COASTAL EROSION ASSESSMENT IN WETLANDS ON THE GULF OF MEXICO

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The relevance of the services provided to humankind by coastal wetlands is undeniable, however in many places around the world these ecosystems are still considered as secondary elements in coastal management plans or even worse they are in a state of abandonment. This work is focused in presenting a combined methodology based on previously published works, which is intended to be permanently applied in coastal wetlands to allow having an updated view of the wetland status, a description and the location of its main problems and the identification of the elements that are increasing the vulnerability of the system. This information is then used to have a permanent plan for resilience recovery or holding and also to set the basis for a quick response after the occurrence of a natural or artificial threat. The methodology is applied to two coastal wetlands in the Gulf of Mexico which feature chronical erosion problems and where the goodness of the results is shown in the form of recommended measures to recover the resilience of the ecosystems.

Keywords: Coastal Wetlands; Beach erosion; Gulf of Mexico; Wetland vulnerability

INTRODUCTION

Coastal wetlands were originated by marine and fluvial sediment that was deposited in coastal embayments during the last marine transgression and until nowadays. This accumulation of sediments occurred in naturally sheltered areas (*e.g.*, in the lee of sand spits) where the vegetation found proper conditions to slowly cover large areas. The ecosystemic distribution generated by the vegetation capable of living with different salt contents in the water derived in the formation of three habitats: a marine foreland, a continental hinterland and, between this a wide brackish strip (Corlay, 1993). The natural dynamics and extension of the wetlands, make their limits difficult to be strictly set, thus the management policies, the use of land regulations and its conservation is also a great challenge worldwide.

Wetlands offer many important services to humankind, ecology and coastal dynamics, but although they easily adapt to relevant changes, they are quite sensible to the alteration of a group of critical balances. This is the reason behind the attention that has recently been directed towards the sustainable management strategies for wetlands. Among the most important critical balances that keep the sound equilibrium of wetlands it is accepted that natural wetland functions are closely linked to hydrology (Sather and Smith, 1984). Regarding the latter, the major wetland hydrology related functions can be grouped in three main categories: ground water recharge and discharge; flood storage and desynchronization; and shoreline anchoring and dissipation of erosive forces.

As fragile as the wetlands may seem they often bear the stress induced by human activities, which makes them almost invaluable suppliers of socio-economic services. The socio-economic functions of the wetlands are can be separated in two categories: The consumptive category includes products that are physically harvested for human utilization (food, fuel, or fiber); the non-consumptive category includes the scenic, recreational, educational, aesthetic, archeological, heritage, and historical values.

A reasonable question, given the worldwide recognized value of the wetlands, is why they are still being ignored or devaluated in policy processes and their loss or degradation has been allowed to continue. Several examples can be cited as wetland stressors, such as port expansion, industrial sprawl, urban growth, pollution, changes in hydrology, water shortages, tourism, oil and gas exploitation and conversion by agriculture and fisheries (Turner *et al*., 2000). This large variety of stressors only illustrate the huge number of interests of different groups that coincide in the wetlands; it is desirable that any conversion performed in a wetland benefits the best interests of the society, unfortunately it has not always been like that.

It is paradoxical to consider that systems that supply so many benefits to the society have been the object of such a great abandonment and even worse, the human action is clearly the main impairer of the wetland balances and ecosystems. As a response, studies have been held to characterize the damage driven to wetlands, as an example, from the social point of view, the alteration to a wetland can be assessed assigning one of various forms of anthropization (Corlay, 1993) that is, how artificial a marsh

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geosystem is can be used as a criterion to set up a typology. Type one corresponds to wetlands that have never been managed, a few in number can be found in industrialized countries and more in the developing countries, in general, their hydraulic system functions naturally, and effects on the marine foreland are very beneficial. Type two is diametrically opposed to type one, it includes those wetlands which have lost their balances because of a maximal anthropization of the environment, and the majority of these wetlands' hydraulic network has been simplified to the benefit of freshwater. Type three corresponds to a condition in which wetlands are moderately occupied, this wetlands are hard to characterize and spatio-temporal studies need to be performed.

Another effort focused on the quantification of the state of a particular wetland is the use of a combination of indices (*e.g*., Seilheimer, *et al*., 2009), so that indices exist regarding water quality (Chow-Fraser, 2006), and biotic elements as plants (DeKeyser *et al*., 2003), invertebrates (Kerans and Karr, 1994), and fish (Karr, 1991; Wang *et al*., 1997). Recently the application of methodologies for ecological risk assessment of wetlands can be found (*e.g*., Malekmohammadi and Blouchi, 2014) which in turn can be used to determine the status and set adaptation and mitigation measures to restore wetlands. In Mexico, the vulnerability of wetlands has been evaluated as a function of land use changes, *e.g*, Vázquez-González, et al., 2013.

Considering the difficulties involved and the lack of integral methodologies available to characterize the state of a wetland, finding the possible causes of its degradation and setting a hierarchical list of restoration measures, from an engineering point of view; this paper presents a combined methodology which if permanently applied allows the managers to evaluate the state the wetland, proposing restoration/mitigation measures, monitoring the performance of the measures and getting back to the beginning in a virtuous loop. The methodology is applied in two wetlands in the Gulf of Mexico *i.e*., Carmen-Pajonal-Machona, Tabasco system and Alvarado wetland, Veracruz, both in Mexico.

DESCRIPTION OF THE METHODOLOGY

The methodology presented here is a combination of previous methodologies (Sterr, 2008 and Steyer and Llewellyn, 2000) and relies on two mayor guidelines: One is that the first step in coastal wetlands management should be the stabilization of the coastline. This has to be achieved accepting that not only natural processes are involved but also industrial and other human activities. Therefore the actions required must take into account all the uses of these coastal zones and management plans must (disregarding if restoration, rehabilitation or construction is decided to be the best option) clearly define the most profitable activity and consider this as overriding the needs of any other coastal exploitation. The second guideline is that together with the assessment of coastal erosion and its causes, the long and short term vulnerability of the coastal zone needs to be estimated as well as any element that would limit the natural adaptation and/or resilience of the wetlands, given an increase of hydro-meteorological threats, such as transport infrastructure and human settlement, not only as developed at present, but also in the next 10 to 20 years. The main premise behind the methodology is that the adaptation measures and the management policies derived may seek reducing the vulnerability by maximizing the resilience.

Given the above directives, the proposed methodology can be viewed as a cycle of evaluating the degradation of the wetland, proposing and applying measures and policies, monitoring the effects of those actions and re-evaluating. The process is divided in three main steps: a) Exploration, includes the identification of the hot spots, which are the elements or areas from where the wetland is receiving most damage or where the damage is worse, this step as well as all the methodology can be delineated as deep as possible or necessary. In this sense, the quantification of the impacts of the elements causing degradation is considered in the exploration step; b) Vulnerability, this step refers mainly to define the activities, infrastructure, uses and even natural elements that are reducing the resistance and resilience of the system and c) Planning, the integration of possible solutions including hard and soft engineering measures, management policies and conservation plans are set in this step, the objective horizon is flexible and depends on the specific needs, the degree of damage, the stress and the resilience of the wetland.

The information gathered from the methodology is collected in an evaluating element called status chart, which is a document where the data can be hierarchically ordered and which can be also used for consultation or as a decision helping tool. Some of the elements included in the status chart are: a list of the main elements of the wetland and its characteristics (climate, hydrologic conditions, infrastructure present, geomorphology, economic activities, populations, etc.), the present state of the water bodies, the causes and effects of degradation and damage, a diagnosis of the wetland and the basis for achieving a solution to the problems found. The status chart is the key element of the methodology as it is a document (as large as necessary or possible) that will contain the history of the wetland, the mitigation, adaptation or restoration measures taken, their performance, the reason of their removal or leaving and any data the incumbent decision taker may need. The principal advantage of this methodology is its flexibility as it can be taken as deep as the available data lets. The application and details of the methodology will be further explained by the presentation of two case studies in the Mexican coast.

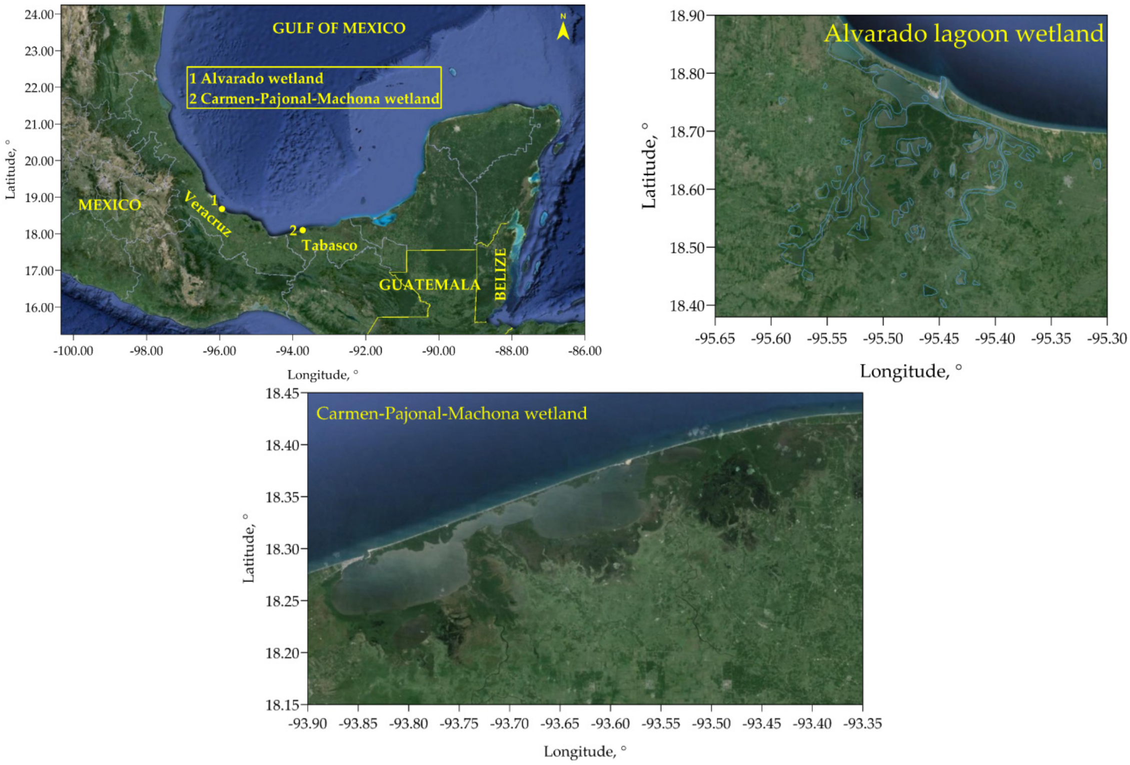

Figure 1. Location of the case studies

CASE STUDIES

Two wetlands were selected for the application of the proposed methodology, both are located in the low Gulf of Mexico and even the distance between them, they have common features such as: reported coastal erosion, high vulnerability to hydro-meteorological threats and populations and economic activities at high risk. The first case, Alvarado Lagoon system, is a river dominated coastal wetland with a small lagoon, where intense port and agricultural activities are developed, while the second; Carmen-Pajonal-Machona wetland (from now on CPM) is a lagoon system where the main economic activity is hydrocarbons extraction. The location of both wetlands in the Mexican coast is presented in Figure 1.

Alvarado Wetland

Exploration

Alvarado system is located 66 km southeast from Veracruz port (the most important Mexican port) within the coordinates 18°30'27'', 18°53'12'' latitude and 95°33'50'', 95°58'56'' longitude covering an area of 83 821 ha, it belongs to the hydrologic region number 28 which main river is the Papaloapan River. This wetland comprises Camaronera, Buen Pais, Alvarado and Tlalixcoyan Lagoons (SEMAR, 1998) and it has the largest protected coastal areas in the country, approximately 614 km long. (INECC, 2009). The top right panel of Figure 1 shows a Google Earth satellite image of Alvarado wetland.

The weather is warm-humid with a rainy season in summer, the mean yearly precipitation is 286-320 mm and the mean temperature is 25 °C. This estuarine system features a combined river and surface runoff of more than 5600 m^3/s that feeds the lagoons and marshes. Alvarado Lagoon is naturally protected by sandy barriers more than 50 m high and wide areas of coastal dunes that reach 10 km landwards (INECC, 2009). In its natural state, the bathymetry and morphology were dominated by the natural water balances; the area is threatened yearly by strong storms produced by cold fronts and occasionally the coast is hit by hurricanes. The leading economic activities held in the wetland, in order of relevance, include: port, agriculture, industry, fisheries, mining and tourism.

Although several conversion, land reclamation and other actions have been taken in the wetland, the identified hot spots are located in the port neighborhood and have been mainly produced by it. These are: the coastal region downdrift from the entrance of the port which is in a critical erosion process due to the longshore sediment transport interruption, the river margins which are also rapidly eroding inducing high risk to La Trocha population (West margin) and to ecosystem values (East margin). Figure 2 shows the hot spots, in it the erosion process from 2005 to 2010 can be seen (some areas have lost up to 40 m of dry beach) as the historical coastline positions have been drawn; La Trocha town and the eroded East margin of Papaloapan River can also be seen.

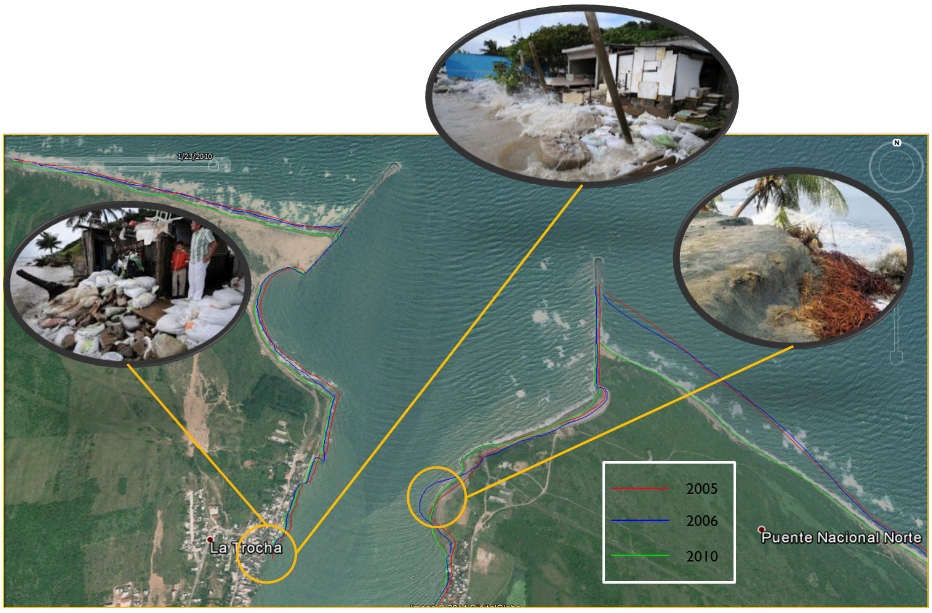

Figure 2. Hot spots identification in Alvarado system (Satellite image from Google Earth)

The data gathered during the exploration step is included in the status chart and is complemented with data revealing the present status of the wetland, for simplicity some examples of the information for Alvarado system has been summarized in Table 1.

Table 1. Alvarado Lagoon status chart	
Main Characteristics	-The lagoon is separated from the sea by a littoral barrier with dunes up to 50 m height -The only communication with the sea is by the Alvarado mouth (port) -The lagoon system includes Camaronera, Buen País, Alvarado and Tlalixcloyan lagoons
Climate	-Wind velocity: 15.5 kt; direction: NE, E and NW -Wave height of 2.5 m related to “Nortes” and 10 m due to hurricanes -Diurnal tides of 0.5 – 0.7 m amplitude, the maximum high tide is 0.75 m and low tide is 0.56 m
Hydrology	-Annual precipitation of 2077.9 mm and mean temperature of 25.23 °C -Runoff from land by cyclonic rains -The residence time of the flow in the lagoon is medium
Land use	-Land use change from hydrophilic and dune vegetation to grassland and seasonal agriculture -98% dune vegetation loss in the coastal zone -Change in vegetation due to stockbreeding and agriculture

As seen in Table 1, the status chart includes the characterization of the system elements and the status in which they are found at the moment the data was gathered. The great advantage of having all these information together is that it simplifies the identification of causes and effects of degradation as well as the performance of measures or policies which is the goal of the vulnerability step. Many more aspects can be added to the status chart depending on the specific wetland and local interests.

Vulnerability

From the status chart data it is clear that the erosion process is critical and, as said before, the stabilization of the coastline is the first step in the management of any wetland. In this sense, a list of causes and effects can be constructed to get a full panorama of the mechanisms acting in the wetland that have resulted in beach loss. The following is an example of a summarized causes-effects list for Alvarado system. It is relevant to note that the causes and effects are not listed in any particular order, neither a cause is related to its same level effect.

CAUSES	EFFECTS
Seasonal agriculture	Coastal erosion
Stockbreeding	Coastal dynamics altered by structures
Polluted discharges	The coastal zone has lost 98% of its natural vegetation
Fishing over-exploitation	
Deforestation of coastal dune vegetation	
Port infrastructure	

In addition to what has been listed above, the construction of dams for electricity generation has severely altered the hydrologic network and has reduced the sediment supply to the system. The sedimentary unbalance has derived in large areas of silting, where the water has no more energy enough to transport the material and areas of erosion as the sediment is no longer been properly distributed along the wetland. These effects have also produced changes in the vegetation distribution inducing a high risk of losing the wetland characteristics of large areas. The diagnostic for Alvarado wetland is that the system has fallen into a state of sediment inbalance.

CPM Lagoon System

Exploration

The CPM lagoon system is located in the Tabasco state and is part of the hydrologic region number 30; it is formed by flooding plains of rivers Mezcalapa and Usumacinta. It features variable altitudes from 2 to 17 m over the mean sea level; covering more than 67 500 ha within coordinates 18°10’44’’, 18°26’9’’ latitude and 93°20’57’, 93°53’35’’ longitude. Lagoons Carmen and Machona are the most important water bodies of this wetland which is located 137 km northwest from Villahermosa city. Figure 1, in the bottom panel presents a Google Earth satellite image of CPM wetland.

The weather here is war sub-humid with mean annual temperature of 26 °C. The summer season is rainy but in winter strong storms occur related to cold fronts. In this area a yearly mean precipitation of 1500 mm is reported (INECC, 2009).

The economy of the region is related to hydrocarbons extraction and in less intensity agriculture, stockbreeding, fishing and tourism are present. The lagoons are separated from the Gulf of Mexico by a 35 km long but 300 m wide barrier with elevation between 1 and 6 m over the mean sea level; this means that barrier breaching commonly occurs. Over this barrier a straight highway was constructed. The permanent communication of the lagoons with the sea is through two mouths; one natural in Carmen Lagoon which is silting and another artificial in Machona Lagoon which is eroding.

The hot spots analysis in CPM showed that the attention should be focused on the beach erosion all along the barrier where the highway that was built on the coastal dunes have degraded the resistance and resilience of the beach and is now at very high risk; even in low intensity storms the highway is hit by waves. This highway cannot be left to be destroyed because it is the only way that terrestrial transport can get to the oil industry facilities, it is then a political and economic relevant element. A second hot spot is Sanchez Magallanes town. The beach in front of this population is suffering a chronic erosion process of 3 to 5 m per year (Hernandez, 2008) derived from the infrastructure built to keep open the natural mouth in Machona Lagoon. Figure 3 shows Google Earth images of the hot spots of CPM system. In both panel of Figure 3 the historical position of the coastline has been drawn; clearly the coastline is not stabilized and is dramatically increasing the vulnerability of all the wetland as the present distribution of marine, brackish and fresh water environments may change abruptly producing a severe ecological damage in the area.

A summarized version of the status chart considering the data collected during the exploration step and the present state of the wetland is presented in Table 2.

Figure 2. Hot spots identification in CPM system, coastal barrier (top) and Sanchez Magallanes town (bottom), (Satellite images from Google Earth)

Table 2. Status Chart Carmen-Pajonal-Machona Lagoon	
Main Characteristics	-Boca Santana (at the northwest) is being affected by sedimentation -Boca Panteones (at the northeast) is eroding and the intrusion of saltwater into the lagoon is uncontrolled -Severe beach erosion
Climate	- Wind speed 41 km /h; direction E and SE -Currents parallel to the coast (E to W direction) with velocities of 2 to 4.5 kt -Wave height 1 - 2 m related to “Nortes” and máximum of 5 m
Hydrology	-Annual average precipitaton: 1695.7 mm; and mean temperature 20.5 °C -Almost no river discharges
Land use	-Land use changes due to seasonal agriculture and stockbreeding

Vulnerability

Again, the status chart is the key to identify the elements and processes that need primary attention. The summarized list of elements increasing the vulnerability of the wetland and their effects is as follows:

CAUSES	**EFFECTS**
Building on the coastal dunes	Coastal erosion
Infrastructure to keep the mouth open	Uncontrolled salt water intrusion
Highway for oil industry	Siltation in the natural mouth
	Interrupted longshore sediment transport

It has to be pointed out that the situation at CPM is more complicated as the ecological and technical arguments are not the only ones to be taken into account; the oil industry is still one of the primary income providers to the national government and the continuity of its related activities are not a matter discussion. In this sense, the planning step needs to consider that the restoration of the wetland has to be designed in harmony with the needs of the oil industry. The general diagnostic fod CRM wetland is that severe dry loss has occurred due to human poorly planned actions.

Planning

This step is presented simultaneously for both wetlands to let the reader compare the conclusions that can be addressed from the status chart. A recommended sub-step in the methodology is to set a list of hints to the wetland resilience recovery, this practice helps setting the problem that needs attention first and gives an idea of the subsequent problems in a hierarchical order. Table 3 shows the hints list for both wetlands already in order of importance.

Table 3. Hints for resilience recovery

Problem	Wetland	
	Alvarado	CPM
Erosion	Recover sediment sources Set a balanced hydrologic network Reestablish coastal dynamics	Restore coastal dunes Reestablish coastal dynamics Recover longshore sediment transport
Siltation	Recover the depth of the water bodies	Set a new balanced hydrologic network
Flooding	Protect coastal populations Let the system self-adapt in natural conserved areas	Recover the natural protection by coastal dunes
Vegetation	Modify farming practices to be sustainable	Modify farming practices to be sustainable

As can be seen in Table 3, there are some actions that may be suitable for the solution of more than one problem. This is the main strength of the hints list.

From all the data and information included in the status chart, it is now possible to propose some specific actions to be taken in the wetland firstly to attack the diagnostic but also as part of a long term plan which will be applied by parts giving the managers the opportunity to evaluate the performance of each part and monitor the response of the wetland and then begin the application of the net measure. The purpose of the proposed methodology is to be permanently followed, updated and modified independently of the incumbent authorities. This intends to keep the wetland in a sound state with the possibility of quick response to natural or human threats. As an example, Table 4 shows the recommended measures for both wetlands, note that although some actions are common, they are not recommended in the same order as they have been set according to the specific wetland needs.

Table 4. Recommended measures to recover the resilience of the wetlands

Alvarado	CPM
Dredge the Alvarado lagoon	Update or remove coastal structures
Update or remove coastal structures	Perform beach nourishment and design new coastal defenses
Restore and reforest the coastal dunes	Dredge the lagoons
Substitute economic activities	Mangrove reforestation
Set land sediment traps and perform beach fills	Protect the dune and re-plan the highway

An essential part of the methodology is a monitoring plan which should include, at least: bathymetry and topography measuring at the coast, water bodies and variable areas (this may be done with the help of satellite images and/or LIDAR data if the resources to perform field works are limited); vegetation species and distribution recognition; water salinity and temperature distribution; evaluation of the condition of the infrastructure. Depending on the resources and available the monitoring can be performed at pre-stablished dates or at least after severe storms or after the implementation of resilience recovery measures.

CONCLUSIONS

A simplified application of a combined methodology for resilience recovery of wetlands has been presented, the data has been summarized to help the reader conceptualize the philosophy behind the methodology.

CPM wetland is more vulnerable than the Alvarado lagoon as the narrow barrier naturally features high vulnerability. Even though, human activities that are taking place at CPM are more concentrated and aggressive. While in Alvarado the main conversion actions are related to agriculture substituting the natural species by commercial plantations, in CPM large wetland areas have been reclaimed and hard infrastructure has been built.

Both systems present a high degree of sediment imbalance showing erosion in some areas and sedimentation in others. This is the result of the coincidence of several interests such as agricultural, fisheries and electricity generation; the absence of management plans in both wetlands is evident.

The identification of hot spots and elements causing vulnerability showed that immediate action is needed to deal with possible future scenarios. The present vulnerability and thus risk of some elements of both wetlands is unsustainable, populations and infrastructure related to oil industry cannot be left at their actual status.

Uncontrolled agriculture and stockbreeding have severely degraded both wetlands, furthermore the actions taken to facilitate these activities have worsened the situation.

The resilience of the systems can be restored if radical action is taken.

The combined methodology has shown to be a useful tool that lets the mangers get a deep overview of all the wetland as a whole and from it, they can be guided to select the optimal measures.

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