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Sedimentation Processes in the Tinto and Odiel Salt Marshes in Huelva, Spain

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Abstract

Global warming is a key factor to take into account when a study is conducted on tidal wetlands. Both Odiel and Tinto salt marshes are the major wetlands in Andalusia (Spain). From the mid-1950s to date, the land use changes (LUC) have caused a great landscape alteration that along with the effects of climatic variables and sea wave energy have given rise to a hard impact on the environment. The advent of new image processing procedures and use of high-resolution images from satellites gave precise patterns of erosion. In this work, a new method patented by the author is presented and used to obtain the total cubic meters of eroded soil in both salt marshes. Moreover, the different factors that begin this phenomenon as well as the influence of intertidal processes are discussed. The results show how the greater integration of remote sensing and geographical information systems (GIS) technologies, with regression model, was most useful to describe, analyze and predict the volumetric change process in both salt marshes.

Keywords: eroded soil, salt marshes, south of Iberian Peninsula, remote sensing, high-resolution images

1. Introduction

According to [1], marshes are ecosystems that tend to go away as a result of silting process. Nonetheless, human beings have accelerated this process giving rise to loss of its surface. Several researchers, such as [2, 3], think that marshes are possibly a type of ecosystem that has experimented important alteration by anthropic action. Indeed, the present estimates [3–5] specify that the European marsh areas have decreased by about 80%.

Though both ecosystem processes and their implications for the future mitigation of land degradation have been taken into account in different field researches around the world, it is

difficult to extrapolate findings from field studies at patch scale in other areas [6]. Although satellite platforms may bring out the solution of this problem, the use of high-resolution images obtained by satellites has a significant advantage because it allows us to depict all the physical features of the marshes, which are often insufficiently reflected in classical contour lines mapping [3, 7], thereby supplying the spatial information needed to study the relationships between climate variables and soil erosion at marshes-scale analyses.

In both Tinto salt marshes and Odiel salt marshes, the residence times of sediments in their respective river systems are long with much intermediate storage of eroded material, as is common to most large river systems around the world, for example, as occurs in Chile [8], while on the other hand, increased storage of sediments can result in substantial changes to Tinto and Odiel river's physical form as well as their ecological health. This last aspect is key as a result of the importance of Tinto river to the study of life in extreme conditions.

A further consequence of long residence times in rivers, and in accordance with [3, 4, 8], is that the major historical changes will influence river behavior for many decades to come. Likewise, it is essential for us to obtain and evaluate the trajectory of response to global historical change, being the temporal scale of analysis of great relevance to predict the relationship the net response of sediment to the distribution of floods over many years.

Up to now, in most of the remote sensing studies, researchers have made an effort to approach soil loss and its erosion processes solely through mapping changes in canopy and vegetal abundance, or LUC in general sense, and even with different methods capable of deriving state variables based on the reflectance characteristics of soils [6] and/or the characteristics of the vegetable canopy, while, on the other hand, though the use of high-resolution images can be considered novel, the ratio of published manuscripts is much greater, perhaps, it can be due to the massive potential of these images in the distinct techniques used in remote sensing.

The quantification of erosion processes through high-resolution techniques, scientific procedures based on previous-generation iterative processes, with the help of ground work, can make available for use new required insights to predict the total volume of eroded soil not only in any wetland but also elsewhere in the world. However, when the area is compound for a complex network of catchments and/or aquifers, it is necessary to use high-resolution orthophotography. A possible solution is the use of new image treatment techniques [9], which are nowadays accepted by all researchers around the world. In this sense, the main aim of this work would be to obtain the prediction of mean erosion in the study area (Tinto and Odiel salt marshes). In order to achieve that goal, it will be necessary to obtain, firstly, the prediction of volumetric change processes, which is a required secondary objective.

2. Research methods

2.1. Study area

Both Tinto and Odiel salt marshes, with a total area of 32,867,946.31 m² and 7185 × 10⁴ m², respectively, are located in the province of Huelva (southwest of the Iberian Peninsula), associated with both Tinto and Odiel river mouths, respectively (**Figure 1**).

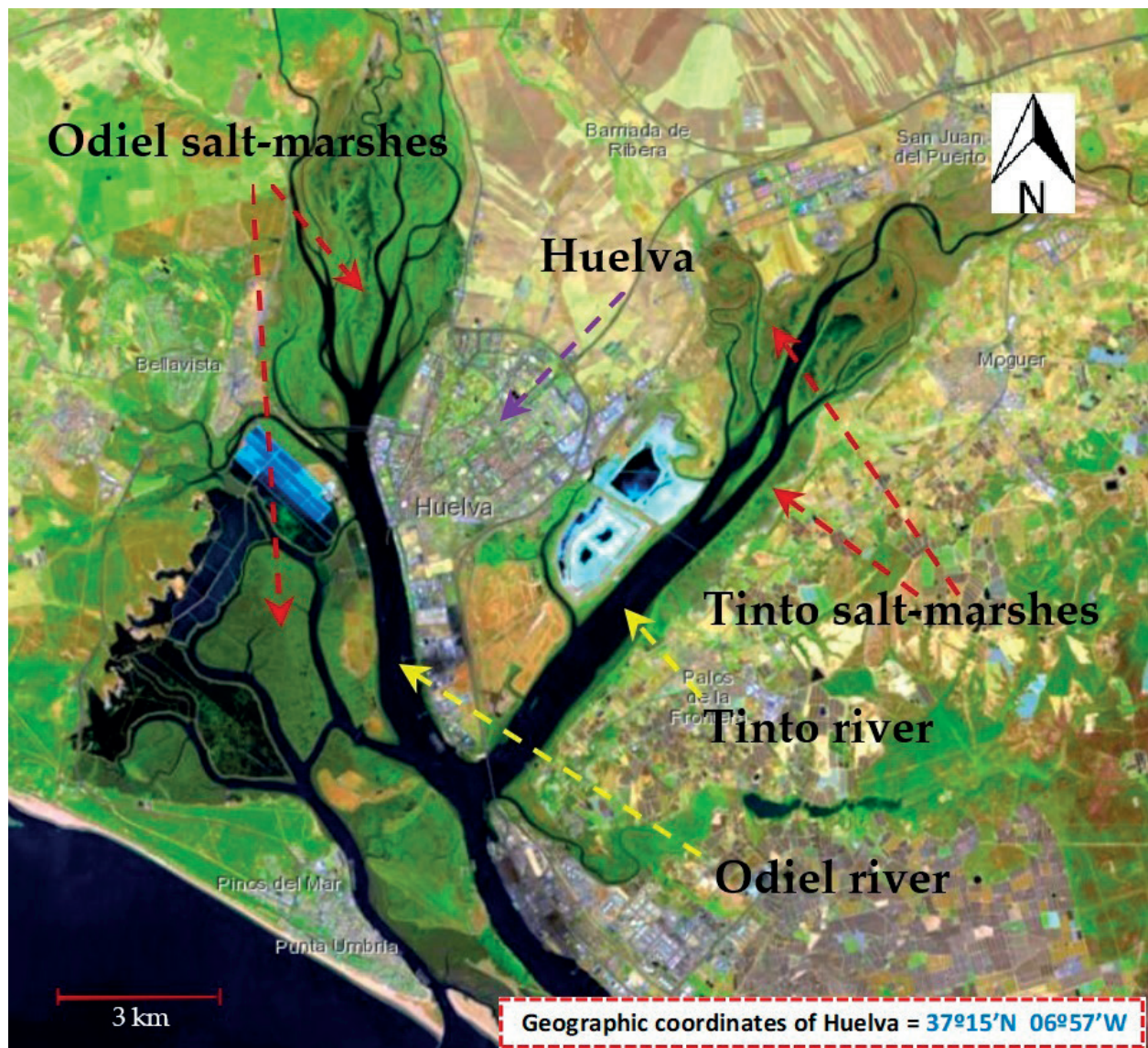


Figure 1. Location of study area (Landsat 8, bands 652).

In accordance with [4], the area is integrated in a complex system of estuaries of recent sedimentation affected, in their genesis, by the level of changes in the Earth's crust [10]. All sets are surrounded by tertiary formations of yellow silt and Miocene marls, Pliocene sands and marls, and remains of a Pleistocene erosive glacia. In the study area, both sedimentation and erosion processes are given simultaneously, influenced by a variation in space and time, creating a lot of seasonal or long-lasting physiographic characteristics giving rise to an appreciable diversity of habitats. The tidal movement is the key conditioning factor in shaping of these ecosystems.

On the one hand, Odiel salt marshes are composed of a set of islands crossed by numerous natural pipes. They are divided into the north marsh, comprising the Occidental, Central and La Yegua islands, and the south marsh, constituted by Bacuta, De Enmedio and Saltés islands. Moreover, Tinto salt marshes consist of a well-preserved tidal marsh area and another area, Dehesa de Alquería, where both woods and dry-land crops are predominant. The part of dry land located in the North is composed of clayey soils on which both native and migratory birds breed.

In the environment, the anthropic influence is very high. The raw sewage and solid waste from the Tartessos' Industrial Park (nearby to Tinto salt marshes) pour into the area. In the West is located the solid waste landfill of Huelva, where abounds discharges of debris due to the existence of the brownfield site. The vulnerability of the Tinto salt marshes area is variable (16% very high, 49% high, 34% moderate, 1% low) as a consequence of the risk of threat.

On the other hand, the area offers a Mediterranean maritime climate, with an insolation rate very high in comparison with North of the Iberian Peninsula. The decrease in the temperature in the winter season is responsible for the increase in the rainfall, while in the summer season, the temperature can reach up to 44°C (Tinto salt marshes) and 40°C (Odiel salt marshes), respectively. The average annual rainfall is 483.922 mm (Tinto salt marshes) and 506.6 mm (Odiel salt marshes), respectively, concentrated in the months of December and January, presenting, likewise, a dry season with deficient water balance between May and September [3, 4].

2.2. Methodology

For this study, a total of 24 control points (12 at Tinto salt marshes and 12 at Odiel salt marshes) were distributed throughout the study area (**Figure 2**), each of which was georeferenced in the ETRS-89 system.

In June 2017, the acquisition of images of both marshes were initiated using an Unmanned Aerial Vehicle (UAV) equipped with a radar system. During the low tide, along with the radar and RGB images were taken panchromatic images of 0.5 m resolution (Pléiades) collected from the AIRBUS DEFENSE & SPACE platform, from which data necessary for the study of the physical

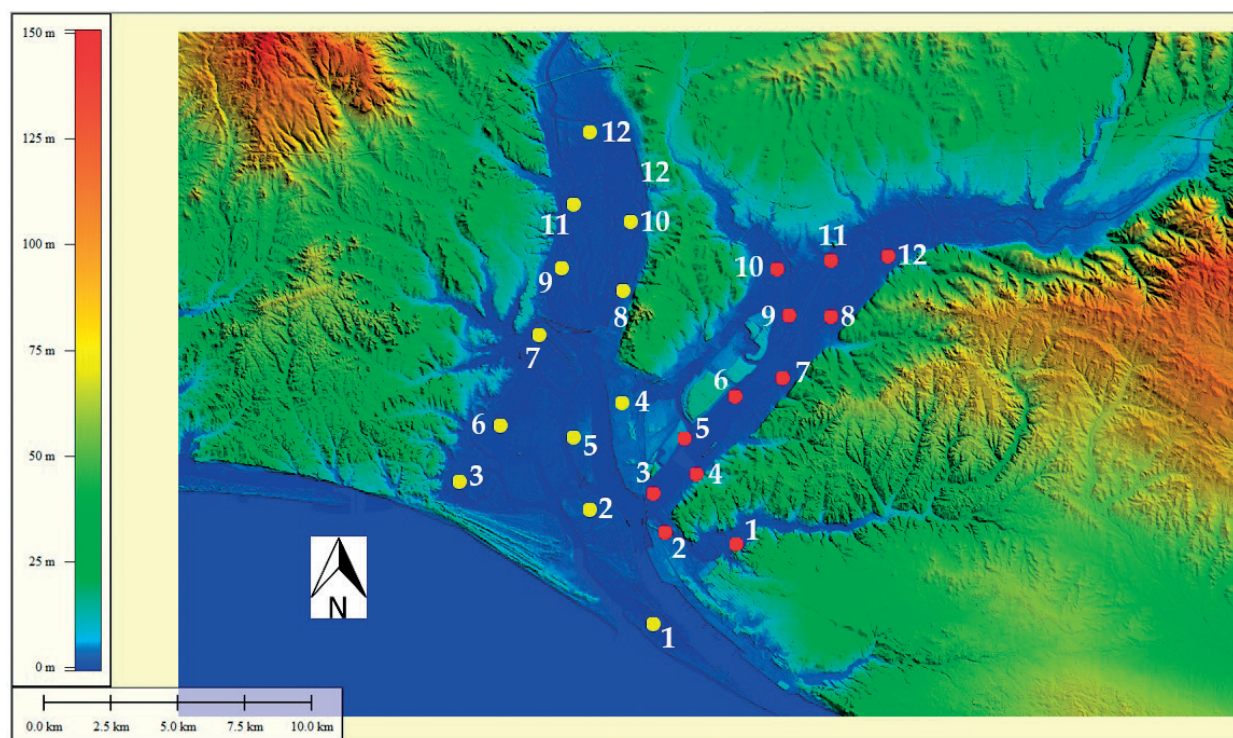


Figure 2. Distribution of control points (yellow points = Odiel salt marshes; red points = Tinto salt marshes) in the study area.

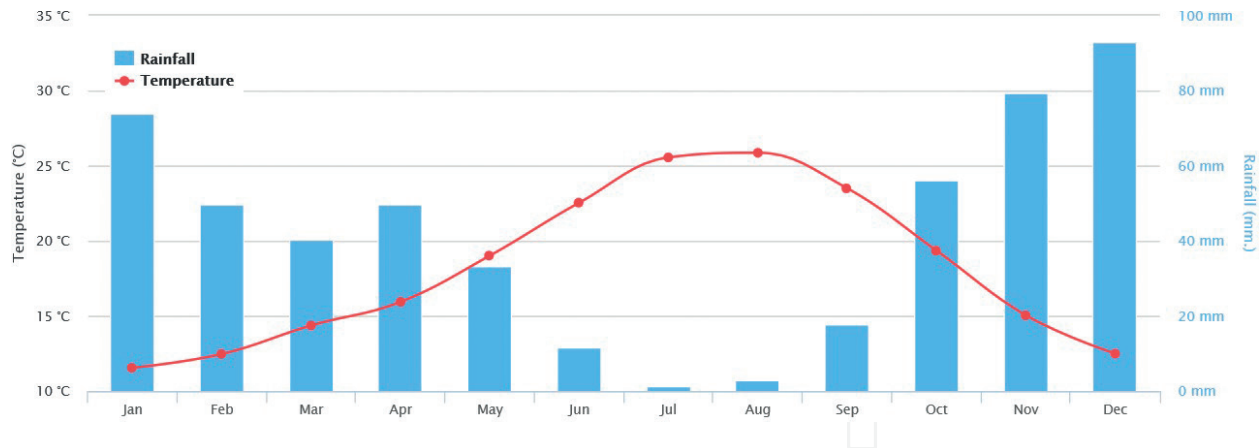


Figure 3. Average monthly temperature and rainfall for the period from 1901 to 2012.

characteristics of the marshlands was extracted), for the period from January 2016 to June 2017, and obtained in July 2017 (three high-resolution images were obtained per month since January 2016 to June 2017 in the study area), helped to adequately characterize the study area.

With a view to obtain the total cubic meters of eroded soil in the area under study, all the collected images were orthorectified by means of respective digital elevation model (DEM) of 25 m (of the year 1992–1999 and of 3 m of vertical precision) and 10 m (of the year 2001–2002, corresponding to LIDAR data with a dimension accuracy from the range of 0.15 to 0.30 m) resolution. The images obtained by the drone were orthorectified based on the DEM finished in the second half of July 2017, at 1.5 cm/pixel resolution, solved from the data captured by the radar sensor. All DEMs were complemented with selected control points in order to be able to calculate the total volume from iterative processes [11]. In the same way, the data treatment based on iterative processes was employed in order to obtain the average depth of the water in the study area, which was necessary to obtain the data on the soil eroded in the natural reserve.

According to [4], an exhaustive literature review was conducted in order to determine the potential existence of a rainfall record that covered a sufficiently broad time to obtain results, discussion and conclusions consequent with this study. From this point of view, the rainfall data were analyzed based on data provided by [12], which is necessary for the prediction of rainfall in the study area from 1982 to 2012 based on the correlation between the weather data from the nearby locations. A first approximation to climatic data is shown in **Figure 3**.

3. Results and discussion

3.1. Results

3.1.1. Land use changes

Both Tinto and Odiel salt marshes have undergone a major transformation due to an increase in the area dedicated to tourist activities. Based on [13] and by considering the LUCs between

1956 and 2007 in the altered areas, a significant growth was seen in these marshes as a result of the expansion of the urban fabric in coastal areas due to an increase in the tourism rate in the study area.

Crop evolution has been varied, while arable land has remained stable in terms of land area; the extent of another land uses, such as forestation has enormously decreased by 60% between 1956 and 2007. In the meantime, the area under irrigation has been aided by technological advances, giving rise to a huge area increase rate between 1956 and 2007.

Though there was a slight increase in Odiel salt marshes area in 2007, as a consequence of the increase in aquaculture, nature reserve total area was about 9% smaller compared to the existing area in 1956.

In order to be able to visualize the changes that occurred between 1982 and 2012, and in relation to rainfall data mainly, maps of detected changes were obtained in the study area from 1975 to 1990 (**Figure 4**), from 1990 to 2000 (**Figure 5**), from 2000 to 2005 (**Figure 6**) and from 2005 to 2012 (**Figure 7**). All maps were obtained by the difference between the NDVI values of images corresponding to the end date and start date of each time period.

In **Figures 4–7**, most areas are gray, indicating no change because each pixel has comparatively equal value in start date and the end date. Areas that show up green had more vigorous vegetation in the initial date, while areas that show up in magenta were brighter in the end date (meaning more vigorous vegetation on this date).

3.1.2. Prediction of volumetric change processes

Based on [3, 4, 7], and after having analyzed all the available data, a progressive decrease was detected in the surface water in the study area as a consequence of the dry period to which the area is subjected.

Afterward, and using the software Ilwis GIS, an analysis was conducted [7] between the average DEMs of each natural area (Tinto and Odiel salt marshes) and the climatic peculiarities of

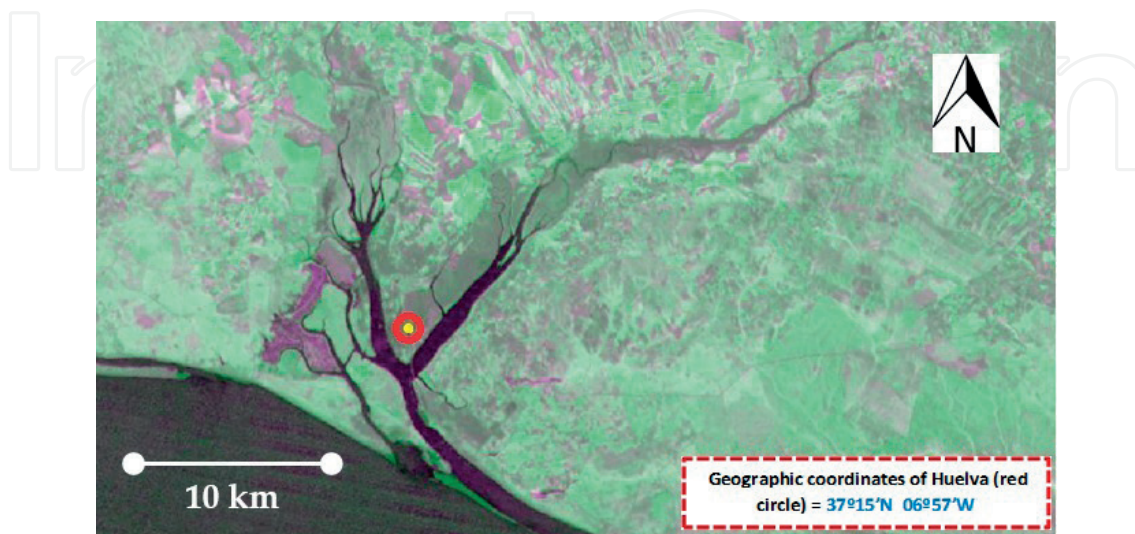


Figure 4. Detected changes in study area between 1975 and 1990.

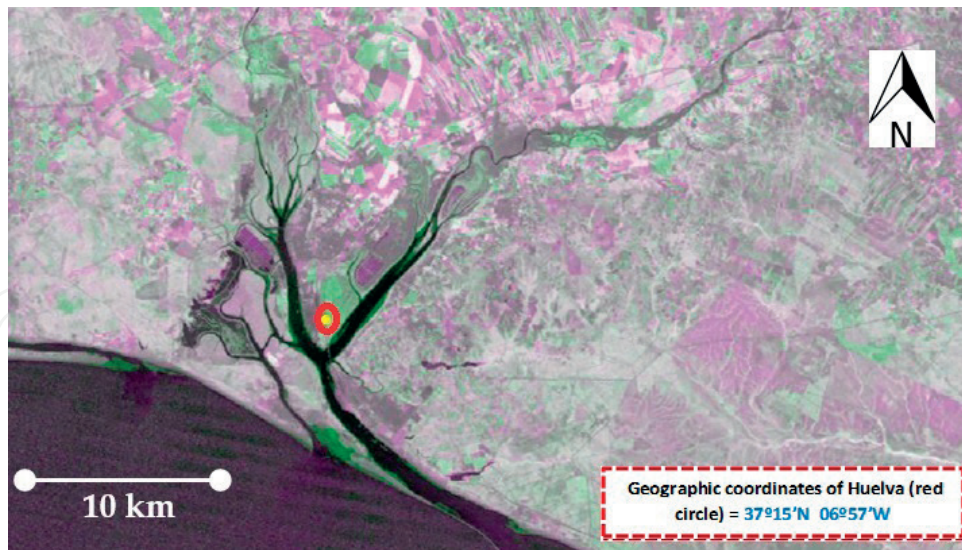


Figure 5. Detected changes in study area between 1990 and 2000.



Figure 6. Detected changes in study area between 2000 and 2005.

the area in order to obtain the prediction of the average cubic meters of flooded area in terms of the DEM used and salt marsh (Tinto or Odiel) taken into account (**Table 1**).

The estimated depth (**Table 2**), in each salt marsh, was obtained through iterative processes using a total of 1500 random sample points selected in the Pléiades images, a necessity to identify the eroded soil in both the Tinto and Odiel salt marshes.

As can be seen in **Table 1**, significant relationships were observed between the volume of water and the Tinto salt marsh surface, not becoming part of the model, the estimated depth (contrariwise, in Odiel salt marshes, estimated depth plays an important role in the model).

After having made the volumetric prediction of the Tinto and Odiel marshes, and based on the data of precipitation and on the topographical characteristics of the area of study, it was

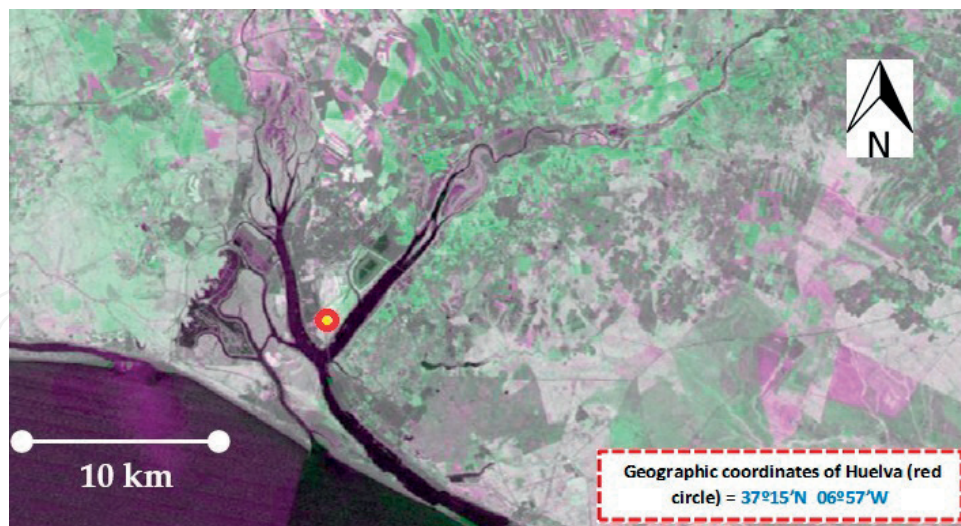


Figure 7. Detected changes in study area between 2005 and 2012.

Average DEM in:	Equation	Significance
Tinto salt marshes	$y = -8.490 + 1.627 \cdot Sr = 0.98 R^2 = 0.913 (1)$	≤ 0.001
Odiel salt marshes	$y = -18.269 + 2.059 \cdot S - 4.208 \cdot ED_r = 0.957 R^2 = 0.936 (2)$	≤ 0.001

“y” is the volume obtained in each marsh in hm^3 , “S” is the estimated area occupied by the volume in km^2 , and “ED” is the estimated depth in meters.

Table 1. Prediction of average flood volume based on the average DEM used in each marsh.

Control point no.	Estimated depth (m) for each salt marsh	
	Tinto salt marshes	Odiel salt marshes
1	0.16	0.40
2	0.35	2.97
3	1.51	3.04
4	1.94	3.08
5	2.74	3.08
6	3.00	3.10
7	3.07	3.19
8	3.10	3.22
9	3.11	3.24
10	3.21	3.35
11	3.23	3.37
12	3.30	3.91

Table 2. Estimated depth per control point based on the average DEM used in each salt marsh.

found that the total area of the Tinto marshes, 32,867,946.31 m², corresponded to a flood volume of 48.35×10^6 m³, while the total area of the Odiel marshes, 7185×10^4 m², corresponded to a flood volume of 110.28×10^6 m³. **Figure 8** shows the graph equivalent to the estimated surface area of both Tinto marshes and Odiel marshes, while in **Figure 9**, the graph of estimated volume in study area can be observed.

Furthermore, an analysis of the variance of a factor for correlated samples was conducted for the estimated depth variable (this analysis has been done after taking into account only the values shown in **Table 2**) and in terms of the average DEM used in each marsh. These results are shown in **Table 3**.

As can be seen in **Table 3**, there are significant differences ($p \leq 0.05$) between the estimated depth in both the marshes, which was expected based on the particular conditions of the Tinto marshes. Similarly, we must consider the level of anthropic pressure at the Odiel marshes as another factor of great importance.

3.1.3. Prediction of mean erosion in Tinto and Odiel salt marshes

The transport of sediments was obtained using the procedure patented by [9], whose results are shown in **Figure 10** (considering that both marshes are unique natural systems). In **Figure 10**, sediment transport is simulated for the period between 1982 and 2012, based on the sediment characteristics, precipitation and temperature existing in each marsh. It is very important to specify that these results are based on an algorithm that is dependent on the superficial shape factor existing in study area.

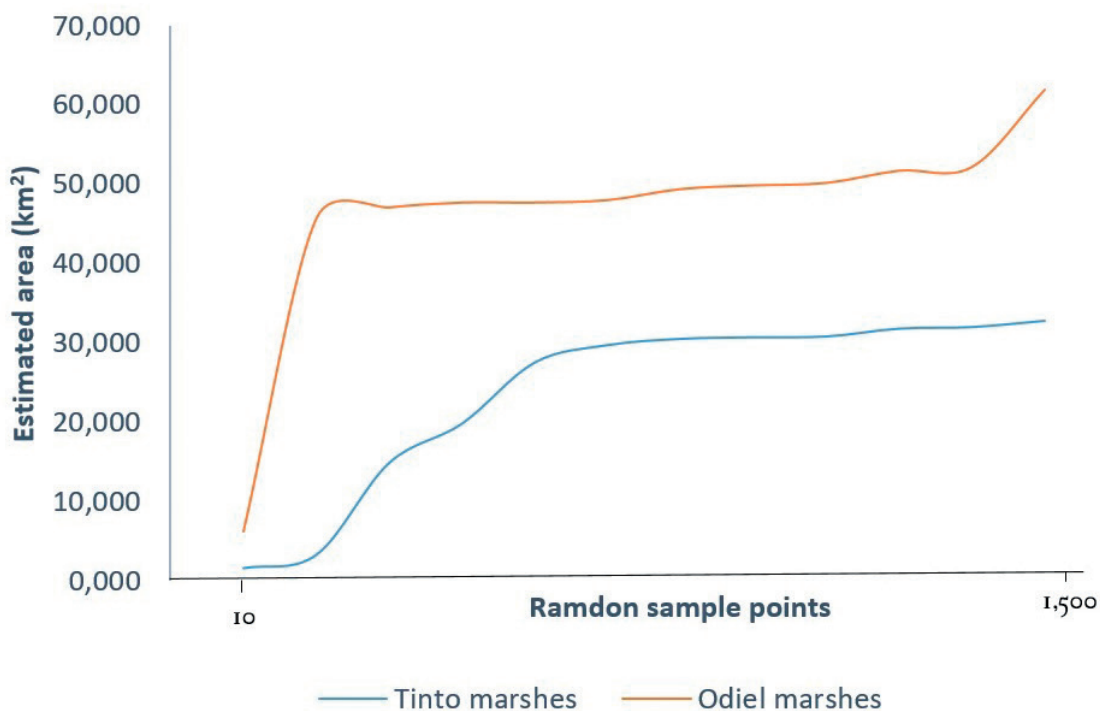


Figure 8. Estimated surface area by random sample points “1500 in total selected with Ilwis GIS”.

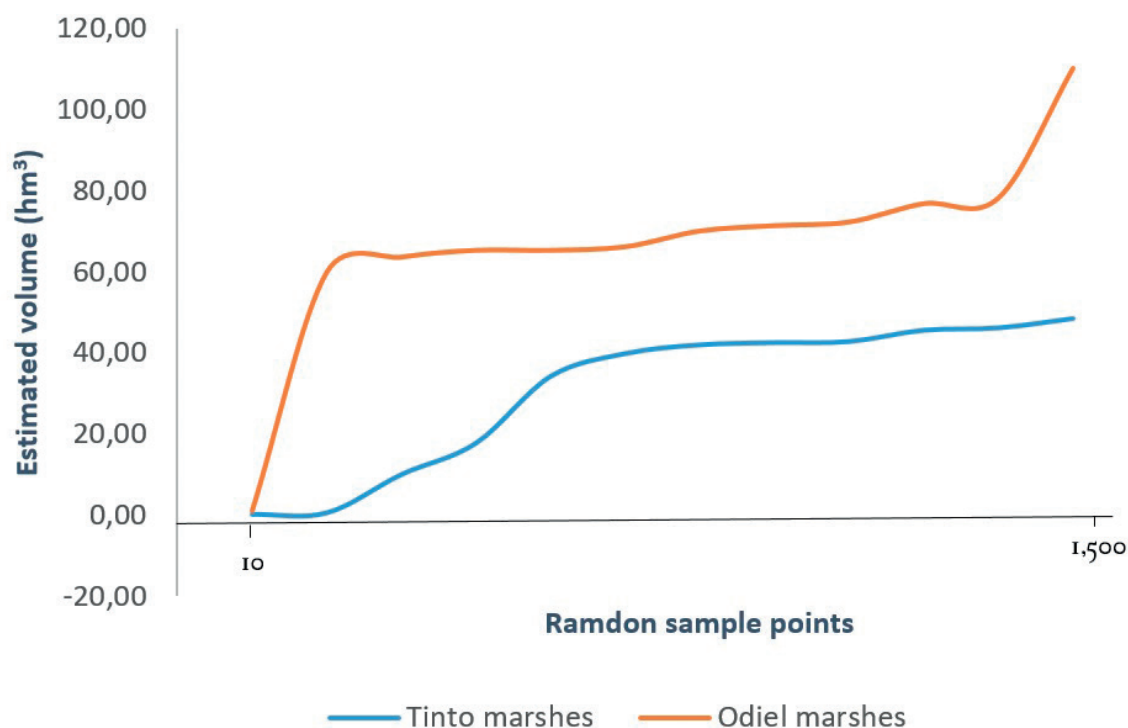


Figure 9. Estimated volume by random sample points “1500 in total selected with Ilwis GIS”.

	SS	df	MS	F	P
Treatment (between groups)	2.178	1	2.178	7.06	0.022303
Error	3.3946	11	0.3086		
Block (DEMs)	18.917	11			
Total	24.4896	23			

SS = sum of squares; df = degrees of freedom; MS = mean squared; F = value of the test statistic; P = significance.

Table 3. Summary of the analysis of the variance (ANOVA) for the estimated depth variable.

Based on **Figure 10**, and with the purpose of correctly visualizing the areas affected by the sedimentary transport in the study area, a simulation was carried out, using the patented algorithm by [9], corresponding to the levels of ± 0.05 m (**Figure 11**) and ± 0.1 m (**Figure 12**) of the eroded soil. As can be observed in both the figures, the main changes started in the western area.

In respect of Tinto salt marshes, it is important to specify that dynamics of the process of eroding divides these marshes into two zones. Firstly, the Southward zone has 0.20 m (mean value) of the total erosion, industrial activities being responsible for the erosion increase [3]. Secondly, the Northward area, with 0.10 m of the total erosion (mean value), and with the existence of the Tartessos' Industrial Park, presents a great problem related to the dumping of raw sewage and solid waste, which gives rise to the increasing vulnerability of the area.

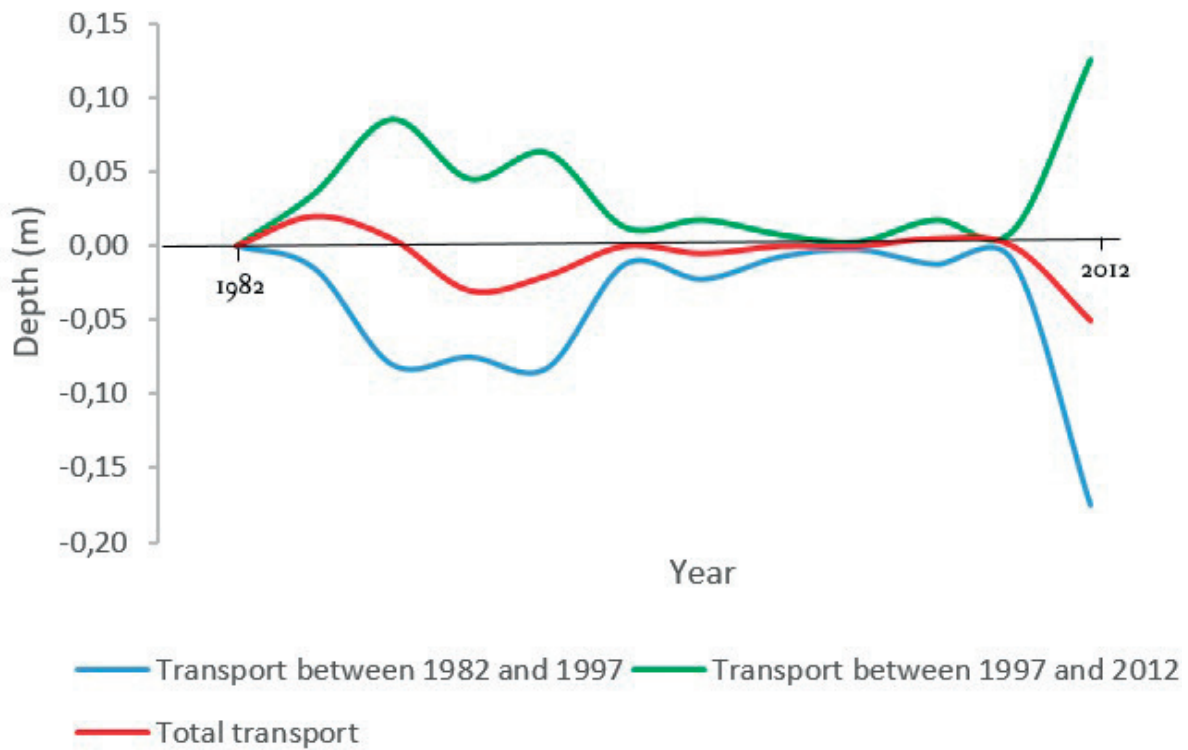


Figure 10. Variation of the depth in both the salt marshes in terms of average sediment transport from 1982 to 2012.

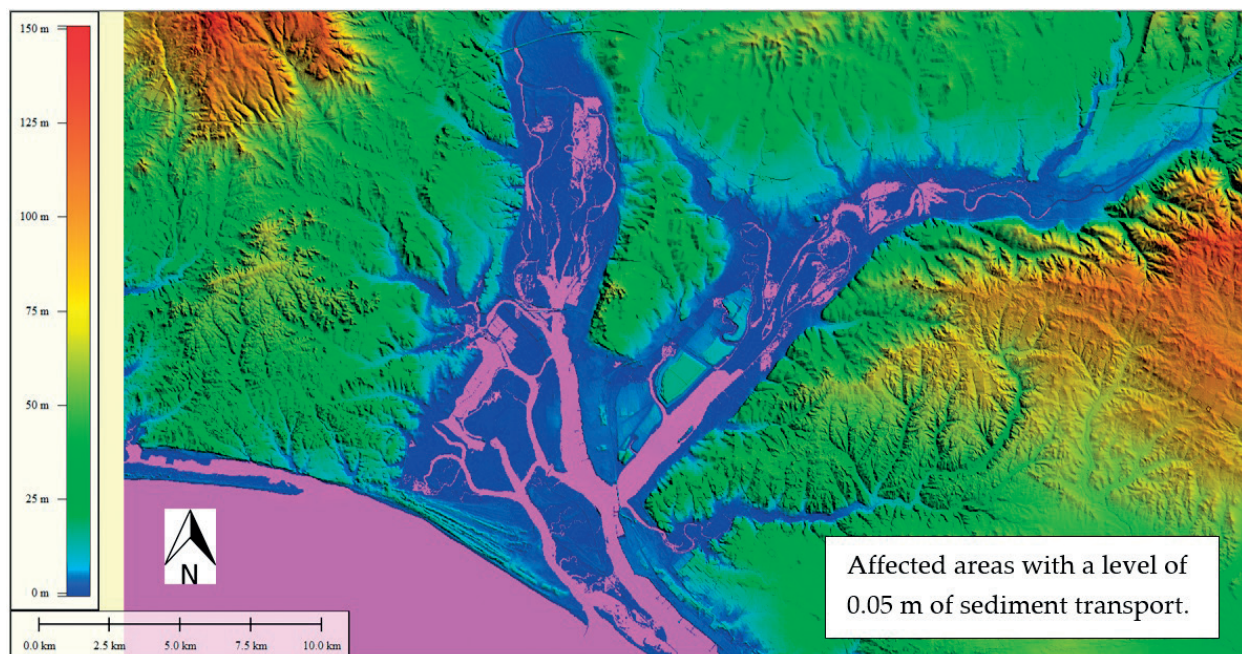


Figure 11. Eroded soil affected with a level of 0.05 m of sediment transport (in magenta).

3.2. Discussion

According to [14], one of the main causes of the rise of the tidal level in the study area, as well as its speed and drag force, is the wind speed (from 30 to 50 km/h). This fact is very important, since in the present work, it has been possible to verify that the maximum levels of sedimentary

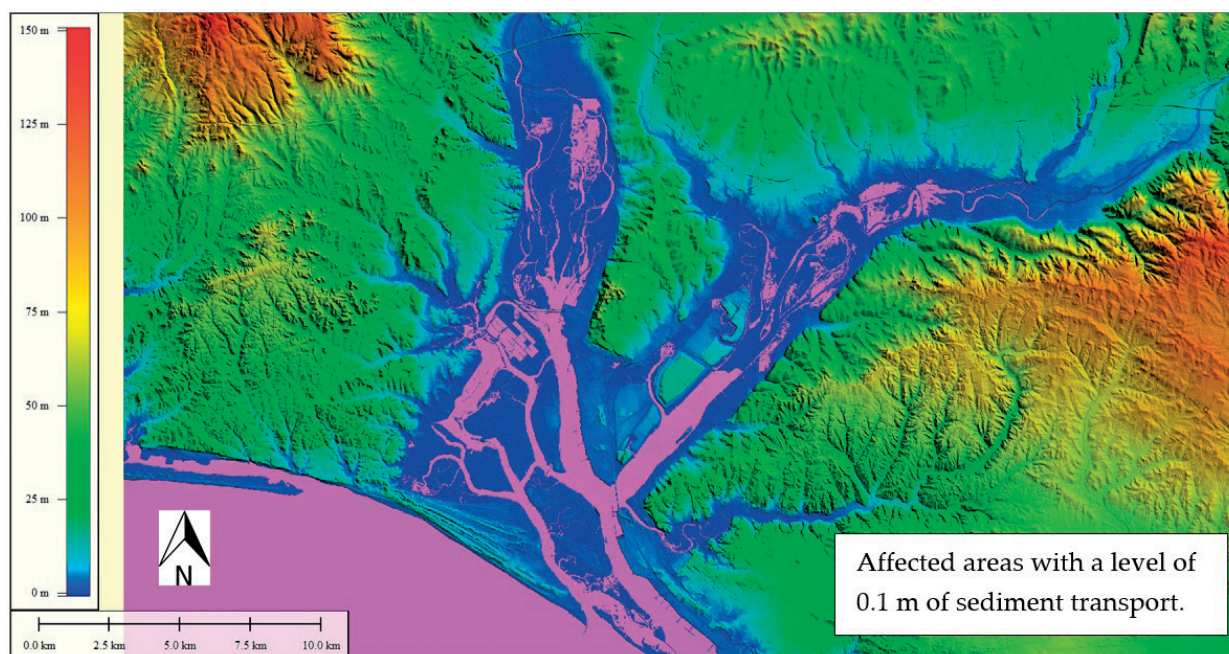


Figure 12. Eroded soil affected with a level of 0.1 m of sediment transport (in magenta).

transport present a direct correlation with the wind speed (always in the direction toward the Iberian Peninsula). Part of the LUCs that occur in the study area depend on this effect.

In relation to the transport of sediments, one aspect that needs to be taken into account is the construction of the Juan Carlos I breakwater, which interrupts the natural flow of sediments in the study area and gives rise to the fact that the marine currents carry these sediments toward Isla Cristina salt marshes [7], which causes an over silting-up in this natural area.

On the other hand, although the predictions of tides made by the Hydrographic Institute of the Spanish Navy for the ports are calculated with an accuracy of 1 cm in height, and 1 min in time, [14] showed that there are significant differences between the theoretical predictions and the real ones recorded by the tide gauge of the Port Authority of Huelva. This converts Eqs. (1) and (2) in an important prediction instrument, especially as a consequence of both the non-dependence of tide predictions and its high probability of success with reality.

Although this is the first time that predictive models have been obtained from the study area as a whole, it is important to specify that these could be used in other tidal-marshes independent of the South of the Iberian Peninsula, although correcting the results obtained with the prevailing climatic variables in each area.

4. Conclusions

Both the marshes existing at the study area experience an annual filling process coinciding with the months of highest rainfall and a water loss focused during the summery period. Comparing the occupied volume by water between 1975 and 2012, a slight decrease of the

annual water volume coming into these salt marshes was observed, which is related to the global warming in the study area.

The results obtained in the present study agree with those carried out by [3, 4, 7, 14] in distinct wetlands, so it can be deduced that the methodology patented by [9] has been validated, and it is completely safe and reliable.

According to [7], both remote sensing throughout UAV and satellite remote sensing of surface water fluxes and storages in wetlands is an immature but rapidly growing field. This research showed that combined remote sensing and GIS approach was very successful in visualizing the differences in salt marshes levels existing in the study area throughout the analysis period (1975–2012). In addition, Pléiades data were found to be very suitable for this analysis. Although hitherto Landsat data have been utilized for different types of remote sensing applications, other important platforms (Sentinel or SPOT) cannot be forgotten, whose resolution is better than Landsat in the majority of its bands.

The results show that high-resolution imagery can be used to visualize water-level variations as a result of changes in climatic variables. This may be required to create a public awareness about socio-ecologic problems caused by global warming.

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Conflict of interest

The author declares that there is no conflict of interest.

Notes/Thanks/Other declarations

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