alexandrakis, A. Karditsa, S. Poulos, G. Ghionis, N. A. Kampanis, Vulnerability Assessment for to Erosion of the Coastal Zone to a Potential Sea Level Rise: The Case of the Aegean Hellenic Coast, in *Environment Systems* (Ed.: A. Sydow), Encyclopedia of Life Support Systems (EOLSS), EOLSS Publishers, Oxford **2009**.

[66] C. Szlafsztein, *PhD Thesis*, University of Kiel, Kiel, Germany **2003**.

[67] M. El-Raey, Y. Fouda, S. Nasr, GIS Assessment of the Vulnerability of the Rosetta Area, Egypt to Impacts of Sea Rise, *Environ. Monit. Assess.* **1997**, *47*, 59–77.

[68] P. Hughes, G. B. Brundrit, An Index to Assess South Africa's Vulnerability to Sea-level Rise, *S. Afr. J. Sci.* **1992**, *88*, 308–311.

[69] D. King, Uses and Limitations of Socioeconomic Indicators of Community Vulnerability to Natural Hazards: Data and Disaster in Northern Australia, *Nat. Hazards* **2001**, *24 (2)*, 147–156.

[70] A. Fekete, Validation of a Social Vulnerability Index in Context to River-floods in Germany, *Nat. Hazards Earth Syst. Sci.* **2009**, *9*, 393–403.

[71] M. Kaplan, F. G. Renaud, G. Lüchters, Vulnerability Assessment and Protective Effects of Coastal Vegetation during the 2004 Tsunami in Sri Lanka, *Nat. Hazards Earth Syst. Sci.* **2009**, *9*, 1479–1497.

[72] E. Evans, R. Ashley, J. Hall, E. Penning-Rowsell, A. Saul, P. Sayers, C. Thorne, et al., *Future Flooding, Scientific Summary*, Vol. I, Future Risks and Their Drivers, Foresight, London **2004**.

[73] H. Oumeraci, J. Jensen, G. Gönnert, E. Pasche, A. Kortenhaus, M. Naulin, T. Wahl, et al., Flood risk analysis for a megacity: The German XtremRisK project, in *Proceedings of the Conference on Road Map towards a Flood Resilient Urban Environment*, Paris **2009**.

[74] M. Naulin, A. Kortenhaus, H. Oumeraci, Failure Probability of Flood Defence Structures/Systems in Risk Analysis for Extreme Storm Surges, in *32nd International Conference on Coastal Engineering (ICCE)*, Shanghai **2010**.

[75] P. Sayers, I. Meadowcroft, RASP – A hierarchy of risk-based methods and their application, *Defra Flood and Coastal Management Conference*, York, UK **2005**.

[76] A. Burzel, D. Dassanayake, M. Naulin, A. Kortenhaus, H. Oumeraci, T. Wahl, C. Mudersbach, Integrated Flood Risk Analysis for Extreme Storm Surges (XTREMRISK), *32nd International Conference on Coastal Engineering (ICCE)*, Shanghai **2010**.

[77] J. W. Hall, E. P. Evans, E. C. Penning-Rowsell, P. B. Sayers, C. R. Thorne, A. J. Saul, Quantified Scenarios Analysis of Drivers and Impacts of Changing Flood Risk in England and Wales: 2030-2100, Global Environmental Change Part B, *Environ. Hazards* **2003**, *4*, 51–64.

[78] D. Crichton, C. Mounsey, How the Insurance Industry will Use Its Flood Research, in *Proceedings of the Third MAFF Conference of Coastal and River Engineers*, 1997, pp. 131–134.

[79] D. Crichton, The risk triangle, in *Natural Disaster Management* (Ed.: J. Ingleton), Tudor Rose, London **1999**, 102–103.

[80] D. Crichton, *The Implications of Climate Change for the Insurance Industry*, Building Research Establishment, Watford **2001**.

[81] K. Granger, Quantifying Storm Tide Risk in Cairns, *Nat. Hazards* **2003**, *30*, 165–185.

[82] A. Felix, A. Baquerizo, M. A. Losada, J. M. Santiago, Decision making under risk in the management of a stretch of the coast, *Second International Conference on Coastal Zone Engineering and Management (Arabian Coast 2010)*, Muscat, Oman **2010**.

[83] FLOODsite, Modelling Breach Initiation and Growth-Executive Summary, *FLOODsite EU Integrated Project, Research Report T06-08-01*, European Community, Brussels **2009**.

[84] S. N. Jonkman, M. Bockarjova, M. Kok, P. Bernardini, Integrated Hydrodynamic and Economic Modelling of Flood Damage in The Netherlands, *Ecol. Econ.* **2008**, *66*, 77–90.

[85] G. Kaiser, H. Römer, D. Arp, H. Sterr, R. Ludwig, Use of High Resolution Geodata for Inundation Modelling as Part of a Tsunami Risk Assessment in Thailand, *Coastline Rep.* **2010**, *16*, 25–34.

[86] H. Munderloh, Costs of Sea-level Rise under Different Climatic and Socio-economic Scenarios: An Application of the DIVA Model, *Coastline Rep.* **2010**, *16*, 101–103.

[87] E. Valpreda, U. Simeoni, Assessment of Coastal Erosion Susceptibility at the National Scale: The Italian Case, *J. Coastal Conserv.* **2003**, *9*, 43–48.

[88] A. Baquerizo, M. A. Losada, Human Interaction with Large Scale Coastal Morphological Evolution. An Assessment of the Uncertainty, *Coastal Eng.* **2008**, *55*, 569–580.

[89] M. A. Losada, A. Baquerizo, M. Ortega-Sánchez, A. Ávila, Coastal Evolution, Sea Level, and Assessment of Intrinsic Uncertainty, *J. Coastal Res.* **2011**, *59*, 218–228.

[90] CENAPRED (Centro Nacional de Prevención de Desastres), Guía Básica para la Elaboración de Atlas Estatales y Municipales de Peligros y Riesgos, *Series: Atlas Nacional de Riesgos*, CENAPRED (Centro Nacional de Prevención de Desastres), Ciudad, México **2006**.

[91] D. M. González Turrubiates, Valoración y Gestión del Riesgo por Inundaciones en Municipios Costeros (Una aproxImación Con Base en Indicadores), in *Cambio Climático en México: Un Enfoque Costero y Marino* (Eds.: E. Rivera-Arriaga, I. Azuz-Adeath, L. Alpuche Gual, G. J. Villalobos-Zapata), Universidad Autónoma de Campeche, CETYS – Universidad, Gobierno del Estado de Campeche **2010**, pp. 591–606.

[92] G. Seingier, I. Espejel, J. L. Fermán, O. Delgado, Vulnerabilidad de las Poblaciones Costeras Ante la Peligrosidad Natural, Enfoque Estatal y Municipal, in *Cambio Climático en México: Un Enfoque Costero y Marino* (Eds.: E. Rivera-Arriaga, I. Azuz-Adeath, L. Alpuche Gual, G. J. Villalobos-Zapata,), Universidad Autónoma de Campeche, CETYS – Universidad, Gobierno del Estado de Campeche **2010**, pp. 669–688.

[93] M. T. Sánchez-Salazar, O. Oropeza Orozco, *Atlas Regional del Istmo de Tehuantepec*, Instituto de Geografía, Universidad Nacional Autónoma de México, México **2003**.

[94] O. Oropeza, C. Enríquez, Zonas Susceptibles a Inundaciones, in *Nuevo Atlas Nacional de México*, Sección Naturaleza, Instituto de Geografía, Universidad Nacional Autónoma de México, México **2007**.

[95] G. Palacio Aponte, et al., Carta Zonas susceptibles a desastres por fenómenos naturales, in *Atlas Nacional de México*, Sección Medio Ambiente, Instituto de Geografía, Universidad Nacional Autónoma de México, México **1992**.

[96] G. Posada, B. E. Vega, G. Villalobos, R. Silva, G. Durán, G. Ruiz, R. Zetina, et al., Atlas de Peligros Naturales del Estado de Campeche, *Jaina* **2009**, *20 (2)*, 49–56.

[97] E. G. Bautista, *Marea de Tormenta Inducida por Ciclones Tropicales*, Facultad de Ingeniería, Universidad Nacional Autónoma de México, México **2005**.

[98] G. Durán, *Análisis del Peligro por Marea de Tormenta en el Golfo de México*, Facultad de Ingeniería, Universidad Nacional Autónoma de México, México **2010**.

[99] G. D. Rivillas, *Re-análisis de Oleaje Para México: 1948–2007, Facultad de Ingeniería*, Universidad Nacional Autónoma de México, México **2008**.