A methodology for the classification of estuary restoration areas: A management tool

Mirian Jiménez a,*, Sonia Castanedo a, Raúl Medina a, Paula Camus a,b

a Environmental Hydraulics Institute IH Cantabria, Universidad de Cantabria, C/Isabel Torres nº 15, Parque Científico y Tecnológico de Cantabria, 39011 Santander, Spain
b Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada, 4905 Dufferin Street, Toronto, Canada

A R T I C L E   I N F O
Article history:
Available online 7 September 2012

A B S T R A C T
Planning the recovery of estuarine areas represents a major challenge for environmental managers, who must find a balance between the desired environmental restoration, understood as the return to natural conditions, and the different socioeconomic uses currently borne by the estuaries. This work presents a methodology to optimize decision-making in accordance with the objectives which might arise in projects for the hydrodynamic restoration of estuaries. Socioeconomic issues are not considered in this study. The new approach is based on a classification of the zones to be restored according to characteristics representing their hydrodynamic performance and the possible morphodynamic effects of the restoration on the rest of the estuary. To achieve this, the four following parameters were chosen: (1) changes in tidal prism induced by restoration of that zone ($\Delta D$), (2) the distance between the concession and the estuary inlet ($l$), (3) the tidal wave phase lag ($\varphi$) and (4) the flood potential of the restoration area ($f$). The classification combines self-organizing maps (SOM) and the K-means algorithm. The methodology was applied in a total of 139 areas (concessions) on ten estuaries along the entire coast of Cantabria (Northern Spain) where a Spanish Ministry of the Environment Recuperation Plan is under way. The results classify the 139 areas of restoration into five clusters. Empirical relationships were used to estimate the effects the restoration of each cluster may have on the estuary’s various morphodynamic elements (cross-sectional area of the estuary mouth, area of tidal flats, volume of tidal channels and volume of the ebb tidal delta), giving managers an overall view of the potential effects of the restoration in each zone and providing a basis on which to plan these actions.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Estuaries present relatively important gradients in their physical, morphological, chemical and biological characteristics, making them systems of great complexity and variability, providing a habitat for a large diversity of flora and fauna species (Barne et al., 1995; Struyf et al., 2009). Moreover, estuaries act as a barrier to flooding and flooding on the coastal front, dissipating swell and tide energy (Möller and Spencer, 2002) with great capacity to abate flooding and, on the other hand, supporting many socioeconomic services and activities (fishing, accommodation, recreation, etc.).

However, in spite of these functions, in Spain many estuaries were negatively impacted by projects officially aimed at improving public health but whose real purpose was the drying and filling of these areas (Spanish Coasts Act, Act No. 22/1988). These actions led to a drastic reduction of intertidal zones in the nineteenth and twentieth centuries when they were subjected to drying and drainage policies, while the granting of concession titles stimulate their conversion toward agricultural, livestock or urban uses (in this context we use the term “concession” to describe an area of an estuary whose exploitation rights are granted, for a prescribed period of time, to a public or private entity in order to carry out different activities).

Subsequently, in the second half of the twentieth century, increased understanding and awareness of the importance of these zones led to the development of diverse protection policies, for example the international Ramsar Convention (1975) and European Directives like the Habitats Directive 92/43/CEE and the Water Framework Directive 2000/60/CE. The last of these requires all European countries to attain good conditions in the quality of all water masses, including transition waters (i.e. estuaries).

Currently in Spain, wetland restoration is fomented in the current Coasts Act, Act No. 22/1988, according to which all concession titles expire 30 years after the Act (2018). This represents a challenge for managers who must plan the restoration of
these zones, which sometimes account for a high percentage of the total estuary area.

Restoration is understood as the recovery for the estuaries of former intertidal zones currently used for other purposes, and to return them as far as possible to their natural state (Mitsch and Gosselink, 2000). In principle, the natural state is the name given to the situation in place prior to any human intervention. However, the restoration of these areas often comes into conflict with well-established uses. It may even be that the artificial state of a wetland has endowed it with characteristics which, for various reasons, may be of interest to conserve. Thus in planning the restoration of an estuary, not just hydrodynamic and biological considerations come into play but also those of a legal and socioeconomic nature.

A review of the literature shows that restoration techniques focus mainly on recovering the estuary long-term tidal level distribution by reestablishing its tidal flow (Pethick, 2002; Cox et al., 2006; Jacobs et al., 2009; Yang et al., 2010b). In other cases, authors do not just analyze the hydrodynamic restoration but seek to ecologically restore the area (Mitsch and Day, 2006; Milano, 1999). Diefenderfer et al. (2005) and Yang et al. (2010a) evaluated the hydrodynamic response and the cumulative effects of various restoration projects on specific estuaries. Finally, there are some guidelines for hydrodynamic and biological restorations of intertidal zones but they focus mainly either on restoring a specific site or on technical issues (e.g. Niedowski, 2000; Leggett et al., 2004). However, as far as we know, there has been no study analyzing the planning of a large-scale (regional) restoration to provide managers with a methodology to assist in the decision-making process. Providing such a general methodology is the objective of this work.

With this in mind, this study offers a methodology for the classification of the areas to be recovered in an estuary according to the characteristics representing their hydrodynamic behavior and the possible morphodynamic effects of the restoration on the rest of the estuary. Legal and socioeconomic constraints are assumed to be fixed for the purposes of this study. Thus, depending on the objective sought, it will be possible to prioritize restoration in the concessions.

This methodology is applied at the regional level, specifically in Cantabria (Northern Spain) where managers must plan the restoration of 139 concessions on ten estuaries along over 200 km of coast. The outcome of this study is to provide a tool which, together with other aspects such as those of a biological or legal nature, will facilitate decision-making in the process of planning this type of action.

This work is novel in its use of advanced clustering techniques (Self-Organizing Maps, (SOM) and the K-means algorithm) pointing to different types of areas for restoration depending on the magnitude of the changes the restoration will have on the estuary.

The remainder of this article is structured as follows: Section 2 introduces the area of study; Section 3 describes the methodology developed for the classification of concessions; Section 4 shows the results of the application of the methodology in the Cantabria estuaries, Section 5 includes a brief discussion and Section 6 presents the study’s main findings.

2. Study area

Cantabria is a region located in northern Spain (see Fig. 1), a coast mainly made up of cliffs, interrupted locally by river mouths, forming estuaries of very diverse sizes (75–2346 ha). Regarding the wave climate, NW sea states are the most frequent (51%); NNW sea states (25%) are also important. 50th and 80th percentiles of significant wave height are 1.5 and 2.5 m, respectively. Tide is semi-diurnal with a mean and spring tide range of 3 m and 5 m respectively.

The estuaries on this coast are of similar hydrological characteristics, meaning that they are of a single type characterized by large intertidal surfaces and dominated by the tidal dynamic, making them well-mixed estuaries. The rivers flowing north are relatively short, the longest one being the Deva (65 km – Tina Mayor estuary), characterized by relatively pronounced slopes in the area of the waterhead, which are less marked in the middle and lower sections. The flow contributed by the rivers, Qr, is negligible compared with that from tides. Galván et al. (2010) analyze the relation between the volume of river water entering the estuary during a half-tide cycle (Qr6) and the tidal prism, Q, concluding that in all these estuaries the tidal dynamic dominates over the fluvial dynamic ([Qr6/Q] < 0.2), taking values between (0–0.12), except on the Tina Mayor estuary which is governed by the fluvial dynamics, where ([Qr6/Q] > 0.2), reaching a value of 0.36 (see Table 1).

All these estuaries, and in particular the Oyambre, Santander Bay, and San Martín de la Arena estuaries, have been greatly pressured by numerous human activities in their environments (Galván et al., 2010). A feature of the Oyambre estuary is the presence of artificial structures which sharply restrict tidal flow,
affecting approximately 50% of the estuary surface. Similarly, Santander Bay has been greatly modified by the urban development and port activity pursued there.

As a summary, Table 1 presents the main characteristics of each of the estuaries studied and the number of concessions on each one, while Fig. 2 shows the location of these areas.

As seen in Fig. 2a, Santoña is the estuary with the largest number of concessions (55) and the greatest area for restoration (9.15 km²). At the other extreme is the Tina Menor estuary (Fig. 2j) with just one concession. As Fig. 2 shows, the morphology of these concessions varies, and they range from 0.0021 ha to 91 ha in area.

3. Methodology

For a classification which evaluates restoration from a hydrodynamic and morphodynamic standpoint, a set of variables has been identified allowing us to describe the hydro-morphodynamic performance of each concession. The concessions were then grouped according to the variables selected, combining two techniques: (1) Self-Organizing Maps (SOM) (Kohonen, 2000), a technique included in neural networks (ANN’s, Artificial Neural Networks), and (2) the K-means algorithm (Hastie et al., 2001).

The following is a description of the variables selected and the methodology used for the classification.

3.1. Selection of variables

According to a large number of authors, the fundamental aim of a restoration project is to reestablish the tidal flat (Mitsch and Gosselink, 2000; Weishar et al., 2005). The effect of the restoration of each concession on the morphodynamics of an estuary is related to the degree to which this tidal flat is reestablished. Many authors have investigated the relation between the tidal prism, \( Q \) (the volume of water which enters and exits an estuary in one tidal cycle) and the estuary’s morphodynamic elements. O’Brien (1931), Jarret (1976), Van de Kreeke and Haring (1980), Eysink (1990), Gerritsen et al. (1990), Watanabe et al. (1991), Hume and Herdendorf (1993), Kraus (1998), Hughes (2002), Gerritsen et al. (2003), Powell et al. (2006), and Stive and Rakhorst (2008) establish relations of equilibrium between the tidal prism and the cross-sectional area of the estuary mouth. On the other hand, Renger (1976), Eysink (1990) and Eysink and Bieg (1992) develop relations between the volume of the tidal channels and the tidal prism. Walton and Adams (1976) and Marino and Melta (1987) establish empirical relations with the volume of the ebb tidal delta. Other authors have investigated the relation between different morphological elements, e.g., Renger and Partenscky (1974), proposing a relation between the tidal flat area and the area of the bay, while Eysink (1991) relates the tidal flats area and their volume.

After this review, it is clear that any action involving a change in the tidal prism will cause changes in the various morphological elements of an estuary. This fact led us to adopt the change in tidal prism, \( \Delta Q \), as one of the decisive variables in classifying the effect of a restoration.

Reestablishment of the tidal flat as a consequence of a restoration project will mean that a greater volume of water will enter and exit the estuary. This exchange of water, nutrients and sediment flow takes place along an estuary’s tidal channels which, as a consequence of the restoration, will adjust their morphometrics to the new conditions. Thus, restoration of concessions furthest from the mouth area will affect a larger extension of each channel and a larger area of the estuary will then be affected by the amount of sedimentary material put in movement. In other words, the further from the mouth a change is made the longer distance of the estuary may be affected by the change. However, this fact does not imply that the affection will be more or less important; it only refers to the extent of the estuary affected. The variable selected here to describe this aspect is the distance between the concession and the estuary mouth, \( L \).

Changes to the hydrodynamics and morphodynamics of an estuary resulting from interventions do not depend only on distance \( L \), but also on the channel configuration (Rinaldo et al., 1999; French and Stoddard, 1992) which will influence the way the tidal wave propagates through the estuary. The variable which provides information on this aspect is the tidal phase lag, \( \phi \), defined as the time between the instant of the high tide outside the estuary and the instant of the high tide at a point inside the estuary. This parameter is responsible for the asymmetry of current velocities, which has major implications for the sediment transport (Pingree and Griffiths, 1979; Aubrey and Speer, 1985) and consequently in the estuary’s evolutionary tendencies. Changes in the asymmetry of currents may modify the tendency in sedimentation or erosion which will alter an estuary’s morphology locally and overall.

As well as focusing on the reestablishment of the original hydrodynamics present in the area, restoration efforts aim to ecologically rehabilitate it as well. Although this document does not set out to establish the criteria for ecological recuperation, it has been thought that, as a consequence of the change in the floodable surface which may be caused by recovery of the concessions, the flora and fauna in these intertidal zones will be affected, impacting species distribution. The long-term distribution of flooding level is closely related to hydrological and biological processes and determines the distribution of vegetation and fauna (Mitsch and Gosselink, 2000; Roman et al., 1994; Montalvo and Steenhuis, 2002; Todd et al., 2010) and is linked to sedimentation processes.

Table 1

<table>
<thead>
<tr>
<th>Estuary</th>
<th>Area, A (km²)</th>
<th>Perimeter, P (km)</th>
<th>Tidal prism, Q (hm³)</th>
<th>Number of concessions, Nc</th>
<th>Total area to be restored, A (km²)</th>
<th>Ar (%)</th>
<th>Qr6/Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santander Bay</td>
<td>21.57</td>
<td>85.25</td>
<td>68.19</td>
<td>39</td>
<td>5.46</td>
<td>25.19</td>
<td>0.003</td>
</tr>
<tr>
<td>Santoña</td>
<td>18.68</td>
<td>76.79</td>
<td>52.38</td>
<td>55</td>
<td>9.15</td>
<td>48.58</td>
<td>0.007</td>
</tr>
<tr>
<td>San Vicente de la Barquera</td>
<td>4.33</td>
<td>27.28</td>
<td>12.27</td>
<td>6</td>
<td>1.42</td>
<td>32.79</td>
<td>0.004</td>
</tr>
<tr>
<td>San Martín de la Arena</td>
<td>3.39</td>
<td>30.27</td>
<td>8.5</td>
<td>3</td>
<td>0.15</td>
<td>4.42</td>
<td>0.065</td>
</tr>
<tr>
<td>Mogro</td>
<td>2.23</td>
<td>26.78</td>
<td>4.2</td>
<td>8</td>
<td>0.93</td>
<td>41.7</td>
<td>0.123</td>
</tr>
<tr>
<td>Tina Menor</td>
<td>1.35</td>
<td>13.44</td>
<td>2.97</td>
<td>11</td>
<td>0.26</td>
<td>19.25</td>
<td>0.011</td>
</tr>
<tr>
<td>Ajo</td>
<td>1.28</td>
<td>18.78</td>
<td>2.14</td>
<td>6</td>
<td>0.15</td>
<td>11.71</td>
<td>0.04</td>
</tr>
<tr>
<td>Tina Mayor</td>
<td>1.17</td>
<td>13.44</td>
<td>1.43</td>
<td>4</td>
<td>0.26</td>
<td>22.22</td>
<td>0.36</td>
</tr>
<tr>
<td>Oyambre</td>
<td>1.01</td>
<td>13.64</td>
<td>0.8</td>
<td>5</td>
<td>0.45</td>
<td>44.55</td>
<td>0.0</td>
</tr>
<tr>
<td>Oriñón</td>
<td>0.57</td>
<td>9.35</td>
<td>0.75</td>
<td>11</td>
<td>0.55</td>
<td>96.49</td>
<td>0.124</td>
</tr>
</tbody>
</table>
To take this aspect into account, flood potential, \( I \), was considered, defined as the change in the number of hours per annum during which each concession is flooded, another of the variables selected in this work. Consequently, the four variables selected for this study to create a general classification of concessions to be restored are: changes in tidal prism, \( \Delta Q \) (m\(^3\)), distance to the estuary’s mouth, \( L \) (m), tidal wave phase lag, \( \varphi \) (hours) and flood potential, \( I \) (h/year). For each concession, \( L \) was measured on a 20 m resolution DTM (digital terrain model) using a Geographical Information System (ArcGIS 9.2 by ESRI) and \( \Delta Q \), \( \varphi \) and \( I \) were calculated using a two-dimensional hydrodynamic model, H2D, which resolves the well-known vertical-averaged SWEs. This model has been employed and calibrated in numerous estuaries in Northern Spain (Bárcena et al., 2011). The model provides the free surface level and the vertically averaged currents resulting from the propagation of the tidal wave into the estuary.

### Classification of the estuarine zones to be restored

#### 3.2. Statistical analysis

Prior to the classification, the variables selected (\( \Delta Q \), \( L \), \( \varphi \) and \( I \)) must be analyzed to ensure that they fulfill the requirement of independence. This was done using Spearman’s non-parametric rank-correlation method. Spearman’s correlation coefficient, \( \rho \), can have values between −1.00 and 1.00. At 0 it indicates that there
is no correlation between the two variables. A positive coefficient indicates that the value of variable A increases with that of variable B, and the value $+1.00$ is identified as a perfectly rising linear relation. If the coefficient is negative, variables A and B vary in opposite directions, and value $-1$ is identified as a perfect inverse relation.

3.2.2. Application of SOMs and K-means

SOMs (self-organizing maps) constitute a technique which arose in the field of neuronal computation used to work in high-dimensional spaces and to project them into a 2D-dimensional space (Kohonen, 2000). It is a classification method which detects patterns or classes in a set of data, preserving the neighboring relations. This means that similar clusters in the multidimensional space are located together in the projection vector. Data projection on a 2D grid allows the data to be visualized intuitively. In this study, the map is in the form of a rectangular 2D grid with $l$ by $m$ neurons laid out on a hexagonal lattice ($C = l \times m$ neurons in the output layer).

The SOM is “trained” using an iterative learning algorithm. This process includes a self-organizing neighborhood mechanism, so neighboring clusters of the winning reference vector in the 2D lattice space are also adapted toward the sample vector, thus preserving the topological neighborhood relationships of the high-dimensional data onto the lattice. The starting point of this technique is a data sample where $N$ is the total number of data to be classified.

Each neuron of the output layer $C_k$ is associated with two vectors. The first one has a lattice-position vector $C_k = (l_k, m_k)$ associated to it, which describes the position of the cluster on the lattice. On the other hand, a reference vector $v_k = (x_{1k}, \ldots, x_{nk})$ represents the position of the cluster centroid in the data space. The goal of the algorithm is to minimize an overall within-cluster distance $d(C_k)$ from the data vectors $x_i$ within the cluster to corresponding reference vector $v_k$, for each cluster $C_k$.

$$
\sum_{k=1}^{l \times m} d(C_k) = \sum_{k=1}^{l \times m} \sum_{x_i \in C_k} \|x_i - v_k\|^2
$$

The least distant output neuron is declared the “winner”. The process of training of this classification algorithm includes a spatial neighborhood nucleus in the projection grid which means not only that the winning centroid is displaced toward the input vector, but that the neighboring centroids in the 2D grid are also modified. This learning process is iterative and ongoing, and ends when a quasi-stable state is reached.

This technique has been used recently in many different disciplines, one of them ecology where Giraudel and Lek (2001) used the SOM to observe the distribution of the abundance of tree species in southern Wisconsin (USA). Meanwhile, Gevrey et al. (2006) used the procedure to measure the risk of invasion of certain insect species in specific geographical areas. Another field in which this technique has been used is meteorology, where Hewitson and Crane (2002) and Gutiérrez et al. (2005) used SOMs to detect patterns of atmospheric circulation and relate them to precipitation series. In biology, Ainsworth and Jones (1999) used the SOM to classify data on the concentration of chlorophyll throughout the Pacific Ocean from satellite temperature and color data. More recent work has been done in the field of oceanography where, since the introduction and demonstration of the use of SOMs by Richardson et al. (2003), the technique has been increasingly employed (Risien et al., 2004; Liu and Weisberg, 2005, 2007; Méndez et al., 2009; Camus et al., 2011). The procedure has also been used in other disciplines such as hydrology (Kwang-Seuk et al., 2010).

It must be emphasized that the SOM begins with a given shape (topology) and dimension: it may be rectangular or hexagonal in shape (with 4 and 6 neighbors respectively). In our work, to determine the dimension of the grid, various tests were carried out, to find that the adequate dimension for the number of available data (556: 139 concessions and four variables for each) was $6 \times 6$.

To establish the relative importance of each variable, $X_i$, they were adimensionalized as follows:

$$X_i = \frac{X_i - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}}$$

Where:

$$X_i = \frac{[\Delta \Omega, L_e, \varphi_e, L_c]}{X_{\text{max}} - X_{\text{min}}}$$

As will be shown in the results, the number of groups obtained with the application of the SOMs, 36, is high for the creation of a simple, manageable classification. Thus the K-means algorithm was applied to these groups. The classification procedure starts with random initialization of the centroids. On each iteration, the data nearest to each centroid are identified and the centroid is then redefined as the mean of the corresponding data. The algorithm is iteratively moved until the intragroup distance is minimal and the process converges (Hastie et al., 2001).

Finally, N groups were obtained, each represented by a centroid with one value of the four variables considered where $\{\triangle \Omega, L_e, \varphi_e, L_c\}$ where $i = 1, \ldots, N$.

Many authors in various fields have combined these techniques (SOM and K-means) to obtain a classification. For example, Solidoro et al. (2007) classified water quality in the Northern Adriatic Sea based on multiple biochemical variables and Gevrey et al. (2006) measured the risk of plagues of various insect species in different parts of the planet.

3.3. Effects of estuarine restoration

Once the data have been grouped together, the decision to recover one group or another depends on the objective set by the restoration project manager. As already mentioned, because each of the groups has particular characteristics, each one will have different morphodynamic effects on the estuary. Predicting long term morphological changes is still an unsolved matter. Existing methods use either process-based models (e.g. Lesser et al., 2004; Marciano et al., 2005) or aggregated models that make use of empirical regime theory to define the morphological equilibrium.
state (Kragtwijk et al., 2004; Rossington et al., 2011). Some recent publications compare the performance of process-based models and the empirical relationships (Van der Wegen et al., 2010; Tran et al., 2012).

Several authors have demonstrated that inlet equilibrium is controlled mainly by tidal prism, durations of the flood and ebb phases of the tides, fresh water discharge and sediment transport (e.g. Gao and Collins, 1994; Lanzoni and Seminara, 2002). In this study, because of the time and spatial scales of interest, the long-term morphological changes induced by the restoration of each group were estimated using the empirical or equilibrium relationships available in the literature. These expressions allow us to estimate gross morphological changes caused in the different elements of an estuary based on a change in its tidal prism. This approach has to be taken as a first step in the assessment of morphological effects caused by hydrodynamic changes. The influence of other factors such as extra sediments supplied by the rivers should be considered in detailed studies for each estuary which are outside the scope of this research.

To evaluate the effects of the restoration project on the cross-sectional area of the estuary mouth, the empirical relation developed by O’Brien (1969) was used.

\[ A_c = \text{Be} \cdot 10^{-2} \cdot \Omega_e \] (4)

\[ A_{c \text{ future}} = \text{Be} \cdot 10^{-2} \cdot (\Omega_e + \Delta \Omega_l) \] (5)

Where:

\( \text{Be} \) = proportionality constant obtained in the e estuary for the current situation.

\( A_c \) = cross-sectional area of the estuary’s mouth (m²).

\( \Omega_e \) = tidal prism during spring tides in the e estuary (m³).

\( \Delta \Omega_l \) = tidal prism provided by the l group centroid.

Tidal channels are another of the morphological elements affected by restoration. In this study, this is analyzed by means of the empirical relation developed by Renger (1976).

\[ V_{\text{MLW present}} = D_e \cdot \text{Le}^{0.1566} \] (6)

\[ V_{\text{MLW future}} = D_e \cdot (\Omega_e + \Delta \Omega_l)^{0.1566} \] (7)

Where:

\( D_e \) = proportionality constant obtained in the e estuary for the current situation.

\( V_{\text{MLW}} \) = tidal channel volume below low tide level (m³).

To determine the changes to the ebb tidal delta, we used the relation between ebb tidal delta volume and the tidal prism as proposed by Walton and Adams (1976).

\[ V_{\text{present}} = E_e \cdot \text{Le}^{0.23} \] (8)

\[ V_{\text{future}} = E_e \cdot (\Omega_e + \Delta \Omega_l)^{1.23} \] (9)

Where:

\( E_e \) = proportionality constant obtained in each estuary for the current estimate.

\( V \) = ebb tidal delta volume (m³).

Note that coefficients \( B_e, D_e \) and \( E_e \) in Eqs. (4)–(9) were obtained assuming that the estuaries are in morphodynamic equilibrium and that the different restoration activities will not change the equilibrium parameters of the estuary.

It is worth mentioning that changes were assessed per concession. So, as the problem is non linear, a similar analysis should be carried out when a concession is restored (Yang et al., 2010a).

4. Results

The methodology described above was applied to a total of ten estuaries with 139 concessions for restoration. For each of the concessions, the changes in tidal prism produced by their restoration, \( \Delta \Omega_l \), was calculated, along with the distance between the restoration area and the estuary mouth, \( l_e \), the tidal wave phase lag, \( \varphi_e \), and flood potential, \( l_i \). Spearman’s method was then used to examine the dependence among the variables, the result of which is shown in Fig. 3.

In all cases, the correlation coefficient, \( r \), was found to be less than 0.3, except between the tidal prism, \( \Delta \Omega_l \), and flood potential, \( l_i \), where \( r \) is 0.7, pointing to a clear correlation between these two variables. However, \( l_e \) was included in the classification because, as will be seen in the results below, the consideration of this variable allows establishing a convenient differentiation among the groups created.

With the value of the four variables characterizing each concession, the data set was used to train the SOM and was subsequently projected onto a two-dimensional (2D) map. Different grid dimensions were tested and a \( 6 \times 6 \) SOM was eventually selected as the most appropriate given the number of data studied.

The input layer is composed of a total of 139 neurons and the output layer of 36 neurons organized in a \( 6 \times 6 \) matrix, arranged on a hexagonal grid (see Fig. 4), where each data vector is assigned to a particular centroid (neuron). Similar centroids are located adjacent on the projection plane, so that the magnitudes of the variables defining the centroids vary gradually from one cell to the adjoining one. Fig. 5 shows the distribution of each of the variables \( \Delta \Omega_l \) (Fig. 5a), \( l_i \) (Fig. 5b), \( \varphi_e \) (Fig. 5c) and \( l_i \) (Fig. 5d). The highest values are shown in red and the lowest by the range of blues.

Centroids with maximum values for variable \( \Delta \Omega_l \), ranging between 0.51 and 0.66, are those located in centroid numbers 31, 32, 25 and 26. This distribution is similar to that of \( l_i \), reaching values between 0.73 and 0.78 in the centroids (25, 26, 31, 21 and 33). In relation to the distance to the mouth, the concessions associated with centroids 3, 4 and 5 present values for this variable between 0.77 and 0.8, i.e. matching those furthest from the mouth. And centroids 1, 2, 7 and 13 have the highest values registered for tidal wave phase lag, of between 0.59 and 0.63.

Fig. 5e shows the frequency of presentation or probability of each centroid. In this specific case, cells 5 and 18 are those with more concessions (greater probability) while for cells 8, 15, 20, 27 and 28, the presentation frequency value is zero (blank hexagon), meaning that none of the concessions is represented by the characteristics of these centroids.

Fig. 6 shows all the information simultaneously, with each cell representing a cluster defined by the four variables used in the classification. In each cell, the largest hexagon shows the distribution of variable \( \Delta \Omega_l \) which appears in a scale of blues, the darkest for maximum values reached by the centroids while the lightest are for the minimum values. The smallest hexagon shows flood potential distribution, this parameter appearing on a scale varying between reds (associated with the highest values) and degrading until reaching yellow for the lowest values. The vectors contain triple information. The length of the arrow is proportional to the value of \( l_i \). The vector’s angle to the horizontal axis shows information on the value of the tide phase lag, \( \varphi_e \), in each centroid.
Finally, the color of the arrow indicates the frequency of presentation of that centroid, that is the number of concessions represented in that cell (maximum values in black).

Each cell on the map includes the number of the concessions (see Fig. 2) associated with each centroid.

Note in Fig. 6 that the concessions in which a restoration will cause a greater increase in the total estuary tidal prism ($\Delta \theta_i$ between 0.55 and 0.66) are located in centroids 31 and 32, matching those with high flood potential ($I_i$ of 0.76 and 0.78 respectively). However, as shown by the length of the vector located in those centroids, these are concessions where $L_i$ is small, i.e. they are close to the estuary mouths. Moreover, the tidal wave phase lag, $\varphi_i$, in the concessions in centroid 32 is shorter in their immediate surroundings than for those in centroid 31. The concessions in these two centroids are located in seven of the ten estuaries considered. There are two concessions on the Santona estuary, one on the Santander Bay, one in San Vicente de la Barquera, one on the Oyambre estuary, number 107 on the Ajo estuary, number 116 in Oriñón and two concessions on Mogro estuary.

On the other hand, concessions located further from the estuary mouth (greater $L_i$), belong to centroids 3, 4 and 5, reaching $L_i$ values between 0.77 and 0.80. These centroids offer minimum values for $\Delta \theta_i$ (0.07 and 0.16) and for flood potential, $I_i$ (0.06 and 0.12). The concessions are located in these three centroids on six of the ten estuaries evaluated. Santander estuary is the one with most concessions in these centroids, with a total of 13, located well inside the estuary. This pattern is also found in the concessions on Santona estuary, Oyambre (103 and 104), San Vicente de la Barquera (100), Ajo (111 and 112) and Oriñón (120, 121, 122 and 123), included in these centroids.

Concessions with a greater phase lag, $\varphi_i$, are found in centroids 1, 7 and 13 (values between 0.60 and 0.63). Although there is no
variation for variable $L_i$ in these three centroids (values between 0.66 and 0.68) the remaining variables perform differently. The value for $\Delta \Omega_i$ in centroid 7 is greater than its neighbors. Centroid number 13 has a greater $I_i$ (0.51) than centroids 1 and 7 (0.27 and 0.33) for variable $L_i$. These concessions are in the estuaries of Santoña (9, 19, 37, 40, 41, 42 and 43), Santander (61, 62, 63 and 70), San Martín de la Arena (126) and Mogro (131 and 138).

As can be seen in the results shown in Fig. 6, SOM technique makes the clustering of the data set simple so that it is possible to observe very intuitively how the concessions are grouped according to their characteristics. However, for a more manageable and simplified classification, the K-means technique was applied to the groups obtained from the SOM. During the analysis of the results, and considering the number of variables, it was found that 5 was

![Fig. 6. $6 \times 6$ SOM. Each plan shows the distribution of one of the variables. a) $\Delta \Omega$ distribution on the hexagonal grid, b) distribution of $L$, c) distribution of variable $\varphi$, d) distribution of variable $I$, e) frequency of presentation on the two-dimension grid.](image-url)
the most adequate number of groups (one group for each variable analyzed, plus one permitting the transition between two very different groups). The results obtained with application of the K-means algorithm are shown in Figs. 7 and 8.

Fig. 7 shows the limits of the groups obtained with the K-means technique, and which concessions belong to each of the groups. Fig. 8 shows the characteristics which are representative of the five groups, each represented by a single centroid with a characteristic value for each of the four variables analyzed.

As Fig. 8 shows, the group with the highest value for increased relative prism (0.49) is group 1 (red). Restoration of the concessions in this group will cause a greater increase in the tidal prism and consequently will produce the greatest changes in the morphodynamics of the estuaries they belong in. The maximum flood potential value ($l_i = 0.72$) is also found in this group.

Group 4 (blue) takes in the concessions furthest from the estuary mouth ($l_i = 0.68$). Should these concessions be restored, the changes will affect a larger area of the estuary. Water flow will modify existing channels and possibly create new ones. On the other hand, these concessions will not produce a significant increase in the tidal prism ($\Delta l = 0.03$).

The centroid of Group 3 (orange) represents the concessions located in zones where the phase lag of the tidal wave is maximum. Thus the restoration of these concessions may involve a change in the erosion-sedimentation pattern around them. In this group, the value for the relative distance variable ($l_i = 0.66$) is also high. The authors found that the concessions with a greater phase lag coincide with those furthest from the mouth.

Group 2 (green) and Group 5 (yellow) are transition groups between the groups referred to above.

To examine the relative importance of the variables within each cluster, a ranking was established assigning each variable a value between 1 and 5 depending on its value considering all the groups (see Table 2).

![Fig. 7. 6 x 6 SOM. Delimitation of the groups obtained using the K-means algorithm.](image)

![Fig. 8. 6 x 6 SOM. Characteristics of each centroid associated with the groups obtained using K-means.](image)

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranking of each variable within the groups.</td>
</tr>
<tr>
<td>Group 1</td>
</tr>
<tr>
<td>$\Delta l$</td>
</tr>
<tr>
<td>$l_i$</td>
</tr>
<tr>
<td>$\phi_i$</td>
</tr>
<tr>
<td>$l_i$</td>
</tr>
</tbody>
</table>
Table 2 shows that Group 1 brings together the concessions which contribute more tidal prism to the estuary and with high flood potential, while in Group 4 both variables are in last place. Group 2 is the one with the lowest positions in the ranking for three of the four variables, showing that these concessions will cause fewer morphodynamic changes in the estuary should the restoration take place.

Note how in Groups 2 and 3 the variables $D_{bU}$ and $I_{bi}$ do not have the same ranking within each group despite the correlation found between the two variables. It is confirmed that the inclusion of variable $I_{bi}$ allows differentiating the effects of the different groups more clearly. For example, were parameter $I_{bi}$ not included, the effects of the recovery of groups 1 and 3 considered overall (combining the values of the ranking in each group except for $I_{bi}$) would score the same. However, Group 1 will produce a larger floodable zone ($I_{bi} = 1$) than Group 3 ($I_{bi} = 4$).

Fig. 9 shows the distribution of groups in each estuary. Concessions with greater $\Delta I_{bi}$ are shown in red (Group 1) and these, on the San Vicente de la Barquera (see Fig. 9c), Oyambre (see Fig. 9d), Oriñón (see Fig. 9h) and Tina Menor (see Fig. 9i) estuaries, are the ones with the greatest surface area.

On the other hand, the authors have found that the Group 4 (blue) concessions are mostly on the inner part of Santander Bay (see Fig. 9b), far from the estuary mouth and with low $D_{bU}$.

![Fig. 9. Cluster distribution for every concession in every estuary. It indicates the most important areas for the restoration activities. (a) Santoña, (b) Santander Bay, (c) San Vicente de la Barquera, (d) Oyambre, (e) Ajo, (f) Tina Mayor, (g) Suances, (h) Oriñón, (i) Mogro and (j) Tina Menor. Red color refers to group 1, green to group 2, orange to group 3, blue to group 4 and yellow to group 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image)
general, the concessions are of different types throughout all the estuaries.

5. Discussion

Because of the current situation in Spain, with the expiration in 2018 of numerous concessions located inside estuaries and granted under the current Coasts Act, new methodologies must be established to be applied to the management of the restoration of these intertidal zones. Prior work has defined methodologies for the comprehensive classification of estuaries according to ecological, biological or physical criteria, or to morphological parameters. But there has so far been no methodology which allows the planning of estuary restorations on a regional scale.

The methodology proposed in this work is based on classifying restorations according to the morphological effects of their incorporation into the estuary dynamics. As pointed out, the objective of this study was to propose the use of concession classification as a planning tool making it possible, depending on the aims of a restoration, to decide in which group those aims will be best met.

To illustrate this proposal, an estimate was made of the morphodynamic changes which will be caused by recuperation in each group obtained in previous classification, using the equilibrium relationships available from the literature. These expressions allow us to estimate gross morphological changes caused in the different elements of an estuary based on a change in the estuary's tidal prism.

By way of example, the effects which would be caused by one concession in each group were assessed in the case of a restoration in the Santander Bay, Table 3 showing the results of this exercise.

It is seen how an increased $\Delta U$ due to a restoration in the concessions will lead to an increase in tidal channel volume of a maximum of 0.42% compared with the current situation (Group 1 concession). Exchange of water between the ocean and the tidal inlet takes place through the mouth of the estuary whose cross sectional area, $A_t$, will be more or less increased as a result of the restoration. For restoration in a Group 1 concession, $A_t$ would be increased by 0.28%, a rise of 41 $m^3$ on its current dimensions. On the other hand, if the concession to be restored is in Group 2, the estuarine morphological elements would hardly be disturbed as the changes caused by that concession would amount to less than 0.1%.

This classification provides managers with an overall view of the various restoration options for each group and the potential effects of restoration in one group or another on the various elements of the estuary, optimizing the decision-making process as to which concessions to restore, depending on the aims of a restoration project. The inclusion of legal and socioeconomic considerations in this analysis should be explored in future works.

6. Conclusions

Currently in Spain, wetland restoration is encouraged in the current Coasts Act, Act No. 22/1988, according to which all concession titles expire 30 years after the Act (2018). This represents a challenge for managers who must plan the restoration of these zones, which sometimes account for a high percentage of the total estuary area.

The methodology proposed in this work is based on the classification of restoration processes according to the morphological effects produced on the estuary dynamics. The nature of the classification (classifying not the estuaries but future restoration zones), the spatial scope of the study (10 estuaries), and the classification techniques used are the main innovations found in this study.

The use of clustering techniques such as self-organizing maps (SOM) and the K-means algorithm to carry out the classification allows the original data set to be grouped into a reduced number of clusters. SOMs make it possible, according to the four selected variables, to visualize how 139 restoration areas are grouped into 36 clusters. To design a manageable tool, the number of clusters was reduced using the K-means technique, classifying all the concessions into a total of five groups, each group with hydro-morphological characteristics determining the effects on each estuary element. An evaluation of these effects will provide managers with an overall view of the various restoration options of each group, thereby enabling decision-making on the concessions to be optimized.

In summary, the methodology developed in this study opens up a wide range of applications. Each concession can be evaluated taking account not only the hydrodynamic parameters as proposed in this study, but also others (biological, economic, legal, etc.) depending on the objectives. Thus we may conclude that the development of this methodology is a first step toward the implementation of adequate estuary restoration management.

Acknowledgments

The support of the European Commission through FP7.2009-1, Contract 244104 – THESEUS ("Innovative technologies for safer European coasts in a changing climate"), is gratefully acknowledged.

References


Jacobs, S., Beauchard, O., Struyf, E., Cox, T., Maris, T., Meire, P., 2009. Restoration of tidal freshwater vegetation using controlled reduced tide (CRT) along the Schelde Estuary (Belgium). Estuarine, Coastal and Shelf Science 85, 368–376.


Liu, Y., Weisberg, R., 2005. Patterns of ocean current variability on the West Florida

Liu, Y., Weisberg, R., 2005. Patterns of ocean current variability on the West Florida


