Geomorphological response of the salt-marshes in the Tagus estuary to sea level rise

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ABSTRACT

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Salt-marshes are highly valuable ecosystems due to their role in supporting the aquatic and bird life. Furthermore, many anthropogenic activities such as agriculture, salt production or aquaculture targets these areas. They also act as protective barriers to shores, given their ability to dissipate most of the wave and current energy in high tide. Sea level rise can place these intertidal zones at risk, reinforcing the need to understand their morphosedimentary and dynamic response to the variations on the forcing factors, thus allowing for a better management of these environments. Large expansions of salt-marshes and tidal flats are among the morphodynamic contents of the Tagus estuary. This study focuses on the recent past evolution of Tagus marsh areas in order to understand their geomorphological response to higher sea level scenarios. Cores were taken in four contrasting high salt-marsh expansions in estuarine margins (Trancão – TR, Mouchão da Póvoa – MP, Pancas – PA and Corroios - CO). Marsh surfaces were surveyed using DGPS-RTK and tidal regime characterized at each location. The cores reached at least 1.20m in depth and were sub-sampled every cm for ^{210}Pb and ^{137}Cs radioisotope determination, allowing the derivation of sedimentation rates. In all locations, accretion rates clearly exceed the post-1920 mean rate of sea level rise (+0.21cm/year, Cascais gauge). Their linear extrapolation into the future, until reaching the upper threshold of marsh surface aggradation (MSHT), suggests that Tagus marginal marshes will not drown under the projected sea level elevation scenarios for the end of the 21th century.

ADDITIONAL INDEX WORDS: *Salt marsh, intertidal zones, morphodynamic,Tagus estuary, ^{210}Pb, ^{137}Cs, sea level rise.*

INTRODUCTION

Salt-marshes are upper intertidal morphosedimentary environments, which are generally composed of a muddy substrate hosting a dense stand of halophytic vegetation (Woodroffe, 2003). They can be found in a variety of coasts but are usually present along the sheltered margins of estuaries or low-energy open coasts. Salt marshes are important ecosystems due to their role in supporting the aquatic food chain, exporting nutrients to surrounding waters and providing nesting areas for migratory birds. These environments also act as protective barriers to the shores, given their ability to dissipate most of the wave and current energy in high tide. They can also remove and store pollutants from adjacent waters, which can then be released again if the marshes experience erosional episodes (Allen, 2000). These areas are also a target to many anthropogenic activities, such as agriculture, salt production or aquaculture.

The Tagus estuary is one example of the above statement. Despite being one of the largest and most important estuaries of Western Europe in ecological value (containing a natural reserve), most of its margins are occupied by anthropogenic activities (aquaculture, agriculture, recreational activities, industrial ports). Both the ecological and human values may be affected by near future sea level rise (SLR). This study focuses on the Tagus estuarine margins occupied by salt-marshes and on their ability to cope with expected sea level rise. To achieve this goal, data on sedimentation rates and sea level changes from the last 150 years and projections of these figures into the future have been analyzed. Results will contribute to improve management procedures and allow to fundament choices in what concerns adaptation measures.

STUDY AREA

The Tagus is the longest Portuguese river, having its source in Albarracin (Spain) and outflowing into the Atlantic, near Lisbon.

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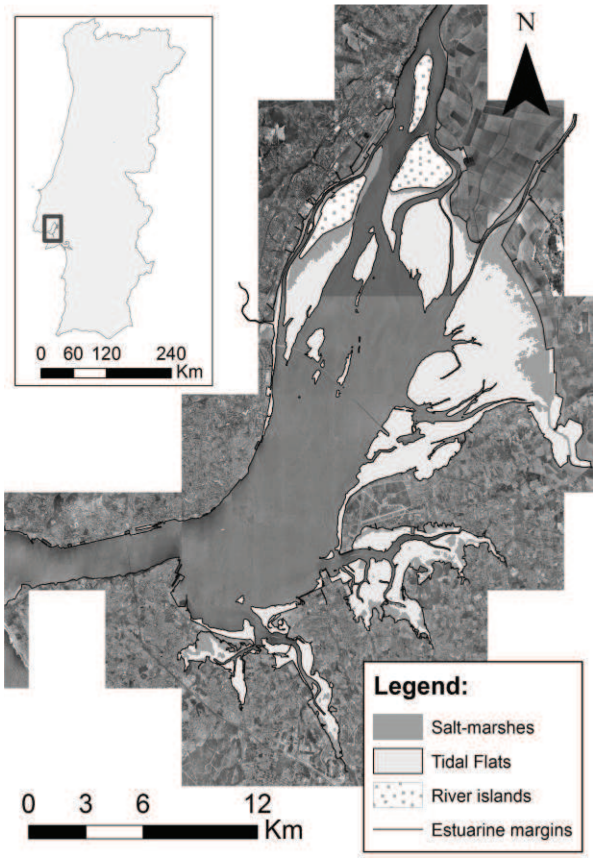

Figure 1. Location of the study area and delimitation of subtidal, intertidal and supratidal areas in the Tagus estuary.

In its lowest reach, the Tagus develops a wide and shallow estuary, covering an area of 325km^2 (Figure 1), and extending for 80km upstream until Muge at the limit of the dynamic tide (Bettencourt *et al.*, 2003). The saline wedge extends up to 50km of the estuarine mouth (i.e. V. Franca de Xira) for river discharge below the mean annual value (300m^3/s). The main body of the estuary is NNE-SSW oriented and connects with the ocean through a fault-controlled narrow inlet trending ENE-WSW. The morphology of the inlet (with a maximum width of 1.9km) and depth (ca. 40m) act as a natural barrier preventing oceanic waves from entering the estuary. Thus, the estuary hydrodynamics is mainly controlled by tidal propagation, and to a lesser extent, by fluvial discharge and locally generated waves (Taborda *et al.*, 2009).

The estuary is mesotidal (tidal amplitude varying between 1.5 and 3.2m) and tides are semidiurnal. A delay is observed between the oceanic and estuarine tides that can be as great as 2h in neap tides (Bettencourt *et al.*, 2003).The tidal cycle is asymmetrical, with floods lasting longer than ebbs (ebb dominated system). In the middle section of the estuary, tidal discharges vary from 40000 to 50000m^3/s (Freire, 1999), far greater than those resulting from mean annual fluvial contribution.

The sediments found in the Tagus estuary are to a large extent of fluvial origin. Marine sediments, mainly composed of sand, are restricted to the inlet margins. The bulk of the fluvial sediments consist of fine/medium sand, silt and clay, added by organic matter, which are transported as suspended or bed load; the main contribution comes from the Tagus basin, but the subsidiary streams directly outletting in the estuary, although being secondary contributors to the whole estuarine budget, may predominate in localized depositional areas. This is the case of the left margin, where the geological and geomorphological controls impose an extremely irregular development of the coast with deep and sheltered embayments. At the estuarine head, a tide dominated estuarine delta captures most of the coarse bed load delivered by the riverine channel.

The wide and shallow estuarine morphology, as well as the tidal amplitude, favour the development of vast intertidal areas (Figure 1). These environments, essentially located in the left margin, occupy approximately 40% of the estuarine area, of which 16km^2 consist of salt marshes.

METHODS

Four high salt-marsh expansions located in different settings along both margins of the estuary were selected with the aim of determining recent sedimentation rates (Figure 2). The sites of Pancas – PA, and Mouchão da Póvoa – MP are located upstream, and Trancão – TR, and Corroios – CO, further downstream. PA, MP and PR are marginal marshes, whereas CO develops in the embayment of Seixal, confined by the Alfeite sand spit.

From each studied site, one core was retrieved (Figure 2) using Van der Horst, Livingstone and gauge auger samplers, the minimum core length being 1.20m. Coring locations were selected away from the levees of the marsh creeks since those areas

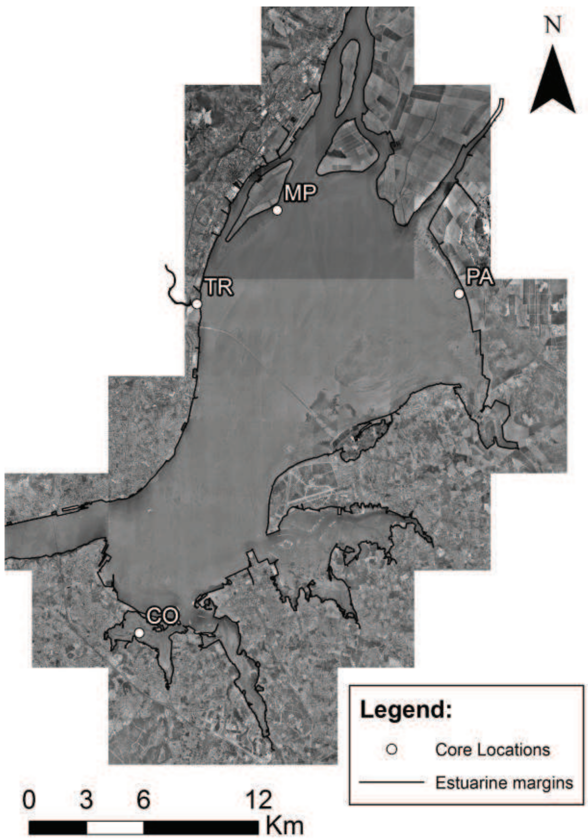

Figure 2. Location of the cores performed in the estuarine high marshes.

normally exhibit higher sedimentation rates (Allen, 2000).

Cores were packed in cling film and stored in PVC gutter to guarantee a safe trip to the laboratory, where they were photographed and sub-sampled every centimetre. Samples were selected from each core to establish the vertical profile of $^{210}Pb_{xs}$ and ^{137}Cs activities. Radionuclide measurements were conducted at the Université of Bordeaux using gamma spectrometry and results interpreted in term of sedimentation rates using the CF-CS model (Schmidt *et al.*, 2009), allowing the establishment of a chronological framework for the sediment deposition.

The marsh surfaces and the specific location of each core were surveyed using a DGPS-RTK (model Leica Viva GS08 NetRover).

Tide tables available in the Instituto Hidrográfico (IH) website were used to collect data from gauges located close to each study site (Table 1) and used to determine the local Mean Spring High Tide (MSHT), Mean High Tide (MHT) and Mean Neap High Tide (MNHT) elevations. Projection of future tidal behaviour considers tidal amplitude invariant. The average rate of sea level rise (SLR) characterizing the 1991-2000 decade (+ 2.1 mm/yr) and its acceleration (+ 0.024 mm yr^{-2}) was taken from Antunes and Taborda (2009) and refers to the Cascais tide gauge. Although Antunes (in press) indicates a greater SLR rate and acceleration of for the first decade of the 21st century, these data was not considered in projections of future elevations of the MSL because of its probable association with the non-stationary effect of the North Atlantic Oscillation (NAO).

RESULTS

Morphology

Topographic surveys of the studied salt-marshes show that their surfaces develop below the MSHT, considered in this study as the upper limit of salt marsh aggradation, in agreement with Davis and Fitzgerald (2004). This means that there is still accommodation space available in all of them for further sediment deposition (Figure 3). The areas of high marsh (characterized by a denser occupation of halophyte plants, scarce and deep tidal creeks and a surface positioned higher in the tidal range) are wider than those of low marsh (with a surface lower in the tidal range, a greater number of shallow tidal creeks and a scarcer colonization by halophyte plants) in all the studied sites. In fact, low marsh

Table 1. Tidal data from IH website. The elevation values refer to mean sea level (Cascais data). * Unpublished data, C. Antunes, FCUL, personal communication.

Location	MSHT (m)	MHT (m)	MNHT (m)	Data source
Pancas/ M. Póvoa	2.01	1.57	1.12	IH (36 yr)
Corroios	1.90	1.37	0.31	IH (2010/2011)
Trancão	1.82	1.49	1.12	* (2008)

expansions restrict to small fringes margining the very edge of the high marsh surface and also bordering creeks and salt pans. This feature, associated with a low density of creeks point to marshes in a mature development stage.

The transition between the high marsh and the tidal flat in Corroios and M. Póvoa salt-marshes is abrupt and marked by a scarp, whereas in Trancão and Pancas the transition occurs without any abrupt break in slope. In the latter cases, although the surface development provides an altimetric domain in which low marsh vegetation could develop, this was not observed in the field.

Sedimentation Rates

Sedimentation rates obtained in the different estuarine locations are not uniform.

At Pancas, the value inferred from the vertical profile of $^{210}Pb_{xs}$ is 2.2 cm/year. This value is in agreement with the location at 105cm of a peak in ^{137}Cs activity, corresponding to the maximum fallout of thermonuclear tests conducted in the atmosphere in 1963 (Figure 4).

At M. Póvoa, surface sediments show a mixed layer in the ^{210}Pb activity; this is not unusually observed and may be the result of the dilution effect caused by grass. The highest correlation of a logarithmic fit to the data (r^2>0.94) is obtained excluding the samples above 5cm and results in a sedimentation rate of 1.4cm/year. Considering the profile in ^{137}Cs activity, two estimates of sedimentation rates may be obtained: one, of

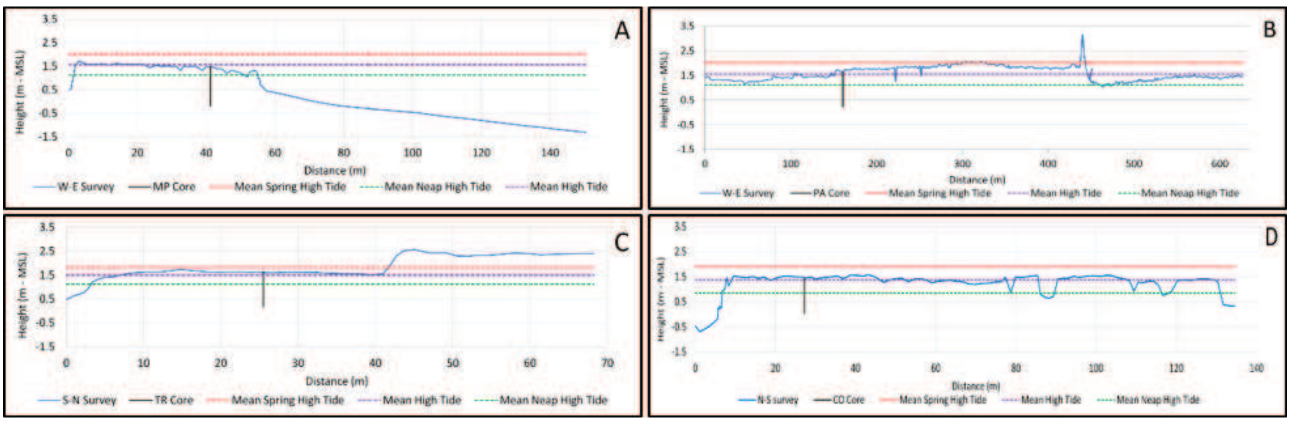

Figure 3. Topographic profiles surveyed on the studied salt-marshes. A- M. da Póvoa salt-marsh; B- Pancas salt-marsh; C- Trancão salt-marsh; D-Corroios salt-marsh.

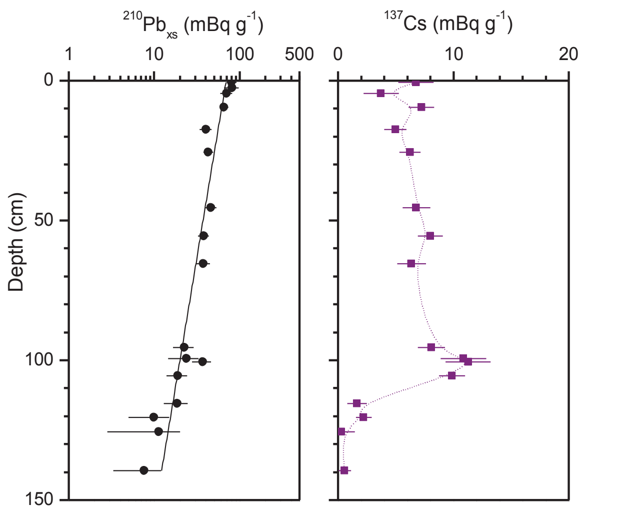

Figure 4. Profiles of $^{210}Pb_{xs}$ (left) and ^{137}Cs (right) with depth in sediments of Pancas sites.

1.2cm/year, taking the peak in ^{137}Cs activity (corresponding to 1963) at 55.5 cm; other, of 1.3 cm/year, taking the appearance of ^{137}Cs activity in the sediment at 72 cm as related with the onset of massive thermonuclear atmospheric detonations in 1954. These figures are mutually consistent and in reasonable agreement with those derived from ^{210}Pb.

In the Corroios marsh, the topmost samples also show a decrease in the ^{210}Pb activity. This, as in the M. Póvoa core, can result from the dilution effect by grass. The highest correlation of a logarithmic fit to the data (r^2>0.76) is obtained excluding the samples above 10cm and yields a sedimentation rate of 0.6cm/year. The ^{137}Cs activity profile shows appearance at 30.5cm and a well-defined maximum at 21.5cm. In both cases, the inferred sedimentation rates are 0.5cm/year, in consistency with ^{210}Pb results.

At Trancão marsh, the estimated sedimentation rates departing from ^{210}Pb are of 0.7cm/year. However, the peak of activity in ^{137}Cs related to 1963, comes out at 17.5cm, i.e., too shallow to be congruent with ^{210}Pb results. Dating this peak using 0.7cm/year indicates 1986, in coincidence with the Chernobyl nuclear disaster. Being the only peak in the profile, it is bizarre that the 1963 maximum is not represented. If the appearance of ^{137}Cs is considered, a sedimentation rate of 0.5cm/year is obtained, which approximates the rate derived from ^{210}Pb.

DISCUSSION

The sedimentation rates characterizing all studied salt-marshes (PA – 2.2cm/year, MP – 1.4cm/year, CO – 0.6cm/year and TR – 0.7cm/year) largely exceed the mean rate of sea level rise (+0.21cm/year) determined at the Cascais tidal gauge by Antunes and Taborda (2009). Accretion rates forwarded here are of the same magnitude, though slightly lower, than those reported by Salgueiro and Caçador (2007) using sediment traps during 9 months. These authors indicate sedimentation rates of 4.0, 1.8 and 0.5cm/year for Vasa Sacos (located near Pancas), S. João da Talha (located just north of the Trancão) and Corroios marshes.

Validation of sedimentation rates determined in this study was also tried by comparison with erosion/accretion maps resulting from bathymetric surveys performed in the estuary in 1928/30 and 1964. Unfortunately, the bathymetric surveys were conducted mainly in subtidal areas, scarcely overlapping the MP salt marsh area. A histogram was constructed using data from this comparison in the area intersecting the MP marsh (Figure 5). Although methodologies and time intervals are different, results are in fair agreement.

Sedimentation rates determined in the upstream area of the estuary are higher and decrease towards the mouth. This is not an unexpected result as the major concentration of suspended sediment is delivered at the estuarine head, namely in relation with the main river channel and the outlet of Sorraia tributary (Bettencourt *et al.*, 2003). Vast areas of tidal flats, which are the main nurturing areas of the salt-marshes (Allen, 2000), can be found in that zone.

Sediment availability is an important factor on whether the sedimentation rates determined in this study will be maintained in the future.

Given that the flow regime of the Tagus is at present fully controlled by engineering works conducted throughout the 20^{th} century, and that no other interventions are planned in the coming decades, it is reasonable to assume that the sediment input to the estuary will not suffer significant changes in the present century. These works will also prevent eventual increase in sediment input due to lower but more concentrated precipitation related to climate change.

Comparison of sedimentation and projected sea level rise rates, suggests that salt-marshes in the Tagus estuary will not be drowned. This projected behaviour is similar to those reported by Pye and French (1993) and Dijkema *et al*. (1990) (*in* Allen, 2000) for other European marshes, namely in Britain and in the Wadden Sea.

The topographic surveys performed in the selected Tagus estuarine marshes show that all marsh surfaces lie under the upper threshold of accretion; hence, accommodation space exists for further deposition of sediment. Thus, it is expected that the Tagus salt marsh surfaces will continue aggrading. Although the rate of

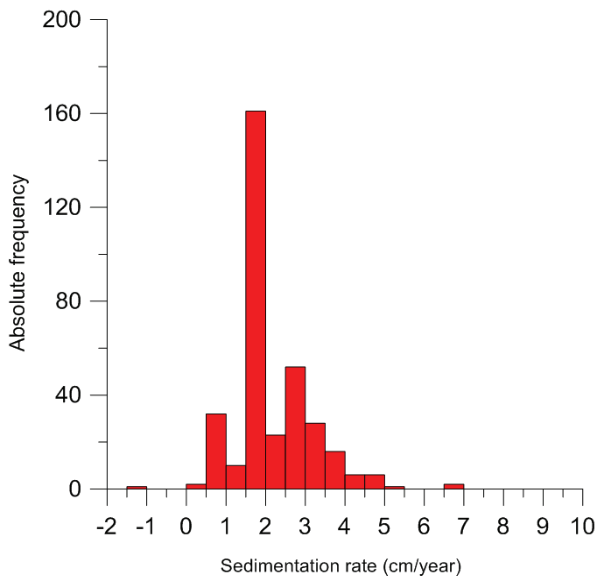

Figure 5. Histogram with the absolute frequency of sedimentation rates determined by topographic comparison on the area surrounding the MP marsh.

marsh surface accretion decreases with the increase in elevation, this inverse relation is quasi-linear in early stages of development of the high-marsh and becomes essentially non-linear close to the upper limit of aggradation. In the case of Tagus marshes, the former case applies, there is plenty of accommodation space, making it reasonable to extrapolate linearly into the future as a first approach.

Applying a linear extrapolation of the sedimentation rates reported in this study into the future a first estimate of the time-window remaining until the MSHT is reached by surface accretion, may be computed (Figure 6). According to this model, the PA marsh will reach the upper threshold in 2031, whereas TR and MP will take longer to reach the same threshold, in 2061 and 2057, respectively. The CO marsh is the only one reaching that upper limit beyond the 21st century.

Once MSHT height is reached, salt marshes will continue to accrete but at the same rate as the rise in sea level. Another possibility is that the marsh areas will start a process of terrestrialization, but that would only be possible if the organic component of the sedimentation rate determined for each marsh is higher than the rate of SLR (Allen, 2000). Further studies are needed to determine if that is the case in any of the selected marshes.

CONCLUSIONS

Sedimentation rates obtained for the Tagus estuarine marshes vary between 0.4 and 2.2cm/year, being higher close to the estuarine head. These values exceed the rate of sea-level rise observed in the recent past (2.1mm/yr). This strongly suggests that the Tagus estuarine salt marshes will not be drowned in the forthcoming decades in a scenario of steady sea level rise.

At present, marsh surfaces are below the upper threshold for surface aggradation (MSHT), thus preserving potential to accrete. Linear extrapolation of rates of sedimentation and SLR, indicate that the upper threshold of accretion will be reached in a time interval varying from 20 to 100 years. The time intervals determined for each site can be considered a minimal estimate because, as marsh surfaces grow in elevation and become inundated during shorter periods, the sedimentation rates tend to decrease.

This preliminary work yields new and useful insights on future responses of the Tagus estuarine margins to projected SLR, contributing to the management of this area and design of adaptation measures.

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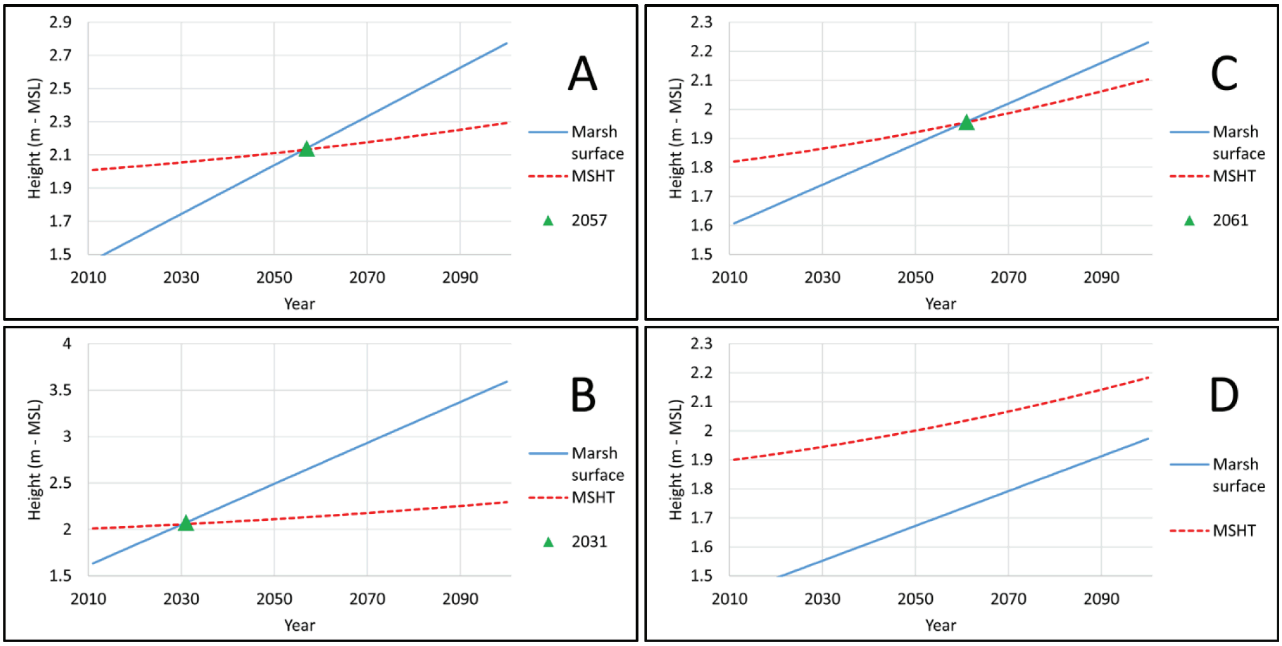

Figure 6. Linear extrapolation of the marsh surfaces heights *vs.* MSL rise until 2100.

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