Vulnerability of wetlands to coastal changes. A methodological approach with application to the Ebro delta

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Abstract

Coastal wetlands are landscape units of very high environmental value, which are frequent along low-lying coasts. In spite of their highly valued "functions", they have been strongly reduced and degraded by human activities, leading to a clear loss of goods/services and characteristic attributes such as biodiversity. This situation forces us to make progress towards more sustainable management approaches for these coastal environments, which, in turn, requires the existence of quantitative tools to assess their vulnerability due to natural and/or human-induced processes. In this work, a framework to analyse and quantify the vulnerability of coastal wetlands to decadal time-scale coastal dynamics is presented. The developed framework makes use of fuzzy logic and it is tested in wetlands along the Ebro Delta (NW Mediterranean coast).

1 Introduction

When coastal managers/planners have to implement a specific management plan for a given coast, one of the main questions is how to foresee which will be the effects of such policy in the system functioning and how the system values can be affected. In others cases, the question is how the system is evolving and how this evolution will affect the existing uses and/or resources. All of this implies that to manage the coastal zone considering it as a multicomponent system, in which one action can propagate within it, the existing scientific knowledge has to be translated to practical tools to be efficiently used by managers. When this is
applied to low-lying coasts such as deltas, in which the economy is based on the exploitation of local resources (agriculture, tourism, etc.), and taking into account that these zones usually contain important areas of wetlands with a high natural value, this need is even more evident.

Coastal wetlands in spite of their highly valued "functions", have been strongly reduced and degraded by human activities, resulting in a severe decline of wetland "functions" and "natural properties", leading to a clear loss of goods/services and characteristic attributes such as biodiversity. This situation makes it especially important to make progress towards more sustainable management approaches for low-lying coasts which is even stressed by the increasing social concern as to their vulnerability and their high natural and human values (e.g. Costanza et al. [1]).

Within this context, the aim of this paper is to present a framework in which coastal changes are addressed to integrate them with other coastal components and to provide useful information on system status for coastal managers. The framework help to quantify the state of the coastal system in terms of existing resources and uses as well as future changes and, especially it will focus on the effects of coastal changes on wetlands. This framework is applied to the evaluation of the vulnerability of coastal wetlands in the Ebro delta (Spain). This area is one of the most valuable areas of Spain in environmental terms, being included in the Ramsar convention as an area of special interest (figure 1).

2 Sustainability and vulnerability

As it can be clearly deduced from the previous introduction, the issue of sustainable management of coastal zones is one of the key questions to be solved in the near future. Although this is world-wide accepted, one of the main problems is how to formalise this concept of sustainability in quantitative terms to be practically applied in management plans. This requires to practically define the involved "big-words" and to develop a coherent framework in which models and tools covering the different disciplines are integrated to measure in quantitative terms the integrated coastal systems performance over time.

Sustainability can be "simply" defined as the ability to maintain "something" over some time period (Leiê and Norgaard, [2]). A quantitative assessment, however, requires answering first three basic questions (Costanza and Patten, [3]): (i) which system, subsystem or characteristics are to be sustained; (ii) for how long they are to be sustained; and (iii) when the assessment (whether or not they have been sustained) will take place. At the scale of "local" systems as this paper deals with, it is possible to define three levels of sustainability with a hierarchical structure: the geomorphic sustainability, the ecological sustainability and the socio-economic sustainability (e.g. Day et al., [4]). By assuming that the coastal system is formed by three major components, it is possible to define three different levels of sustainability, each one contributing to the "integral" sustainability of the entire system.

Thus, the geomorphic sustainability can be defined as the maintenance of land elevation (with respect to mean sea level) and land surface (Day et al., [4];
Sánchez-Arcilla et al., [5]). Both variables are compared to some initial or reference situation and the difference must be evaluated in dynamic terms. The **ecological sustainability** can be defined as the maintenance of human activities and ecosystem health at the same place and time (Callicott and Mumford, [6]). The **economic sustainability** can be defined, in a cost-benefit framework, as the maintenance of the net "gain" for the coastal system. This net "gain" is the difference between benefits "extracted" from the coastal system and the costs/inputs "fed" into the coastal system (see e.g. Hanley and Spash, [7]). This analysis must include market and non-market goods and services, to be applied meaningfully to coastal zones. For non-market goods and services, different valuation techniques can be used: contingent valuation (e.g. Tunstall et al., [8]), hedonic pricing (e.g. Freeman, [9]), travel cost (e.g. Hanley and Spash, [7]) and avoided costs (e.g. De Groot, [10]).

![Figure 1. The Ebro delta (NW Mediterranean Sea, Spain).](image)

To quantitatively estimate the sustainability here we apply the concept of **vulnerability**, which is used to characterise the integrated coastal behaviour, considering both negative and positive responses (i.e. susceptibility and resilience) to a given set of forcing agents or management options (Sánchez-Arcilla et al. [5]). **Susceptibility** implies a negative response and it indicates a
degradation of the system or its inability to cope with driving factors in its present stage. On the other hand, resilience implies a positive response and it indicates an improvement of the system or, at least, the system's ability to cope with driving factors.

According to this, the sustainability of a system will increase as the negative vulnerability (susceptibility) decreases or as the resilience of the system is favoured.

In this paper we shall focus on the vulnerability of coastal wetlands to coastal changes. Although this implies to approach to the problem at a small scale, it will be illustrative since physical changes (natural or human-induced) are studied to assess their implications on coastal ecosystems.

3 Wetland vulnerability to coastal dynamics

Coastal wetlands are landscape units of very high environmental value, which are frequent along low-lying coasts. Due to this importance, a great effort has been put to study factors affecting their stability as well as their response to the major driving forces governing their evolution. In spite of this, most of the existing studies dealing with the physical evolution of wetlands, have been set in a long-term perspective with the balance between vertical accretion and submergence being considered the major control in wetland stability (e.g. Baumann et al. [11], Day et al. [4]). Although this process effectively controls long-term wetland stability, it is also clear that when wetlands are close to the shoreline they will also be conditioned by the coastal dynamics at both short and long time scales. However, although many models have been formulated to simulate wetland dynamics, few of them consider their interaction with coastal dynamics (e.g. Ruth and Pieper, [12]).

The geomorphic vulnerability of wetlands to coastal dynamics is here analysed by considering their response associated to the decadal time-scale scale coastline evolution.

3.1 Wetland vulnerability to shoreline evolution

To illustrate the vulnerability of coastal wetlands to shoreline evolution at decadal scale, figure 2 shows the evolution of the shoreline near the Ebro river mouth from 1957 to 1989. This coastal stretch is subjected to the largest erosion rates along the deltaic coast having experienced in 30 years a coastal retreat of more than 1500 m (Jiménez and Sánchez-Arcilla, [13]). The hinterland of this stretch is characterised by the presence of the “Calaixos”, a 880 Ha wetland area with very important natural values (Generalitat de Catalunya, [14]). As it can be clearly seen from figure 2, coastal dynamics along this area has not only driven the already cited large coastal retreat but also a significant decrease in the surface of the wetland. Thus, from 1957 to 1996 a total of about 98 Ha of wetland surface has been lost in this area. This has mainly affected to the vegetation populations closest to the sea, being the populations of Salicornia one the most affected ones (Generalitat de Catalunya, [14]). This implies a loss of natural
values not only in relative terms (at local scale) but also in absolute ones since affected populations have in this area one of the most important communities along the entire Catalonian coast, being some of them composed by species declared by the European Union as natural habitats of EU interest.

Figure 2. Wetland loss due to shoreline erosion at Illa de Buda (Ebro delta) from 1957 to 1989 (modified from Jiménez and Sánchez-Arcilla, [13]).

To quantify the wetland vulnerability to coastal changes two different approaches can be followed: (i) to fully analyse the ecosystem dynamics and to estimate how this will be affected by the influence of incident waves and, (ii) to apply some kind of parameterisation in such a way that by analysing a simpler variable/process the response of the system is properly characterised.

In this work we have followed the second approach by assuming that the ecosystem of interest (composing the wetlands) will disappear if waves directly attack it (this is the known system response). Thus, the full process is simply parameterised as a function of the distance of seaward boundary of the wetland to the shoreline. This is an indicator of the probability that the wetland will be influenced by wave action.

It has to be stressed that this parameterisation is "dedicated" to the case of interest and that, to be extrapolated to other sites, they must be of similar characteristics. Thus, one of the points to be considered is that the studied wetland is not a "free" one since its landward boundary is a fixed one composed by small dikes. This fixed boundary represents a constraint for ecosystem migration over time, which ideally should be the response of coastal wetlands when are subjected to disturbances in their seaward end.
3.2 A fuzzy logic approach to estimate the wetland vulnerability

Once selected the way of parameterisation of the system response to the targeted forcing (in this case coastal dynamics), we can afford the assessment of the wetland vulnerability. This is done following the previous works of Valdemoro et al. [15], who presented a fuzzy logic oriented-approach to the estimation of coastal vulnerability. This approach permits to specify not only if a coast is vulnerable but also to define different degrees of vulnerability.

The fuzzy logic is a multivalued logic that allows intermediate values to be defined between conventional evaluations that usually make use of a binary-type code (e.g. yes/no, true/false, short/large, etc...). It was introduced by Zadeh [16] and since then it has been widely used to model complex nonlinear systems, specially in the area of control engineering to build expert or decision systems. This approach has also been used to build a decision support system in coastal management by McGlade et al. [17].

The vulnerability is calculated by analogy to a fuzzy controller by building a kind of input-output system, where the transfer is done by using expert knowledge. This is done by building a set of rules according to the part of the problem to be analyzed. These rules relate the considered variables by using different operators, and according to a previously specified response-type, the output (the Vulnerability Index, PVI) is obtained. This is formalized as a series of if-then statements as

If <VAR1 is ...> and <VAR2 is ...> then <PVI> is ...

The system's output (vulnerability) is specified in terms of negative high (NH), negative low (NL), zero (Z), positive low (PL) and positive high (PH). These linguistic values represent the membership function given in figure 3, which are bounded in the interval [-1,1]. A vulnerability value of -1 means that the coastal system for the considered variables is highly vulnerable and, in this case, it means that shoreline response will have drastic consequences on wetland survival.

Figure 3. Membership function for the definition of the vulnerability index.
The two considered variables in this analysis are the shoreline rate of displacement (characterising the coastal dynamics) and the distance of the seaward boundary of the wetland to the shoreline (characterising the response of the ecosystem) in agreement with the above described parameterisation of the system functioning.

The first step is to define the rules governing the “expert system” which have to be built in basis to the knowledge of the system functioning. These are built as a matrix of fuzzy rules “firing” (figure 4).

To apply these rules to a specific coastal stretch we need to know the corresponding values of the two involved variables (wetland distance to the sea and shoreline rate of displacement) and to apply the corresponding fuzzy operator that in this case is AND. Once this is done, the final value of the vulnerability index is obtained by converting the fuzzy answer (which is also a fuzzy set) to a crisp value (defuzzification process), which in this case is obtained as the centroid of the fuzzy set (see figure 5).

All this process has been applied to the coastal stretch depicted in figure 2 to estimate the past vulnerabilities of the wetland (using the coastal configuration of 1957) as well as the present one (using the coastal configuration of 1996). The objective is to test if the method is able to estimate a spatial distribution of the vulnerability index along the coast hindcasting the observed wetland response and, to assess any temporal variation in such index (present and future vulnerabilities).
Figure 5. Example of obtention of the vulnerability index including the effects of shoreline evolution on *Salicornia* zones along the Ebro delta coast using a fuzzy logic approach (Valdemoro et al. [15]).

Figure 6 shows the so estimated vulnerability indices at 1957 (vulnerability hindcast) and 1996 (vulnerability prediction) along the Illa de Buda. As it can be seen in the 1957 configuration, the spatial distribution of the indices agrees with the observed reduction of the wetland surface (see figure 2). In other words, the developed technique has been successful in the hindcasting of the vulnerability. Thus, the largest vulnerable areas (for the studied variables and processes) are located in the northern part of the analysed coastal stretch, where erosion rates are higher and the seaward boundary of the wetland is closest to the sea.

On the other hand, the spatial distribution of the vulnerability index at 1996 shows a similar pattern although with some differences. Thus, again the northern part of the area is the one with largest vulnerabilities and, at the same time, a southward “displacement” of the vulnerability is also shown. The major difference is in the central part, where at 1957 a zero vulnerability was estimated (in agreement with a relatively low erosion rates and wider beach protecting the wetland), whereas at 1996 this value changes to highly vulnerable (-0.7), corresponding to a southward increase of the erosion rates (see e.g. Jiménez and Sánchez-Arcilla.[13]) and a decrease in the beach width due to the cumulative action of the low erosion rates from 1957 onwards. This is also reflected in the indices for the two southernmost locations, which experienced a reduction in their positive values (resilience) with respect to those estimated in 1957.

In summary, the proposed technique is able to quantify the wetland vulnerability to coastal changes in an adequate manner and it also permits to
assess its spatial and temporal variation. With this tool, the status of the coastal system can be analysed to characterise not only the physical processes driving coastal evolution but also the implications of such changes in the overall system functioning (the presented example deals with the influence on existing ecosystems).

Figure 6. Indices of wetland vulnerability to coastal evolution along Illa de Buda at 1957—hindcasting—(left) and at 1996—forecasting—(right).

4 Summary

A framework to evaluate the implications of coastal evolution in the uses/resources existing in the coastal zone has been presented. The method measures such implications in terms of vulnerability indices that evaluate the system status by using fuzzy logic. Although the presented application deals with the vulnerability of wetlands to coastal evolution, the framework is general enough to be applied to other coastal variables/processes and it permits the evaluation of spatial and temporal variation in the system vulnerability.

The integrated application of this approach requires to analyse the problem taking into account the combination of processes and responses at the proper scales and to select the combination of the components of the system involved in the problem. Moreover, in some cases it is also necessary to parameterise processes and responses linking the different components, which makes the implementation of this kind of framework a far from trivial task.

Finally, if an overall vulnerability index for the entire coastal area has to be obtained, this implies to use some kind of valuation process to integrate all the "partial" indices. This task is extremely difficult, varying with time, space, social
perception, etc., and moreover, it is also subjected to a final weighting which is given by the managers/planners which have the last decision on policies to be favoured in the environmental planning.

References