Universitat Politécnica de Catalunya

Laboratori d’ Enginyeria Marítima

Coastal Vulnerability to Storms in the Catalan Coast

Memoria presentada por

Ernesto Tonatiuh Mendoza Ponce

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Director:

José Antonio Jiménez Quintana

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Chapter 5

Coastal Vulnerability[c]

5.1 Introduction

As mentioned before, the vulnerability analysis was centred in the transversal dynamics; although the longshore dynamics do exist during the storm events, the cross-shore transport is intrinsic to high energy events and is of greater magnitude.

Once having characterized the response of the beach and identified the main processes, the next step was to introduce the concept of coastal vulnerability which is done in the first section. The next section consisted in defining the nature of indicators and indexes. Subsequently the application of vulnerability indicators in terms of flooding and erosion is described and finally the merging of these two indicators in order to produce the coastal vulnerability index is given.

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[c] Edited and extended version of MENDOZA, E. T. & JIMÉNEZ, J. A. (2008) Regional vulnerability analysis to storm impacts in the Catalan coast, *Proceedings of the Institution of Civil Engineers: Maritime Engineering,* (in review).

5.1.1 Vulnerability

In this work, coastal vulnerability is defined as the potential of a coastal system to be harmed by the processes of flood and/ or erosion caused by coastal storms and its assessment should let coastal managers to anticipate potential damages along the coast to a given agent and to decide where to concentrate efforts in preventing, fighting or counteracting their consequences. This potentiality has originated numerous approaches to assess coastal vulnerability from different standpoints, objectives, processes and spatial temporal scales (see McFaddden *et al*). Here the problem is approached from a partial and specific standpoint, the assessment of coastal vulnerability to the impact of storms. Furthermore, only the physical vulnerability is examined, i.e. without assessing their effects on socio-economic and/ or environmental characteristic of the coast.

5.1.2 Indicators

Indicators have become a state of the art tool in many fields such as environmental assessment, economy, sustainable development, vulnerability assessment, etc.

As a result of this diversity of applications, the different topics involved and the different approaches and scales of application, it is hard to produce a single definition of the term indicator. Different definitions of indicators for environmental assessment given in the literature are compiled in Gallopín (1997) and illustrate the different existing approaches. An indicator has been defined as a variable; a parameter; a measure; a statistical measure; a proxy for a measure; etc. We can also find different definitions such as a variable hypothetically linked to the variable studied which itself cannot be directly observed; a measure that summarises information relevant to a particular phenomenon, or a value derived from parameters, which points or provides information about or describes the state of a phenomenon or environment with a significance extending beyond that directly associated with a parameter value; a measure of a system behaviour in terms of meaningful and perceptible attributes.

Taking into account these different perspectives and the final goal of their use, in general terms, an indicator can be defined as a sign that relays a complex message in a simple and useful manner (Gallopín, 1997; Kurtz *et al*., 2001). CoastView (2002) defines a coastal sate indicator as: A reduced set of parameters that can simply, adequately and quantitatively describe the dynamic-state and evolutionary trends of a coastal system.

The indicators should provide three main functions: simplification, quantification and communication. In this sense, they are becoming an essential part of the communication process between scientists and managers and a way to reduce risk of failure of such a process. Indicators are increasingly recognized as a useful tool in many frameworks such as policy, sustainability, environmental analysis and they are considered to be crucial due to the important role they play in the decision making cycle (Gutiérrez-Espeleta, 1998).

Criteria to define indicators

The use of the indicator basically depends in an appropriate selection. There is a wide experience on environmental indicators (see Kelly & Harwell, 1990; Cairns *et al*., 1993; Pykh *et al*., 1999; Dale & Beyeler, 2001) where it is possible to identify some basic criteria that the coastal state indicators must be useful and consistent. Next there is a brief explanation about the criteria according to Jiménez & van Koningsveld (2002) :

Relevance, the proposed indicator must be conceptually related with the coastal function of interest. Easy to measure, the indicator should be straightforward and relatively inexpensive to be measured. Sensitive, the indicator should be responsive to stresses in the system. Have a known response to disturbances, anthropogenic stresses, and changes over time. Anticipatory, a change in the indicator should be measurable before substantial change in the targeted objective occurs. Integrative, the full group of indicators provides a measure of the key gradients across the analyzed change in the system state in time and space.

Framework for indicators

The usefulness of the indicators to be developed can be increased by putting them into a framework in which main relationships between human activity and environment are considered since one of their major functions is to link the system functioning to management policies. There are numerous models of such relationships (Hodge, 1997), being the most common (and useful) approaches based on the concepts of environmental stress and environmental response.

In most cases, they are derived from the stress-response framework proposed by Rapport & Friend (1979) to be applied to ecosystems. They have been adopted and adapted by many agencies for environmental and sustainable development assessments (see OECD, 1999; UNDSD, 2001). One of the most used adaptations of this stress response approach is the Pressure − State − Response (PSR) model, which in some cases is also referred as the Driving Force-State-Response framework.

Due to the nature of this study which is considering a specific case of environmental assessment, we have used the PSR model which is the most used framework for this kind of analysis. This structure helps to analyze the interactions between environment pressures, the state of the environment and environment responses and based on the concept of causality (see Figure 5.1.1): Coastal storms exert pressures on the beach environment and change it (state) and the beach responds to these changes (erosion-flood).

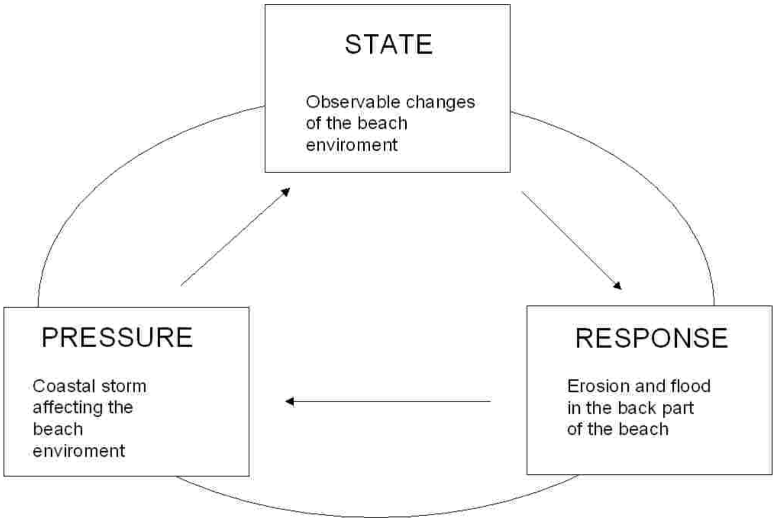

Figure 5.1.1: The Pressure-State-Response model.

The PSR is a powerful approach for environmental assessment although the difficulty with this approach is the consideration of other elements such as coastal processes are affected by human-induced and natural stresses and any management action (policy response) on the system will represent an additional stress on some components of it.

The great majority of studies involving indicators and coastal environments have been developed for aggregated analysis and vulnerability assessment at large scales (see Kaly *et al.*, 1999). At small scale the majority of research has been based in the use of geoindicators (Berger, 1997; Bush *et al.*, 1999; Morton, 2002). In some cases, these approximations are somewhat based in qualitative aspects, that although do not explicitly include information about coastal dynamics and coastal evolution they allow to make a first estimate of the state of the system.

When the indicators are developed and applied to coastal problems, they must help the managers in the decision making in respect to one or various coastal functions of interests (see Jiménez & van Koningsveld, 2002). The coastal manager expects a value that bears in mind the aggregation of different indicators with the same impacts. This ”value” obtained through the aggregation of a group of indicators is generally called index. Ideally, the aggregation method should be based in the knowledge of the part developed by each indicator within the objective function.

Of the existing aggregation methods, one of the most realistic is the development of conceptual models, in which the coastal function of our interest is modelled in a simple manner relating different indicators involved through relations which simulate the interactions which are present in reality.

This chapter deals with the function of the beach as a buffer of the supplied energy by storms, which act as a protection agent of the uses and resources situated on and in the back part of the beach. This implies the measurement of this function taking on account the two aspects estimated in see section 4 (i) flood potential and (ii) erosion potential induced by a storm.

Taking on account these two functions, there are just a few that take into account the effect of sea level change during storms (Kriebel & Dalrymple, 1995; Kriebel *et al*., 1997; Ruggiero *et al*., 2001; Zhang *et al*., 2001). The majority of the existing indicators are mainly focused on quantifying the erosion potential of the beach without considering the back part. Some of these indicators have been developed for barrier coasts (Morgan & Stone, 1985; Sánchez-Arcilla & Jiménez, 1994; Morton, 2002), or for dune vulnerability (Sallenger, 2000; Garcia-Mora *et al*., 2001; Judge *et al*., 2003).

5.2 Methodology to obtain coastal vulnerability index

5.2.1 General indicators

This section presents the development of the coastal vulnerability index which quantifies the role of the beach as a protection buffer, giving emphasis to the assessment of vulnerability to coastal infrastructure in sandy beaches.

The first two parts define the flood vulnerability indicator and the erosion vulnerability indicator in a disaggregated manner in order to determine to which vulnerability the beach is more susceptible to. The third part describes the aggregation of both indicators to obtain the coastal vulnerability index in the Catalan coast.

Both vulnerability indicators were obtained using three kinds of indicators: first order -directly measured-, second order -obtained through data analysis- and third order -derived from the use of predictive models-.

The last part explains the index which has been obtained aggregating two indicators which are based on two conceptual models which reproduce in a simple manner the interactions between the variables and the key processes that control the response of the beach under the impact of storms and that will determine the integrity of existing infrastructure on the beach.

5.2.2 Flood vulnerability indicator

The first indicator is defined with a simple conceptual model: The emerged beach must present a height high enough before the impact of a storm to withstand the induced sea level change and protect the back part of the beach from flooding. In the case that this does not happen, we can say that the beach has failed. The scheme can be seen in Figure 5.2.2.

Effective beach level This is a first order indicator that is defined as the vertical distance between the berm crest and the MWL. In order to be considered in a precise form in the analysis, it must be measured in an appropriate time and spatial scale the higher the frequency of measure the better the alarm capacity to accurately evaluate the second or third order indicators based on their analysis.

Storm water level This indicator characterizes the potentially floodable beach contour under the impact of a determined storm. It comprises a third order indicator (run up) and a second level indicator (storm surge) which combined introduces the different impacts seen in section 4.2.

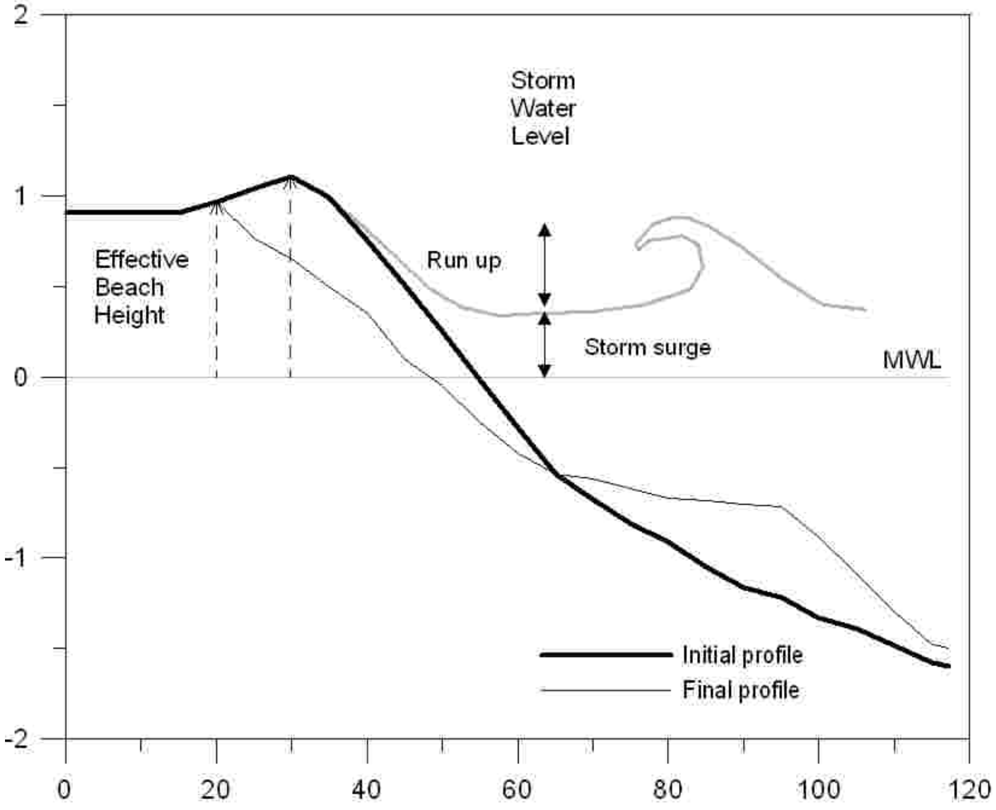

Figure 5.2.2: Scheme of the flood protection function of the beach during storms.

The flood vulnerability indicator is defined in function of a flood intermediate parameter *FIP*, which is defined for each storm class in equation (5.2.1).

$$FIP = \frac{\left(R_u + \alpha\sigma_{Ru}\right) + \xi}{BH} \tag{5.2.1}$$

Where R_u is the representative run up of the corresponding class for the given beach type, σ_{Ru} is the standard deviation of the run-up estimated for all storms within the class. α is a factor to account the level of the desired safety, as the standard deviation value increases, so will the safety level. In the case of this study, a value of $\alpha = 1$ standard deviation is used. ξ is the mean representative storm surge of the storm class (see Table 4.2.1), the standard deviation value for this parameter was not taken into account due to the large variability that each class presented, due to a shortage in the data series, but still is valid for a starting point. *BH* is the max height of the beach/dune crest.

Once *FIP* is known, the component of the vulnerability associated to inundation, the Flood Vulnerability Index ***FVI*** is calculated following the rule represented in Figure 5.2.3 in a scale from 0 to 1. This functional relation assigns zero vulnerability to situations where the total water level of the storm class is less or equals half of the beach/dune crest ($FPI \leq 0.5$).

On the other side, it assigns the maximum vulnerability (1) to situations where the total water level is equal or exceeds the beach/dune crest ($FPI \geq 1$). Between these two situations the vulnerability linearly increases as a function of the *FPI* value. Finally, a qualitative 5-class scale has been defined ranging from very low to very high vulnerabilities by taking intervals of 0.2 units in ***FVI*** (Figure 5.2.3).

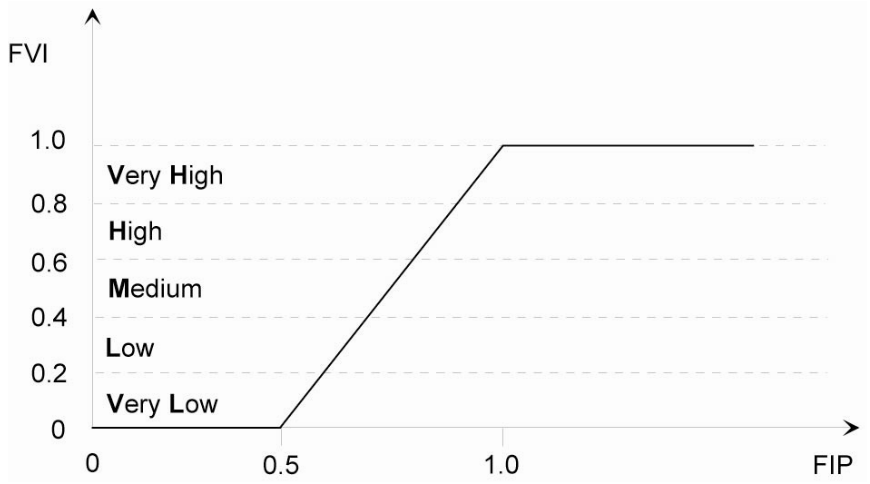

Figure 5.2.3: Functional relationship adopted for the flood vulnerability index.

It has to be emphasized that this linear model has been selected by simplicity. In the case that existing data should support a non linear dependence this model could be easily adapted.

5.2.3 Erosion vulnerability indicator

In the case of the erosion vulnerability a similar approach was applied to obtain the indicator: The emerged beach must present a wide enough beach before the impact of a storm so after it hits it will still protect the structures on the back part of the beach. In the case that during the storm the beach width disappears, we can say that the beach has failed as a protection agent (see Figure 5.2.4). This indicator is based on the one developed by Valdemoro (2005).

Effective beach width This is a first order indicator that is defined as the distance between the infrastructure or feature of interest and the water line. In order to be considered in a precise form in the analysis, it must be measured in an appropriate time and spatial scale the higher the frequency of measure the better the alarm capacity to accurately evaluate the second or third order indicators based on their analysis.

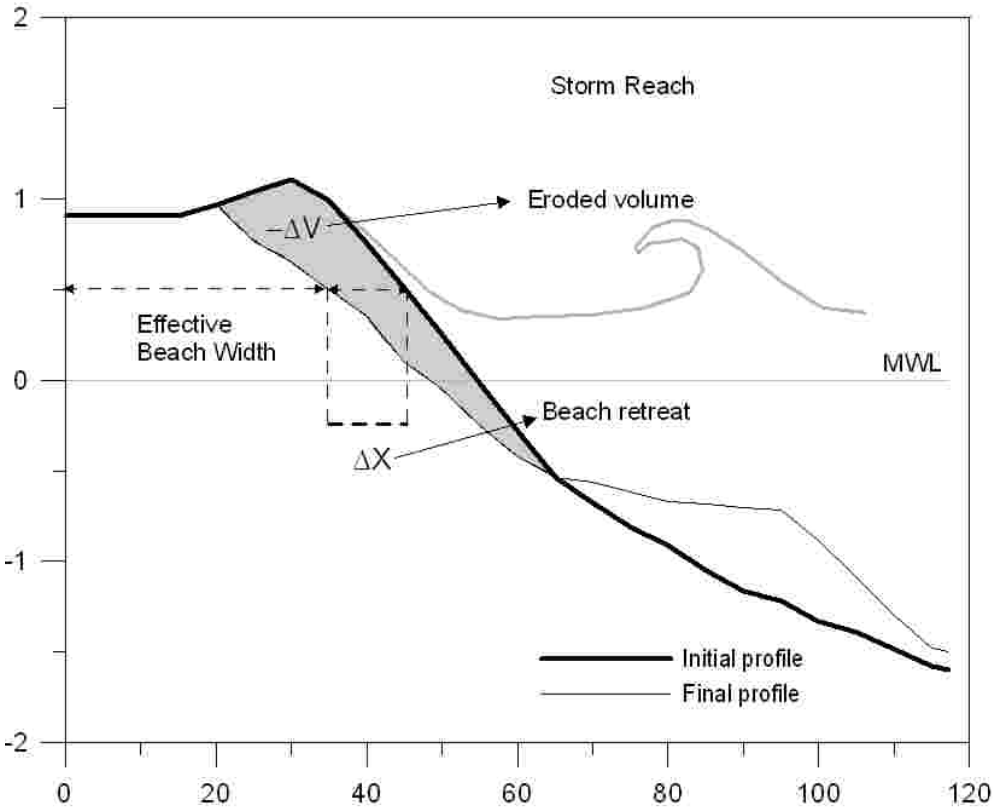

Figure 5.2.4: Scheme of the erosion protection function of the beach during storms.

Storm reach This third order indicator characterizes the potentially erodable beach width under the impact of a determined storm. This indicator introduces the different impacts seen in section 4.3, since it has been derived from a model; it has been validated with a robust model (see section 4.3.1).

The erosion vulnerability indicator is defined as a function of an erosion intermediate parameter (*EIP*) which is defined for each storm class in equation (5.2.2).

$$EIP = \frac{\Delta X + \alpha\sigma\left(\Delta X\right)}{BW} \tag{5.2.2}$$

Were ΔX is the representative beach retreat of the corresponding class for the given beach type, σ is the standard deviation of the estimated beach retreat for all storms within the class in this case the beach retreat which was determined at half of the maximum beach height (see Tables 4.3.2 and 4.3.3). α is a factor to account the level of the desired safety, as the standard deviation value increases, so will the safety level. ΔV is the associated eroded volume (see Table 4.3.7) and *BW* is the beach width.

Once *EIP* is known, the component of the vulnerability associated to erosion, the Erosion Vulnerability Index ***EVI*** is calculated following the functional relationship represented in Figure 5.2.5 in a scale from 0 to 1. This rule assigns zero vulnerability to situations where the total erosion of the storm class is less or equals the half of the beach width ($EIP \leq 0.5$). On the other side, it assigns the maximum vulnerability (1) to situations where the total erosion or beach retreat is equal or exceeds the beach width ($EIP \geq 1$). Between these two situations the vulnerability linearly increases as a function of the *EIP* value. Finally, a qualitative 5-class scale has been defined ranging from very low to very high vulnerabilities by taking intervals of 0.2 units in ***EVI*** (Figure 5.2.5), as in the case of flooding, this linear model could easily be changed by other model if existing data would support it.

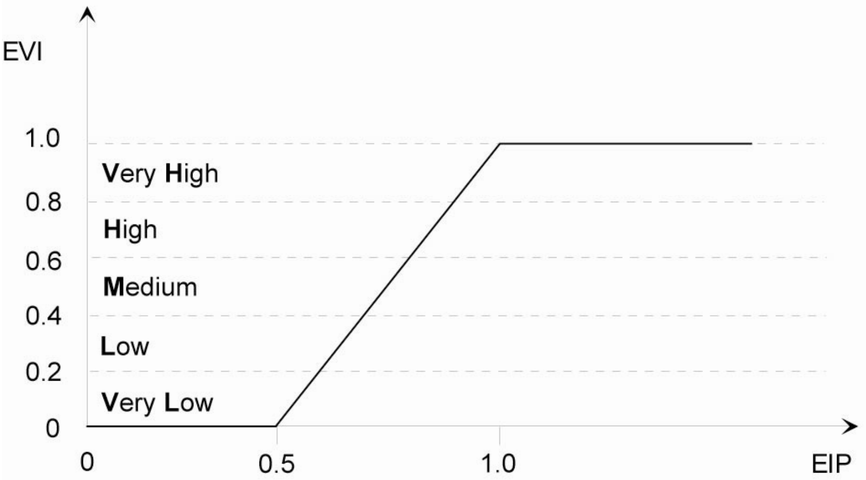

Figure 5.2.5: Functional relationship adopted for the erosion vulnerability index.

5.2.4 Coastal vulnerability index

The added value supplied by the coastal vulnerability index is that quantifies the implication of each of the processes occurring during the storm. Thus, provided we have an updated database with information of beaches along the coast, we are able to map the consequences from the mildest (type-I storm) to the worst case scenario (type-V storm) for each induced process.

The next step was to integrate both indicators into a total coastal vulnerability index. We have tested three different ways of integration of the partial vulnerabilities: (i) using the maximum value of either component, (ii) using the average value of the two indicators and (iii) using a weighed average. In the first method, the maximum vulnerability, the total value is determined by the highest induced impact of both processes. This implies that the vulnerability is individually controlled by the maximum vulnerability of a single process. Although this could be useful for the manager in the sense that it is being warned with a high vulnerability value, the main shortcoming is that it will not take into account possible synergetic responses. Thus, for instance it should be expected that the total vulnerability associated to individual values of 1 and 1 (maximum erosion and inundation values) will be higher than the associated to individual values of 1 and 0.

When the coastal vulnerability is determined by the average value, the final value might present a “levelled” approach, in other words, the result is a smoothed combination of both values (e.g. a very high value and a very low value, yield a medium value) which for the objective of this work does not seem a proper way to assess vulnerability because it would under-predict coastal consequences for some conditions.

Finally, the weighed average is a combination of the previous cases where it takes into account the two partial vulnerabilities and assigns them a given weight. In this work the weighed average has been selected, although it can be adapted or changed to give different results if enough data do exist. As an example, here we assign a larger weight to the larger individual vulnerabilities and the final scores are re-scaled in a 0 -1 scale see Table 5.2.1.

Table 5.2.1: Weighed average of ***EVI*** and ***FVI*** values.

EVI / FVI	*Very Low*	*Low*	*Medium*	*High*	*Very High*
Very Low	Very Low	Low	Low	Medium	High
Low	Low	Low	Medium	Medium	High
Medium	Low	Medium	Medium	High	Very High
High	Medium	Medium	High	High	Very High
Very High	High	High	Very High	Very High	Very High