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LONG-TERM COASTLINE EVOLUTION OF FIGUEIRA DA FOZ – NAZARÉ SECTOR (PORTUGAL)

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ABSTRACT: Some sectors of the west Portuguese coast are particularly endangered by erosion and flooding. Regional to local scale information, on coastline evolutionary trend, is particularly valuable in sectors that includes areas with relevant erosion. A continuous, high-resolution, dataset on coastal evolution, from 1947 and 2015, between *Figueira da Foz* and *Nazaré*, was achieved within the Programme "Geological and Coastal Hazard Mapping at a 1:3000 resolution scale" at the National Laboratory of Energy and Geology (LNEG).

This work, due to the detailed scale of analysis in a wide geographic context, allows to have both, a general overview of the coastal evolution and, at the same time, when zooming in up to 1:3000 scale, to observe the local behaviour and to quantify the occurred changes. Also, the well time-spaced aerial photograph dataset allows to compare the resultant coastline movement between the oldest and the youngest coastline (NSM index), with the total coastline oscillation (SCE index), bringing new insights on the coastline stability at a local scale.

The evolution trend shows an overall erosional behaviour, if considering the entire sector. Erosion occurs predominantly in the north, as the south shows more stability and progradation. Quantification of the land-lost and land-gain due to the coastline shift in a 68-year period shows that 1 164 888 m^2 of land were lost along 30 470 m of the coastal fringe, and 462 330 m^2 were gained along an extension of 21 010 m.

Keywords: Coastal hazard mapping; Western Portuguese coast; Coastline evolution; Coastal erosion and accretion; Digital Shoreline Analysis System (DSAS).

RESUMO: *Alguns sectores da região oeste da costa portuguesa estão particularmente ameaçados por fenómenos de erosão costeira e inundação. A informação sobre a tendência evolutiva da linha de costa, a uma escala regional e local, é particularmente importante em sectores onde se verifica erosão costeira relevante. Dados contínuos, de alta resolução, sobre a evolução da linha de costa entre 1947 e 2015, no sector costeiro entre a Figueira da Foz e a Nazaré, foram produzidos no Laboratório Nacional de Energia e Geologia (LNEG) no âmbito do Programa "Cartografia Geológica e de Perigosidade da Zona Costeira, à escala 1:3000".*

Este trabalho, devido à análise realizada a uma escala de grande detalhe, permite ter uma visão geral da evolução da linha de costa deste sector e ao mesmo tempo, ampliando à escala 1:3000, observar o seu comportamento bem como quantificar as mudanças ocorridas em pequenas áreas. Além disso, a análise de um conjunto de dados de fotografias aéreas, espaçadas no tempo, permite comparar a evolução da linha de costa entre o período mais antigo e o mais recente (índice NSM), com a oscilação total da linha de costa (índice SCE), trazendo um novo conhecimento sobre a sua estabilidade a uma escala local.

A tendência evolutiva mostra um comportamento erosivo global, se considerado todo o sector analisado. No entanto, a erosão ocorre predominantemente no sector norte, sendo que a zona sul apresenta mais estabilidade e progradação. A quantificação da perda e ganho de território devido às variações da linha de costa durante os últimos 68 anos mostra que se perderam 1 164 888 m^2 de território ao longo de 30 470 m da orla costeira, havendo um ganho de 462 330 m^2 ao longo de uma extensão de 21 010 m.

Palavras-chave: Cartografia de perigosidade costeira; Litoral português oeste; Evolução da linha de costa; Erosão costeira; DSAS.

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1. INTRODUCTION

The coastline of the Portuguese mainland extends approximately along 900 km, having a wide morphological diversity and comprising a multiple range of environments, being the beaches, wetlands, hardened and cliffed coasts the main typologies.

As ¾ of the population live in the coastal areas, generating around 80% of the gross national product, this sector has a considerable economic importance (Santos and Miranda, 2006). Moreover, worldwide, but particularly in Portugal, coastal environments are critically endangered by flooding and erosion, which will be expectedly intensified by the climate change effects, consequently placing more emphasis on the need of an urgent holistic approach to a successful adaptive coastal governance (Taveira-Pinto et. al., 2021, Vousdoukas *et al*., 2020; Schmidt *et al*., 2013, Coelho et. al., 2009).

The achievement of updated and reinterpreted regional to local-scale information, on long-term coastline evolutionary trend, is particularly valuable in areas with relevant erosion as the safety measures to apply in those sectors should be strongly supported and backed by scientific information. That is the case of the centre of Portugal western coast, as shown in previous studies, which is significantly endangered by erosion, with average values of rate of change, varying between - 0.19 and - 0.91 m/year (Lira *et al*., 2016).

In order to refine and contribute to the knowledge of this peculiar coastal sector, a high-resolution coastal evolution assessment of the sandy coastline sectors from *Figueira da Foz* to *Nazaré*, for a 68-year period and with an approximately 10-year interval, has been determined within the Programme "Geological and Coastal Hazard Mapping at a 1:3000 resolution scale" of the National Laboratory of Energy and Geology (LNEG) (Nave and Rebêlo, 2018). It is expected that the produced dataset constitutes a valuable tool and a contribute to support coastal managers and users of littoral regions.

2. REGIONAL SETTINGS

The western Portuguese coastline is fully exposed to the strong energetic marine wave climate, which, in combination with an NNW-SSE orientation, is powered by a high magnitude of potential of longshore drift (of the order of 10^6 m^3year^{-1}) (Santos *et al*., 2014).

According to the geomorphological characteristics and sedimentary dynamics cells that characterize the continental Portuguese coastal classification (Andrade and Freitas, 2002; Santos *et al*., 2014), which divides the coast in 8 cells, the study area (figure 1) is located at the western side within the designated first cell (which extends from the mouth of the river *Minho* to *Nazaré*). Cell 1 was, in turn, divided into 3 sub-cells: from *Minho* to Douro (1a), from Douro to Cape *Mondego* (1b) and Cape *Mondego* to *Nazaré* (1c) (Santos *et al*., 2014), being the last sub-cell extent, the focus of the current work. The intense and growing human activity on the coast, and also on hydrographic basins, has led to a sharp reduction in the sedimentary supply (Veloso-Gomes et. al., 2004, Oliveira *et al*., 1982;), to which was associated an erosion tendency of specific segments of this cell, namely *Espinho - Furadouro*, *Costa Nova - Mira* and *Cova Gala - Leirosa*.

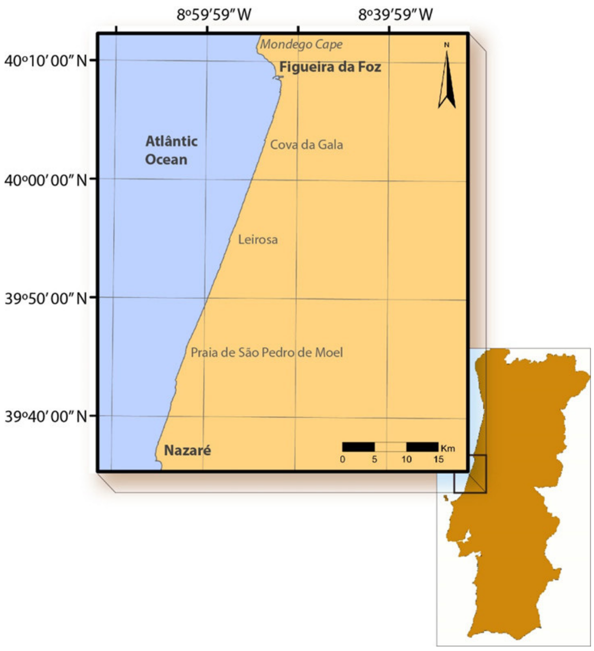

Figure 1. Study area: the western Portuguese coastal sector from *Figueira da Foz - Nazaré* (sedimentary sub-cell 1c).

The *Figueira da Foz - Nazaré* littoral sector comprises, mainly, three types of environments: low-lying beaches, where 72 % of them are backed by dunes (Lira *et al*., 2016), hardened coasts and cliffed shores, bordered, or not, by narrow beaches.

Although showing an apparent continuity, a diverse coastal geology plays an important role in coastal processes and hence, in the different existent coastal morphologies.

At Cape *Mondego*, the coast is rocky, with cliffs and a marine abrasion platform carved mostly in limestones, passing progressively to a sandy beach, which become extremely wide, north of the *Mondego* River, due to the sand retention on the northern breakwater of the *Figueira da Foz* harbour (Santos *et al.*, 2014).

From the *Mondego* River mouth to *São Pedro de Moel*, a straight low-lying sandy coast prevails, with wind-blown sand migrating inland. A foredune or, more rarely, a sequence of foredunes, backed by an extensive transgressive dunefield is the most common geological setting. Rivers play a local role in shaping the coastline and its change. In some sectors a morphological depression between these two different dune systems exists, which favours the marine intrusion when the foredune ridge is eroded. Some foredunes ridges are related with fences, deployed in the recent past as sand traps. Those structures are presently visible in the actual dune erosion scarps and are a good indicator of coastline retreat.

São Pedro de Moel plays nowadays an important role in the coastline evolution for several reasons: (1) it acts as a natural groin, anchoring the shore position and promoting updrift accumulation; (2) south of this locality the coast is dominated by a rocky shore; (3) south of this point the higher altitude of the bedrock, if compared with the northern sector, gives rise to a cliff coast bordered by a narrow beach and (4) the effect of a slightly northward orientation of the coast, induces a small increase in the potential of the coastal drift (Santos *et al.*, 2014), which may contribute, in some sections, to the presence of a small beach, limited by cliffs and promontories. Although the transgressive dunes continue to exist as a top cliff dunefield, the continuity between beach and the dunefield is generally interrupted as a result of a smaller sediment availability. Aeolian ramps and climbing dunes, which allows the inland sand migration, are only visible at the south of the study area, north of the *Nazaré* promontory (an approximately 3,7 km coastal stretch), as a result of sand accumulation against the natural cliff, even in scarce sedimentary periods, as presently.

The two main sources of sediments to this sector (sub-cell 1c) are related with the Cape *Mondego* sediment bypassing and the *Mondego* River sediment discharge. The sediments that cross the *Mondego* Cape are transported southward along *Buarcos* beach to *Figueira da Foz* beach. Here, its natural course is conditioned by the northern breakwater of the *Mondego* River, which promotes a sedimentary retention northward that structure, causing the observed exceptional growth of *Figueira da Foz* beach from 1960 to 1980 (Dias *et al.*, 1994 in Santos *et al.*, 2014). These promoted coastal morphology and river flow changes, alongside with the updrift sediment retention, induced a noticeable retreat of the coastline southward, on the *Cova Gala - Pedrogão* section, which led, as a safety measure, to the construction of a set of rigid coastal protection structures. As result of a new 400 m expansion of the north jetty, that occurred between 2008 and 2010, there was a new increase in the northern beach width, exceeding 500 m. This increased retention reinforced, once again, the previously installed erosive trend on the southward sectors, especially at *Cova Gala*, *Lavos* and *Leirosa*, which likely extends even further south (André and Cordeiro, 2013).

As a result of the observed erosive process, mitigated by the dredging promoted by the port with sediment deposition near shore of *Cova Gala*, it is estimated that the sedimentary transposition is slightly more than half of the potential drift (6×10^5 $m^3 year^{-1}$) (Santos *et al.*, 2014). However, following the saturation of the north jetty, it is expected that the volume of sediments that (naturally and artificially) cross the inlet tends to increase, reducing the observed severe erosion process.

The southern limit of the study area, which coincides with southern limit of the cell 1c, is characterized by two major morphologic features that have a major influence in the littoral drift: the *Nazaré* promontory and the *Nazaré* canyon.

The *Nazaré* promontory acts like a natural groin and is responsible for an updrift sand accumulation. The *Nazaré* canyon, that extends from a water depth of 50m near the Portuguese coast to 5000 m at the edge of the Iberian Abyssal Plain. Even though the canyon constitutes a giant sedimentary sink, its influence on sediment transport is up to the beach (Beach to Canyon (2013). Actually, the canyon system is not draining sediments from a modern river obtaining, instead, its present-day sediment input by capturing of along-shelf sediment transport and depositing much of it in the middle canyon, between about 2700 and 3800 m (Masson *et al.*, 2011). Thus, most of the sand transported southward in the coastal drift (11×10^5 $m^3 year^{-1}$) is conducted, and therefore totally lost, to the deep ocean by the *Nazaré* canyon system (Santos *et al.*, 2014).

3. METHODOLOGY

As the produced data intends to be comparable to the previous systematic works carried within the "*Geological and Coastal Hazard Mapping at a 1:3000 resolution scale*" programme of the National Laboratory of Energy and Geology, the used methodology is similar to the one described at Nave and Rebêlo (2021).

3.1 Coastline indicator

As the objective of the current work is to provide high-resolution quantitative data on the long-term (nearly 70 years) coastline evolution, the foredune shoreward edge was used as a marker of the coastline to exclude short-term (tidal) variations or medium-term (seasonal) variations, as described at Nave and Rebêlo (2018) and references therein. In cliff areas, the position of the coastline was marked using the boundary of the cliff base (Rebêlo and Nave, 2019).

The continuous coastline position was smoothly depicted at the maximum scale of 1: 800 to undoubtedly identify the outer limit of the dune zone. Interruptions in the vegetation line of less than about 150 m were not considered, maintaining in this case the continuity of the line between adjacent segments. In the case of settlements or large infrastructures that hindered the expansion of the dune field, the continuity of the line between adjacent segments of the interruption was also considered (Rebêlo and Nave, 2019).

In order to determine the error inherent to the operator, for each year, the coastline was marked by two different operators using the same criteria. The coastline used for each year thus corresponds to the average position of the lines calculated between the two operators (Rebêlo and Nave, 2019).

3.2 Data sources

Aerial photographs and ortophotomaps from nine different years (1947, 1958, 1973, 1980, 1982, 1988, 2004, 2010 and 2015) were used in order to achieve a near-decadal analysis. The data was provided by Direcção Geral do Território and by CiGeoE (Army Geospatial Information Center). The non-digital aerial photos were scanned at 2400 dpi and then, mosaics were made, using the Adobe Photoshop CS6 image software. This was done with the aim to expedite the georeferencing process, since it allows to avoid marking duplicated links in the overlap area between two consecutive aerial photos (Rebêlo and Nave, 2019).

Additionally, given that the link creation process on the scanned image leads to uncertainties of magnitude similar to the accuracy of the images, the use of mosaics also reduces georeferencing errors. The georeferencing process was accomplished using ESRI software, ArcMap, from ArcGIS Desktop 10.6.1, based on the 2015 orthophotomap as reference map (the most recent one available at the date this work was done). Since the objective was the digitization of the coastline, this process had a greater focus on the area next to the coastline, with increased control points density close to it. Those points were marked, using the Spline interpolation method, preferably with a zoom, at the scale of the order of 1: 400, 1: 600 or, at most, 1: 800 (Rebêlo and Nave, 2019).

3.3 Mapping procedures and DSAS calculation of coastline evolution

After determination of the average coastline position for each of the nine historical aerial photographs, coastline evolution was calculated using the Digital Shoreline Analysis System (DSAS) Software, that is an add-in within the Environmental System Research Institute (ESRI) ArcGIS© ArcGIS desktop v. 10.4-10.6. It, thus, enables a user to calculate a range of statistical change measures derived within DSAS, based on the comparison of coastline positions through time (Himmelstoss *et al*., 2018); (https://www.usgs.gov/centers/whcmsc/science/digital-shoreline-analysis-system-dsas?qt-science_center_objects=0#qt-science_center_objects).

For this work, DSAS allowed us to calculate coastline rate-of-change statistics based on the measured differences between nine coastline positions associated with analysed time periods (1947, 1958, 1973, 1980, 1982, 1988-90, 2004, 2010, 2015), producing three parameters:

(i) *Shoreline Change Envelope* (SCE), which is the measure of the total change in coastline movement considering all available coastline positions and reporting their distances, without reference to their specific dates;

(ii) *Net Shoreline Movement* (NSM), corresponding to the distance between the oldest (in this case, 1947) and the youngest coastline (2015). For the present work the NSM refers to an overall time-frame of 68 years;

(iii) *Linear Regression Rate* (LRR), which is a statistical parameter, that determines a rate-of-change by fitting a least square regression to all coastlines at a specific transect.

Calculations were done using 10 m spaced transects, generated perpendicular to the coast, and the results are represented as a graphic and plotted as a histogram. The coloured histogram, represents two DSAS parameters simultaneously, allowing a fast perception of the coastline evolution over time. The bar length indicates how much the coastline has shifted during the period of analysis (SCE parameter), and the bar colour indicates the NSM and LLR, with the colour (green, yellow, and red) being associated with the evolutionary trend of the coastline. The green scale stands for sectors in accretion and the yellow and red ones, for the sectors in erosion. The absolute value of this variation is shown in the legend of each figure. Due to the scale of the figures presented in the manuscript, the bar length variations are difficult to distinguish. However, they are very well visible at online LNEG GeoPortal, where zoom favours both, the bar length and colour variation perception.

Combining both variables visually, the user may rapidly deduce if, although the coast today is in the same or similar position than it was in the past, it has changed over time, and how much it has changed, in absolute value.

The calculation of the uncertainty of the coastline position, for each year, was determined according to Fletcher *et al*. (2003), where the Uncertainty (U) is the result of the square root of the sum of the squares of the errors associated with 3 parameters (Resolution of the aerial photo image (E_{ir}), Image rectification (E_r) and Digitization of the coastline (E_d):

$$U = \sqrt{E_d^2 + E_r^2 + E_{ir}^2}$$

The component associated with the coastline digitization (E_d) procedure, for each year, was determined with DSAS using the two coastline lines marked by the two different operators for each analysed year. The image resolution, E_{ir} parameter, corresponds to the pixel resolution of aerial / orthophotographs. Given that for the rectification procedure (E_r parameter), the Spline interpolation method, whose associated RMS error is null, was used, the georeferencing error was estimated by using, at least, 35 control points randomly distributed across the mosaics of each flight. Thus, the rectification error (E_r) was assumed to be the average value of the error measured at all control points, for each flight, as listed in table 1.

The uncertainty associated with the overall coastline evolution (U_{ce}) during the time frame of 68 years (t), was determined using the uncertainty values (U) calculated for each year according to Fletcher *et al*. (2012):

$$U_{ce} = \frac{\sqrt{U_{older}^2 + U_{recent}^2}}{t}$$

For this sector, the overall uncertainty (Uce) associated with the variation of the coastline along 68 years is 0.06 m / year.

Table 1. Uncertainty (U) and Errors (Ed, Eir and Er) considered for DSAS calculations.

Year	E_d	E_d^2	E_{ir}	E_{ir}^2	E_r	E_r^2	U(m)
1947	2	4	0.53	0.28	3.49	12.18	4.06
1958	4.04	16.32	0.29	0.08	2.62	6.86	4.82
1973	2.49	6.20	0.2	0.04	2.91	8.47	3.84
1980	3.19	10.18	0.16	0.03	2.78	7.73	4.23
1982	2.39	5.71	0.43	0.18	3.15	9.92	3.98
1988	2.38	5.66	0.44	0.19	3.01	9.06	3.86
2004	1.45	2.10	0.5	0.25	3.54	12.53	3.86
2010	1.41	1.99	0.5	0.25	2.18	4.75	2.64
2015	1.38	1.90	0.5	0.25	0	0	1.47

3.4 Coastline oscillation index (CO)

The ratio between the absolute value of the *Net Shoreline Movement* (NSM), which represents the resultant movement of the coastline during the time-period of analysis, and the *Shoreline Change Envelope* (SCE) value, which gives the maximum length of coastline displacement during the same period of time (Absolute value of [NSM/SCE]), is an index that, when used in comparison with the NSM, may indicate the importance of the coastline oscillation in a particular place, or sector, or, read in a different direction, the relative importance of the NSM in terms of the total displacement during the time-period of analysis. The CO index value should always be used and read together in comparison with the NSM.

4. RESULTS

Historical lines, *Shoreline Change Envelope* (SCE), coastal *Linear Regression Rates* (LLR) and *Net Shoreline Movement* (NSM) were determined and plotted along the *Figueira da Foz - Nazaré* coastal transect, except in areas with hardened and cliffed coasts (southward *São Pedro de Moel, Pedra do Ouro* and *Vale Furado*) (figures 2 and 3).

As previously mentioned, the colour and the length of the bar displayed on both hazard maps (figures 2 and 3) give, simultaneously, information on two DSAS parameters (SCE and LLR on figure 2 and SCE and NSM on figure 3), allowing a fast perception of the historical coastline evolution trend during the last, nearly, 7 decades. Thus, the bar length indicates how much the coastline has shifted (SCE), and the colour of the bars, NSM and LLR, stand for sectors in accretion (green scale) or sectors in erosion (yellow and red colour scale). The LRR map, represents the rate-of-change by fitting a least square regression

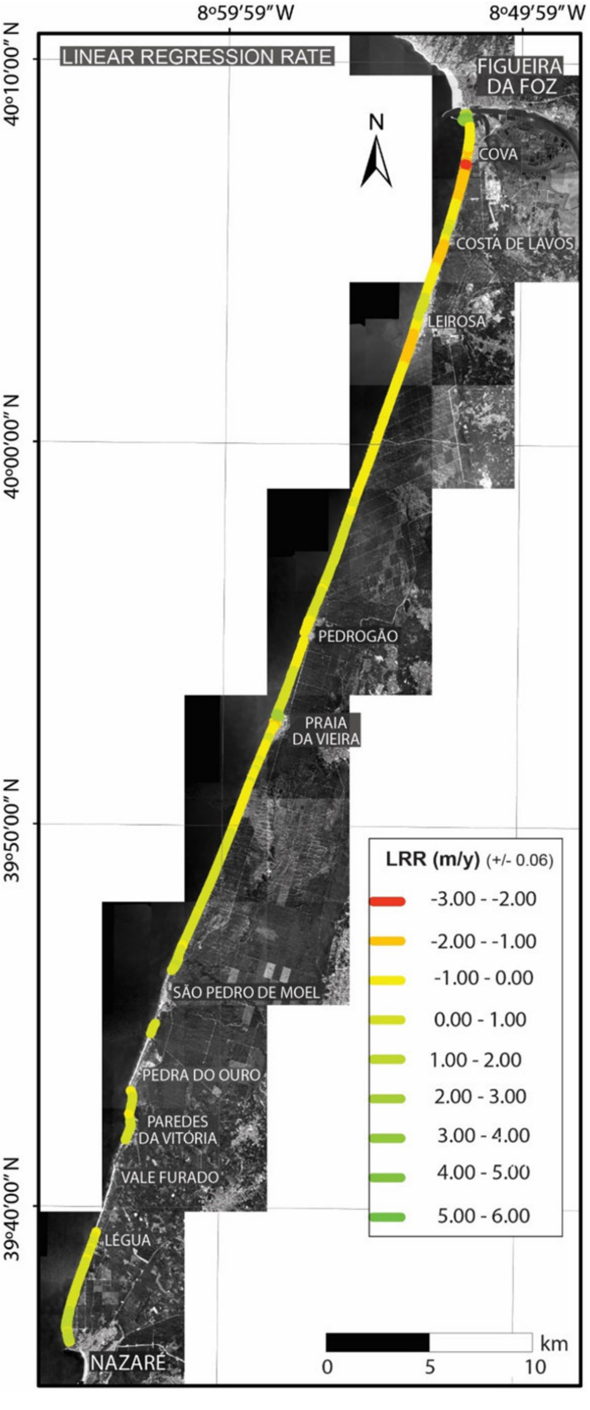

Figure 2. Linear Regression Rates (LLR) for the analysed coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

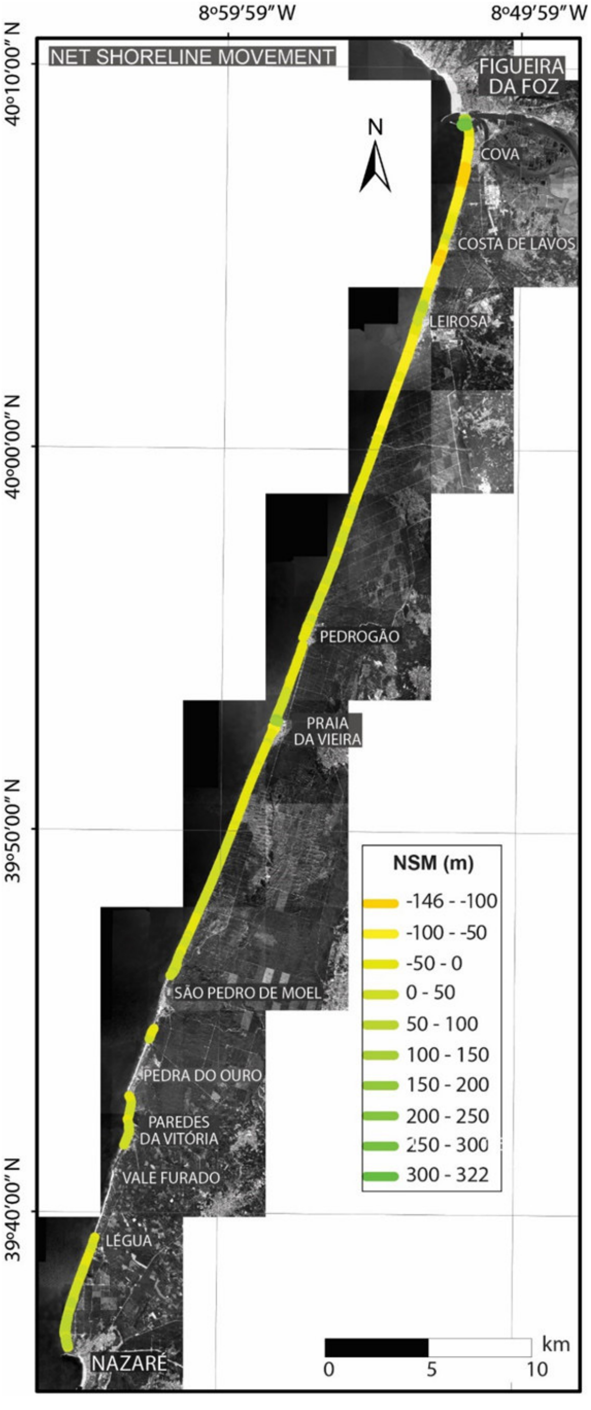

Figure 3. Net Shoreline Movement (NSM) for the analysed sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

to all coastlines at a specific transect (figure 2) whereas the NSM map indicates the absolute distance between the oldest (1947) and the youngest (2015) coastline position (figure 3). All the data is available as polylines with 10 m spaced resolution and openly accessible at LNEG GeoPortal [https://geoportal.lneg.pt/mapa/?escala=4000000&mapa=geologiacosteira#]. Here the produced digital data may be seen in a greater detail and combined with other available layers for this coastal sector (beach profile, sedimentary grain size distribution, photos from the beach area, geology, and others).

Coastline movement analysis, based on the NSM parameter, reveals that 2/3 of the sandy coast between *Figueira da Foz* and *Nazaré* has suffered erosion since 1947 (30.4 km of the 51.5 km total extension). The average retreat, taking only in account the sectors in erosion, is approximately 38 m, with a maximum retreat of 145 m, and the progradation, taking only in account the sectors in accretion (20.1 km in length), is approximately 22 m, with a maximum displacement of 322m. Solely one kilometre of the coastal fringe is in the same position, when compared to 1947. If the overall coastline extension is considered (51.5 Km), an average erosion of 13.5 m is obtained.

The coastline movement rate, which is expressed in this work by the LRR parameter, shows an average retreat of 0.51 my^{-1}, with a maximum value of 2.46 my^{-1}, and an average progradation of 0.43 my^{-1}, with a maximum value of 5 my^{-1} (taking only in account the respective sectors in erosion or accretion, respectively). Taking into account the total studied coastal fringe (51.5 km), the obtained results indicate an average erosion rate of 0.12 my^{-1}.

To a better reading of the DSAS parameters, the *Figueira da Foz - Nazaré* coastal stretch, fully shown in figures 2 and 3, was divided and zoomed in 9 sequential figures, and hence the detailed results, will be presented in the following sub-chapters, which division reflects merely the pragmatic circumstance of map division.

The oscillation index for each sector (table 2) was also calculated to weight the NSM value in a maximum coastline displacement context.

4.1 *Figueira da Foz – Costa de Lavos* coastal sector

This first sector, with a total length of 5860 m (figure 4), has a significant diversity in terms of coastal environments, and hence, the evolution of the coast reflects these differences.

The first subsector, with a 380 m length, is located between two groins of the *Mondego* River inlet. This coastal stretch is characterized by a strong progradation, with NSM values ranging from 86.4 to 322.1 m, and an average NSM of 198.1 m. LRR varies between 1.68 and 5.01 my^{-1}, with an average value of 3.36 my^{-1}.

Table 2. Average value of SCE, average NSM absolute value, and Coastline Oscillation index (CO): NSM absolute values / SCE ratio for the different sectors. The larger the CO ratio, the more significant is the NSM value in terms of the total coastline oscillation during the time-frame analysis.

Coastal sectors	SCE	Abs(NSM)	Abs(NSM)/SCE
Figueira da Foz - Costa de Lavos	80.0	72.8	0.9
Costa de Lavos - Osso da Baleia	71.0	60.9	0.9
Osso da Baleia	48.4	38.7	0.8
Pedrogão	50.0	12.3	0.2
Praia da Vieira	37.7	19.8	0.5
Samouco	21.9	10.4	0.5
S. Pedro de Moel	36.3	14.4	0.4
Vale Pardo - Nazaré	46.7	28.3	0.6

The second subsector corresponds to the coastal stretch directly associated to the presence of defence groins, starting after the south jetty of the *Mondego* River inlet and finishing in the fifth, and last, of the groins built to protect the *Cova* locality. This subsector, with a length of 1590 m, is characterized by erosion, with NSM values ranging from -8.38 to -88.64 m, and an average NSM of -50.79 m. LRR varies between -0.26 and -1.3 my^{-1}, with an average value of -0.62 my^{-1}.

The third subsector, extending from the last groin of *Cova Gala* to the *Costa de Lavos* groin, has a length of 3890 m. Erosion is dominant, although accretion is present in the last 300 m. NSM values ranges from -145.7 to 18.2 m and the average NSM is -68.5 m. LRR varies between -2.46 to 0.21 my^{-1}, with an average value of 0.95 my^{-1}. Considering only the erosion stretch, average NSM is -75.1 m and average LRR is -1.04 my^{-1}.

The CO [Abs (NSM)/SCE] ratio of 0.9 (table 2) indicates that the NSM values are similar to the maximum range of displacement (given by the SCE index).

4.2 *Costa de Lavos – Osso da Baleia (N)* coastal sector

This sector (figure 5) may be divided in two parts, regarding coastline retreat: The *Costa de Lavos - Leirosa* subsector and the subsector south of *Leirosa*. The first sub-sector is located between two groins and the strong erosional behaviour, southward the last *Costa de Lavos* groin, diminishes gradually and shifts to accretion as we approach the *Leirosa* groin, to the

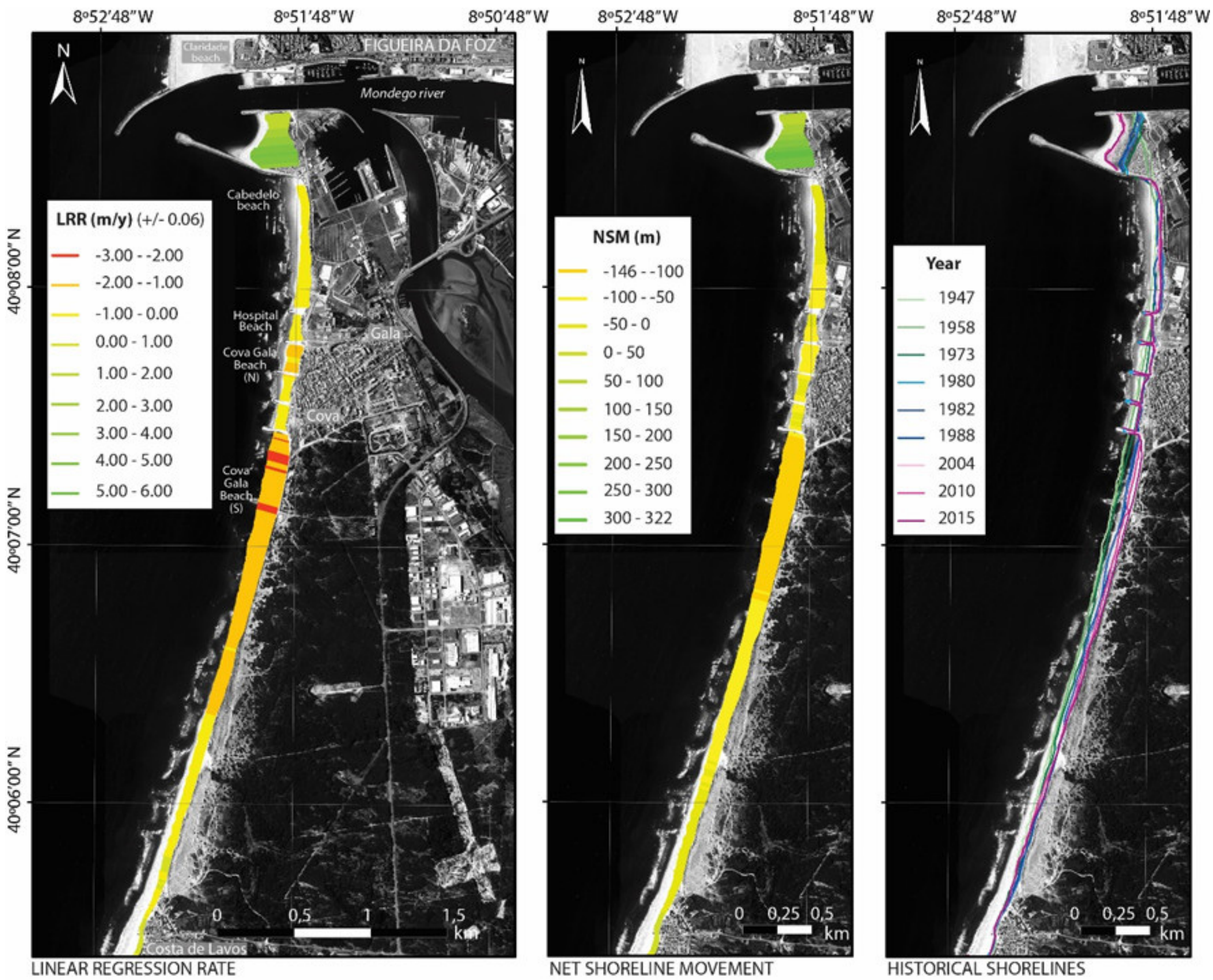

Figure 4. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Figueira da Foz – Costa de Lavos* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

south. This sector, with 2990 m length, has an average retreat of -63 m (NSM) at a rate of 0.88 my^{-1} (LRR). The maximum retreat value found is 117.8 m at a 1.68 my^{-1} rate. The prograding coastal stretch, with 910 m length, has an average advance of 38.8 m (NSM) at a rate of 0.54 my^{-1} (LRR). The maximum offshore displacement value found has a NSM of 77.6 m with a LRR of 0.9 my^{-1}.

The 3000 m coastal stretch south of *Leirosa,* where erosion prevails, shows an average retreat of -65.1 m, at a rate of -1.04 my^{-1}. The maximum retreat, with a value of -103.7 m (and a LRR of -1.37 my^{-1}) is found approximately 1600 m south of the *Leirosa* groin.

Considering the whole sector, the 6890 m coastal strip shows an average retreat of 50.6 m with a LRR of 0.76 my^{-1}.

The CO index, [Abs (NSM)/SCE], of 0.9 (table 2) indicates, like in the previous sector, that the NSM values are similar to the maximum range of displacement (given by the SCE index).

4.3 *Osso da Baleia* coastal *sector*

In the *Osso da Baleia* coastal sector (figure 6), which has a total length of 7070 m, erosion prevails in approximately 6630 m.

Considering only the eroding sector, the average coastline retreat (NSM) is -40.7 m, reaching a maximum value of -78.4 m at a distance of 60 m from the northern sector limit. The erosion nearby *Osso da Baleia* beach has a value of -41 m. For this eroding sector LRR has an average value of -0.58 my^{-1} and a maximum value of -1.05 my^{-1}. Accretion is scarce (only 440 m of the coastal sector) and is mostly located in the south of

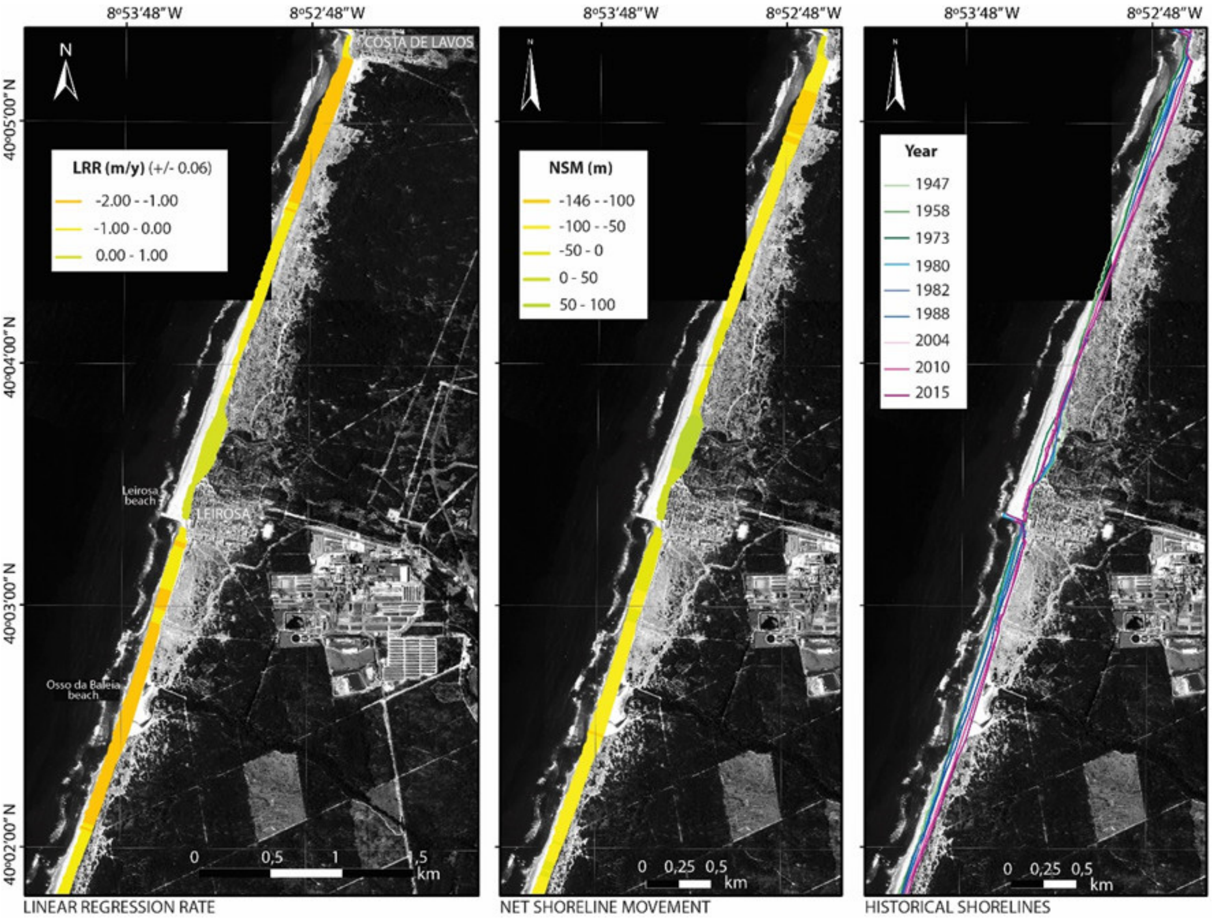

Figure 5. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Costa de Lavos – Osso da Baleia* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

the sector. The average progradation (NSM) is 7.5 m with a maximum of 17.4 m, 230 m northward of the southern limit of the sector.

Considering the 7070 m sector length, the average coastline retreat (NSM) is -37.6 m.

The CO index, [Abs (NSM)/SCE], of 0.8 for this sector (table 2) shows a small decrease in the ratio, however, like in the previous sectors, the NSM values may be considered similar to the maximum range of displacement (given by the SCE index).

4.4 Pedrogão coastal sector

In opposition with the preceding sector, accretion prevails in this coastal stretch (figure 7), although without presenting significant values. The first 6180 m, located north of Pedrogão, shows an oscillation between eroding and accretion zones. The erosion, in terms of NSM, extends for 1680 m, while accretion covers 4500 m. The NSM ranges from -40.4 to 42.3 m, with an average accretion of 5.75 m. The LRR ranges from -0.75 to 0.66 my^{-1}, with an average rate of accretion of 0.17 my^{-1}. If considering only the positive NSM's, the progradation shore extends from 4500 of the 6180 m and has an average NSM of 11.87 m.

South of Pedrogão, erosion prevails in the small 520 m sector, with a minimum NSM value of -28.8 m and an average of -21.1 m. Average LRR is -0.39 my^{-1}, with a maximum retreat rate of -0.55 my^{-1}.

Considering the overall 6690 m sector, NSM ranges from -44.4 to 42.3 m, with an average of 3.71 m. LRR ranges from -0.75 to 0.66 my^{-1}, with an average value of 0.12 my^{-1}.

In this sector, SCE and the absolute value of NSM are significantly

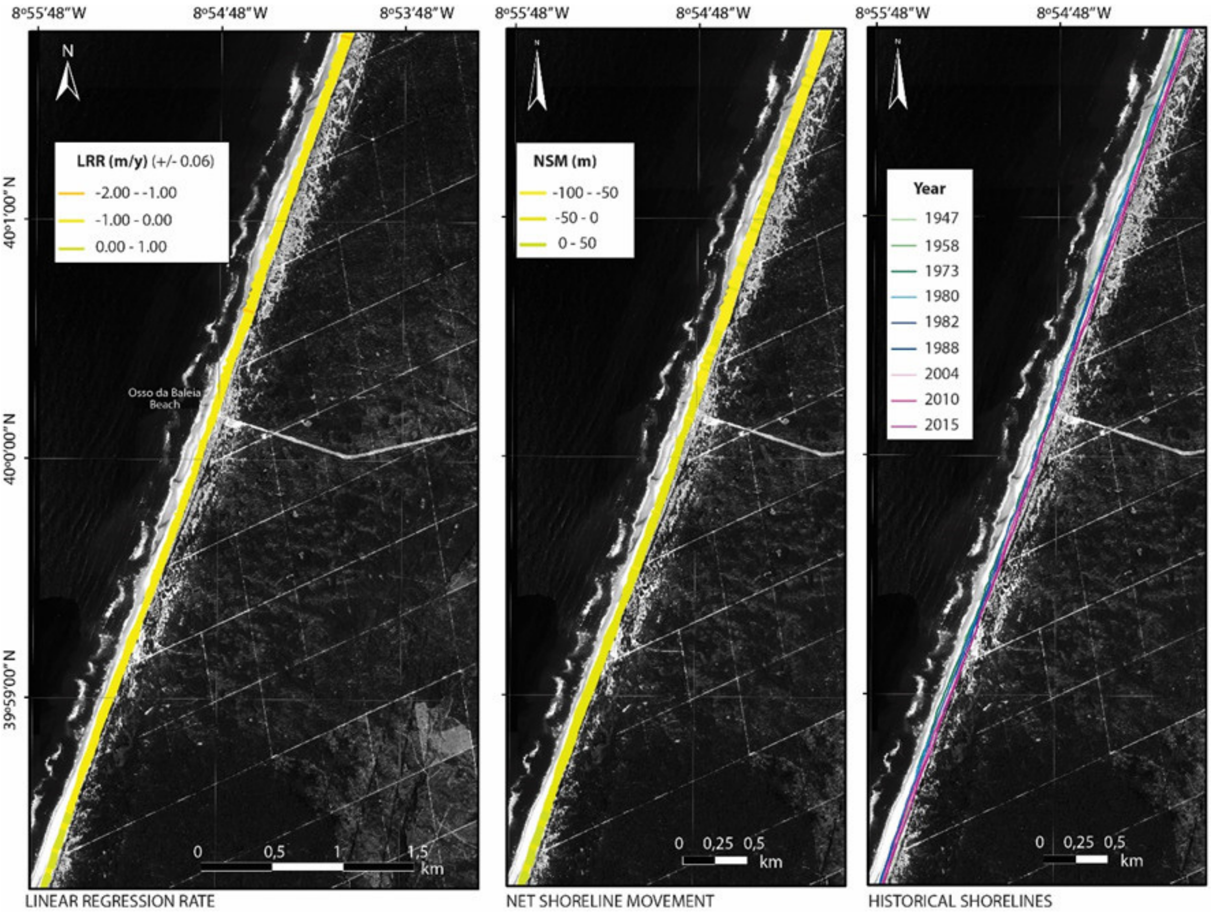

Figure 6. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Osso da Baleia* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

different, with the SCE average being 50.0 m and the Abs(NSM) average 12.3 m, resulting in a CO index, [Abs (NSM)/SCE] of 0.2 (table 2).

4.5 *Praia da Vieira* coastal sector

The erosional tendency observed in the last sector, south of *Pedrogão*, continues in the first part of this sector for approximately 1700 m (figure 8) where it shifts gradually to an accretionary trend that extends southward, for 1710 m, up to the north jetty of *Praia da Vieira*. In this subsector NSM values range from -45.0 to 154.4 m, with an average progradation of 5.6 m. The LRR ranges from -0.54 to 2.51 my^{-1}, with an average rate of accretion of 0.23 my^{-1}.

South of Liz River mouth, which is fixed by two jetties, erosion prevails (figure 8). NSM values range from -84.2 to 12.1 m, with an average erosion of -14.2 m. The LRR ranges from -1.19 to 0.34 my^{-1}, with an average rate of erosion of -0.11 my^{-1}.

Considering the overall 6850 m sector (figure 8), NSM ranges from -84.2 to 154.2 m, with an average of -4.35 m. LRR ranges from -1.19 to 2.51 my^{-1}, with an average value of 0.06 my^{-1}.

The CO index, [Abs (NSM)/SCE], for this sector is 0.5 (table 2) as a consequence of SCE being 1.9 times bigger than NSM.

4.6 *Samouco* coastal sector

The erosional trend detected southwards *Praia da Vieira* continues to the initial part of this sector, with erosion prevailing over the accretion (figure 9) changing, then, gradually towards an accretion tendency, which dominates throughout the south part of the sector. Therefore, in the first 2900 m, where erosion prevails, the average NSM is -11.15 m, while in the last 4260 m, where progradation prevails, the average NSM has a value of 9.87 m.

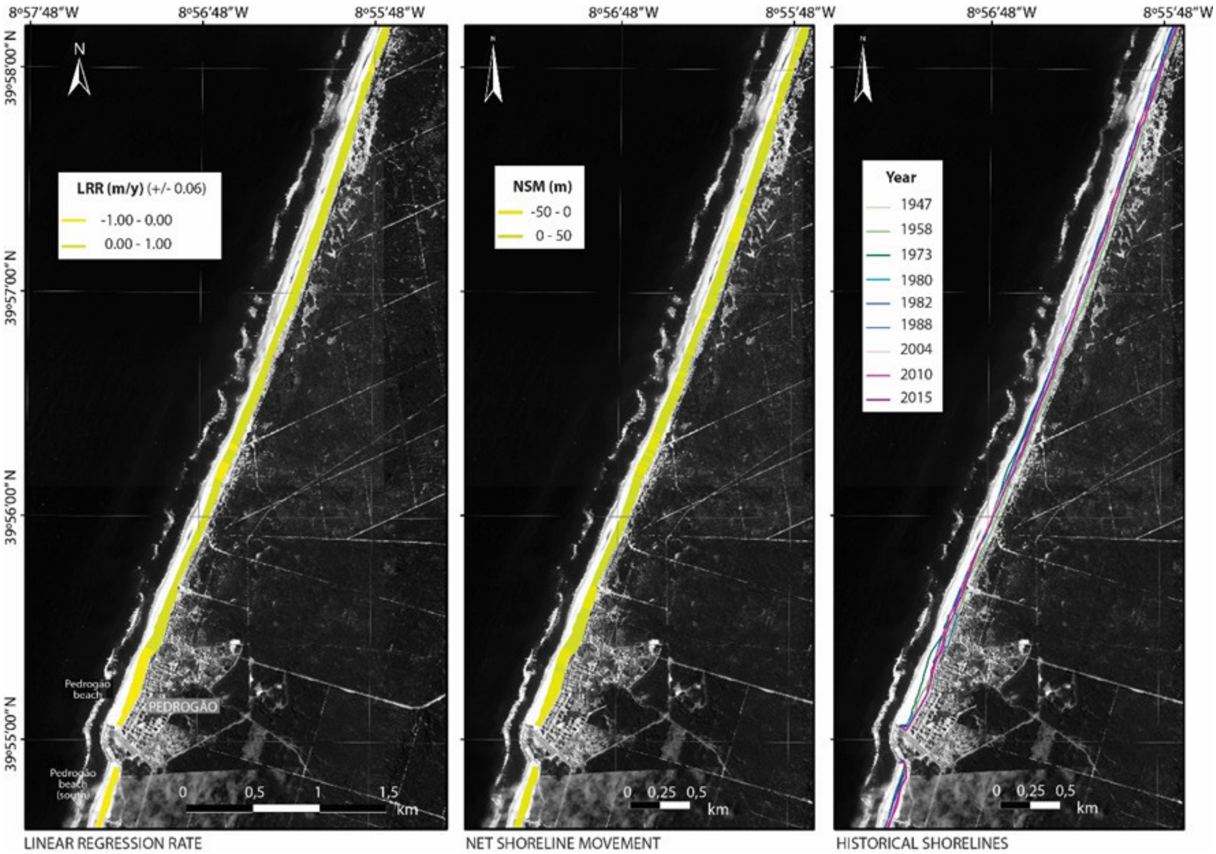

Figure 7. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Osso da Baleia - Pedrogão* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

Considering the entire 7160 m extension (figure 9), NSM ranges from -31.2 to 27.4 m, with an average of 1.36 m. LRR ranges from -0.31 to 0.43 my^{-1}, with an average value of 0.06 my^{-1}.

In this sector, average SCE (21.9 m) is 2.1 times larger (table 2) than the absolute value of NSM (10.4 m).

4.7 ***São Pedro de Moel*** **coastal sector**

The *São Pedro de Moel* sector was not fully covered by DSAS analysis, as may be seen in figure 10, because sandy beaches backed by foredunes are not present in some parts of the sector.

Between the end of *Samouco* sector and *São Pedro de Moel*, the 2450 m of coastal stretch shows erosion and accretion, being the later mainly localized in the southern part. The prograding area, with 1790 m in length, has an average NSM of 17.2 m, and the eroding part, with a length of 660 m, has an average NSM of -6.80 m.

Considering the 2450 sector, NSM ranges from -25.4 to 57.2 m, with an average of 10.7 m. LRR ranges from -0.28 to 1.14 my^{-1}, with an average value of 0.29 my^{-1}.

For this sub-sector, the average SCE value, 36.3 m, is significantly larger than the Abs (NSM), which is 14.4 m, leading to an CO index, [Abs (NSM)/SCE], of 0.4 (table 2).

South of *Valeiras*, the 570 m subsector has a NSM maximum of 3.2 m, a minimum of -10.6 m and an average value of 3.72 my^{-1}. LRR ranges from -0.0 to 0.16 my^{-1}, with an average value of 0.08 my^{-1}.

4.8 ***Paredes da Vitória*** **coastal sector**

As in the previous sector, the *Paredes da Vitória* coastal sector (figure 11) was not fully covered by our analysis since, although beaches are always present, they are baked up by cliffs and not by dunes, hampering these sectors to fulfil the defined criteria for coastline delimitation.

The analysed parts of the sector, with a total length of 2390 m,

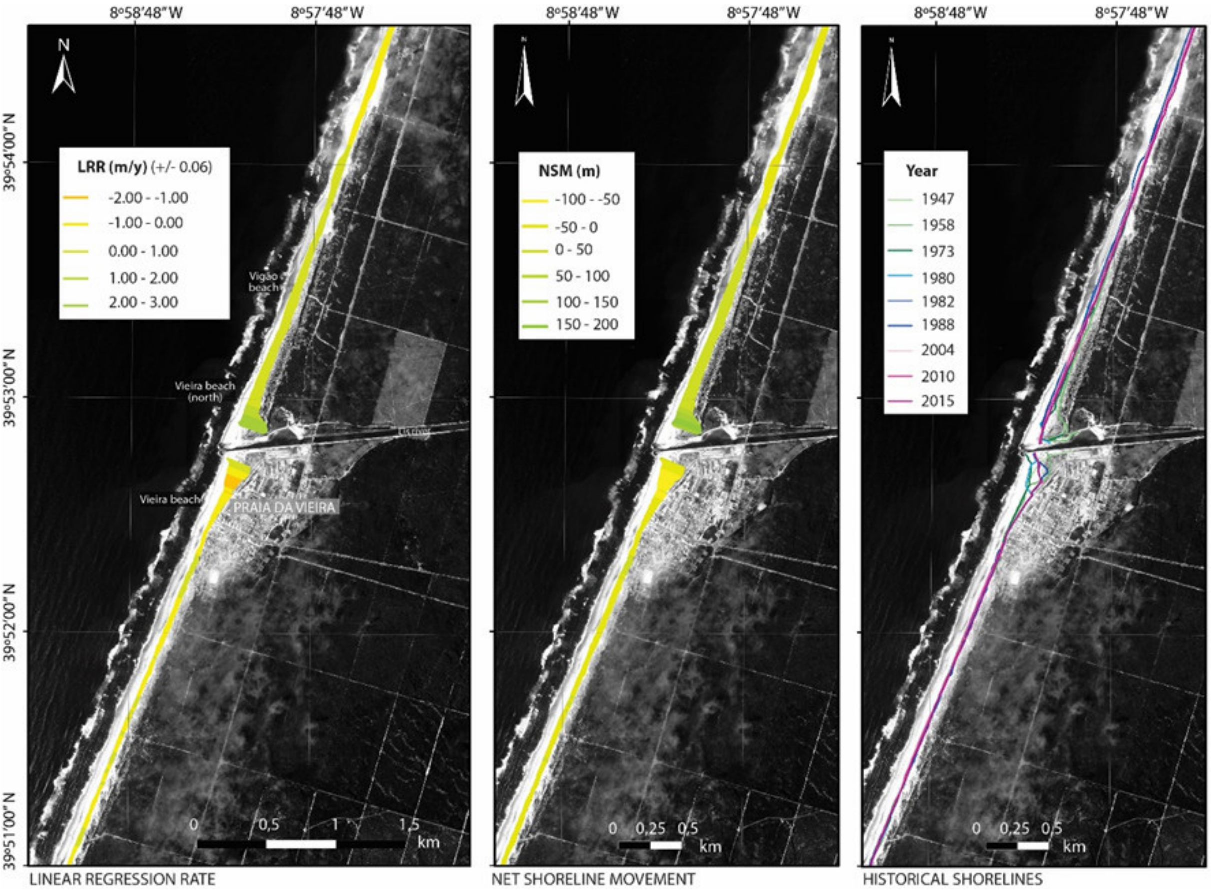

Figure 8. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Praia da Vieira* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

show mainly a stable coastline position with a small accretion tendency, occupying 1990 m of the coastal stretch.

NSM ranges from -9.4 to 36.5 m, with an average of 7.3 m and LRR ranges from -0.06 to 0.61 my^{-1}, with an average value of 0.15 my^{-1}.

4.9 *Vale do Pardo - Nazaré* coastal sector

The *Vale do Pardo – Nazaré* is the last sector of the analysed coastal stretch. With a length of 5560 m (figure 12), it presents an increased accretion trend towards south. NSM ranges from -22.2 to 81.1 m, with an average of 24.62 m, and LRR ranges from -0.10 to 1.67 my^{-1}, with an average value of 0.56 my^{-1}.

Accretion occurs in an extension of 4350 m, with an average NSM of 33.8 m and erosion occurs along 1230 m, with an average NSM of -8.5 m.

5. DISCUSSION

5.1 The importance of coastline evolution trend estimates, at a high-resolution scale

The cartographic assessment of the European coasts exposure to coastal erosion based on spatial data and GIS analysis has been, since the last decades, a mutual international goal as all European coastal states are, to some extent, affected by coastal erosion (Commission, 2004; Ferreira and Matias, 2013). The need of acquired dataset and its analyses, first at a European scale (Ferreira and Matias, 2013), and thereafter at national scale (Lira *et al*., 2016) has been, since then, successfully achieved for the Portuguese scenarios.

However, even though a small-scale dataset is vital for addressing mitigation measures for coastal erosion, the further achievement of updated and reinterpreted regional to local-

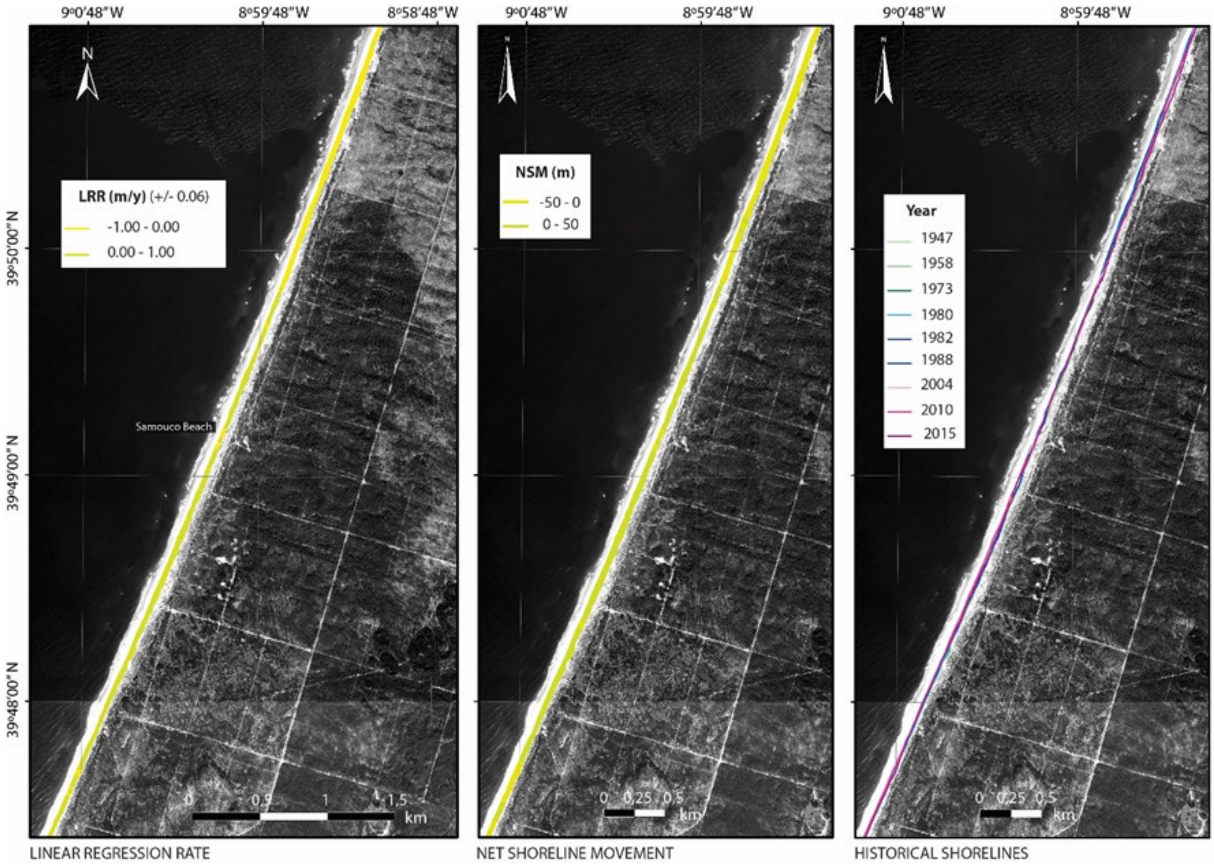

Figure 9. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Samouco* coastal sector, between 1947 and 2015. Background photo is the 2010 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

scale information, on long-term coastline evolutionary trend, is particularly valuable in areas with strong human occupation and relevant beach erosion, as the mitigation and defence measures to apply in those sectors should be robustly supported and backed by detailed scientific information. This would strongly contribute for the planning and implementation of effective adaptive measures on the climate change scenarios particularly in regions significantly endangered by erosion.

When comparing to previously published results produced at a national scale (Lira *et al*., 2016), the erosion and accretion trends are similar, although the mean coastline rates of change are smaller in the present work and differences are noticed locally with maximum retreat or accretion rates identified in distinct areas.

The differences on local coastal Linear Regression Rates detected at this systematic and high-resolution study, in comparison to the previous national-scale dataset (Lira *et al*., 2016), put in evidence the advantage of the achievement of continuous updated and reinterpreted high-resolution data at a local scale, as a zoomed analysis likely favour to apply the mitigation measures (as sand nourishment and others) at the exact key target locations.

5.2 Coastline evolution trend of the last, nearly, 7 decades at the western sector from *Figueira da Foz* to *Nazaré*

The sedimentary flux, already diminished by the reduced fluvial source at the northward limit of cell 1 (i.e., sub-cell 1a), has long been the central issue that explains the generalized retreat of the western coastal shoreline (Santos *et al*., 2014). The average rate of coastal retreat, NSM, of the last 68 years, calculated in this work (-13.6 m) for the sandy coastline, backed up by dunes, from *Figueira da Foz* and *Nazaré* sector, confirms the previously reported readjustments of the coastal system due to

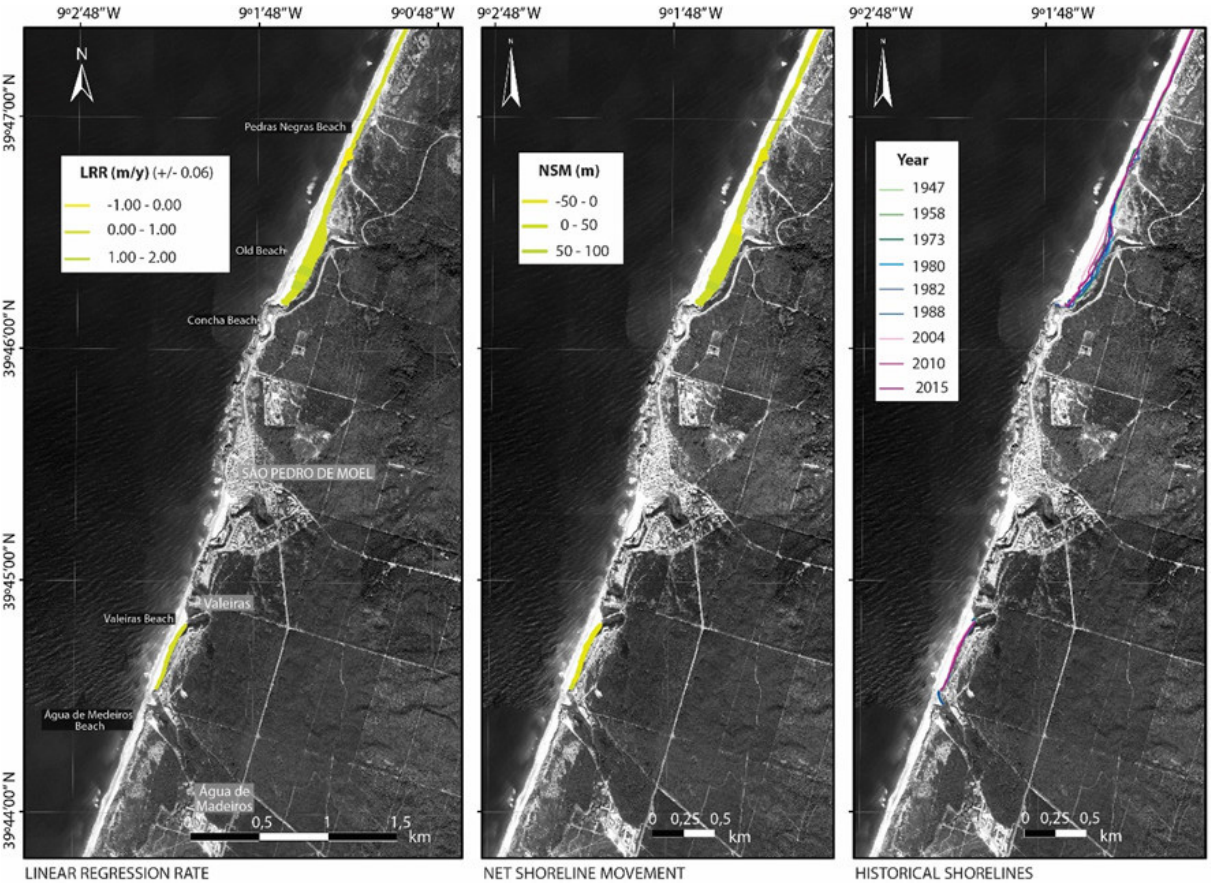

Figure 10. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *São Pedro de Moel* coastal sector, between 1947 and 2015. Background photo is the 2010 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

human occupation and activities, including the introduction of rigid marine structures that hamper and/or retain the sediment transported by the southward course of the coastal drift.

In the present case, the average retreat of the coastline may induce in an error of interpretation since progradation also occurs in a significant extension. Thus, if looking only to the sectors under erosion, which extends for 30 470 m, the average coastline retreat (NSM) is -38.2 m, and the eroded area corresponds to 1 164 888 m^2 (approximately 116 ha). Consequently, the prograding coastline occupies 21 010 m of extension, with an average progradation (NSM) of 22 m, which corresponds to an accretion area of 462 377 m^2 (approximately 46 ha).

It is also important to stress that the NSM data, which in this paper is mostly used to quantify the coastline movement, between the oldest and the most recent coastline position, should be complemented by the SCE to fully understand the coastal behaviour. In the analysed sector, the calculation of the total area associated to the coastline movement resulting from the NSM determination, which is 1 627 265 m^2, is largely exceeded by the area obtained by the SCE value (2 466 377 m^2). Thus, the SCE area, being 52% larger than the NSM area, means that the overall coastline oscillation during the period of analysis was significantly larger than the resultant displacement given by the NSM. This relevant information should be considered when managing local coastal activities, as the SCE index denotes a greater oscillation of the coastline position, in comparison to the NSM index.

5.2.1 Figueira da Foz – Costa de Lavos coastal sector

At the northern limit of this sector there is a small beach anchored between the two southern jetties of *Mondego* River mouth. The evolution of this sector is strongly influenced by the southern jetties of the *Figueira da Foz* inlet. In 1947, a jetty, in the left side of the river, was already in place and downdrift

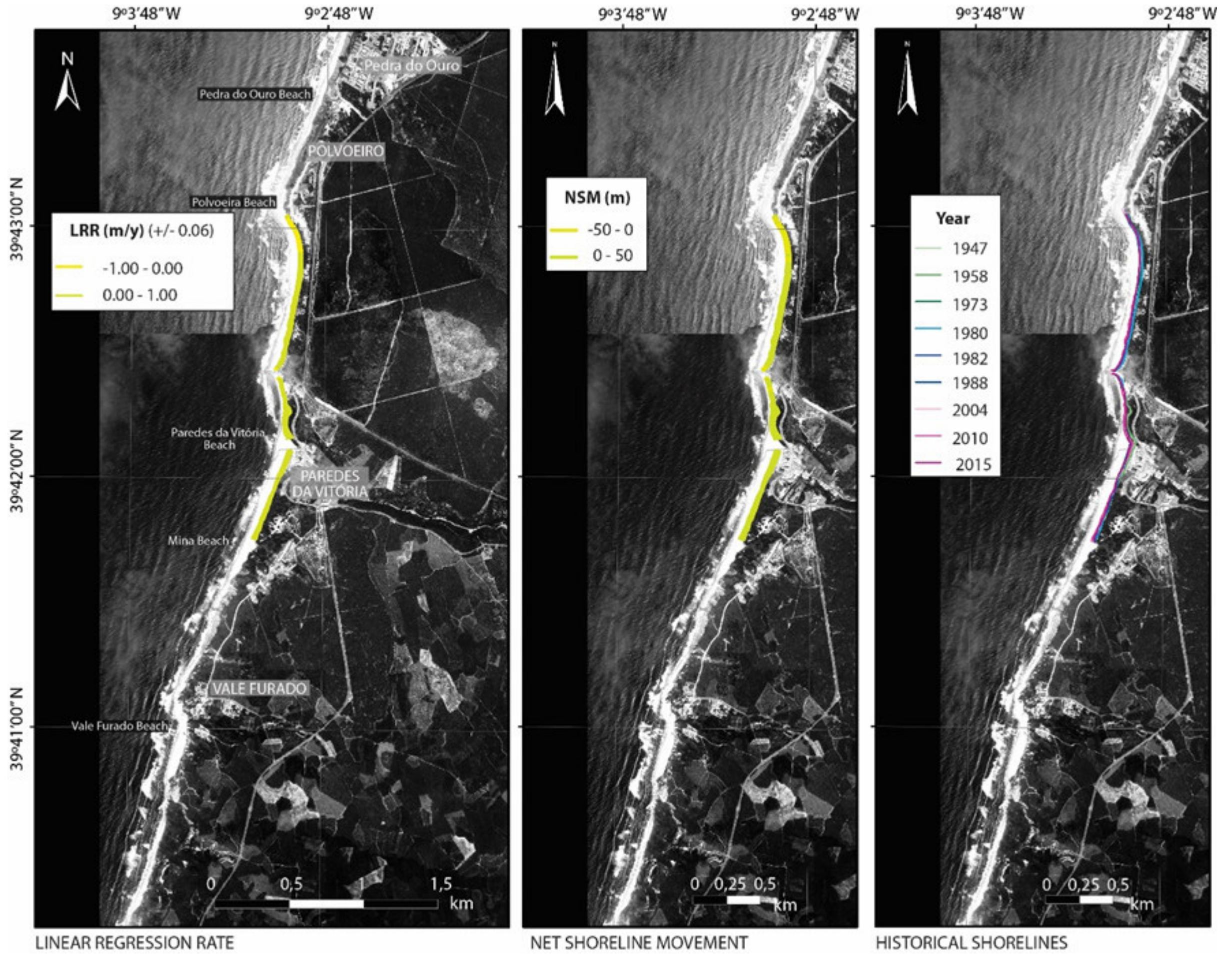

Figure 11. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Paredes da Vitória* coastal sector, between 1947 and 2015. Background photo is the 2015 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

erosion was already present, being visible by the liner aspect of the foredune/beach contact. In 1958 the erosion was even more evident, with foredune destruction and occurrence of overwash at backdune deposits, northward of *Cova Gala*. Between 1958 and 1973 a new and longer jetty was built approximately 500 m further south and, in the right margin of the river, a new jetty was also built (the jetty responsible for the *Figueira da Foz* beach accumulation). The installation of these two long jetties is the major responsible for the beach accretion.

Between 1982 and 1990 the first groin was expanded, together with the placement of a new one in the right margin, in order to straighten the inlet channel. When analysing the coastlines dataset, the influence of these coastal structures (the internals and the externals) is clear, with the coastlines shifting offshore in accordance with the structure development. Three different sets of coastline positions are visible: the most inshore positions during 1947 and 1958, followed by the intermediate positions during the 70th and 80th decades, and finally, the most offshore positions during 2004 to 2015. During the last 68 years, this beach prograded 198.1 m (NSM) at a 3.3 my^{-1} rate (LRR).

South of this beach, this sector presents a worrisome erosion, along a 5400 m coastal strip, that is only reversed at *Costa de Lavos* area, where a groin, placed between 1973 and 1980, helped to stabilize the coastline position. The reduction of the longshore drift led to a continuous inland coastline shift and to the need to deploy coastal defences in front of *Cova Gala*. The five groins, complemented by seawalls, were built between 1973 and 1980 and manage to reduce the coastline retreat, although the protected coastal stretch continued to be vulnerable to overwash, during storms. The 720 m protected seafront suffered

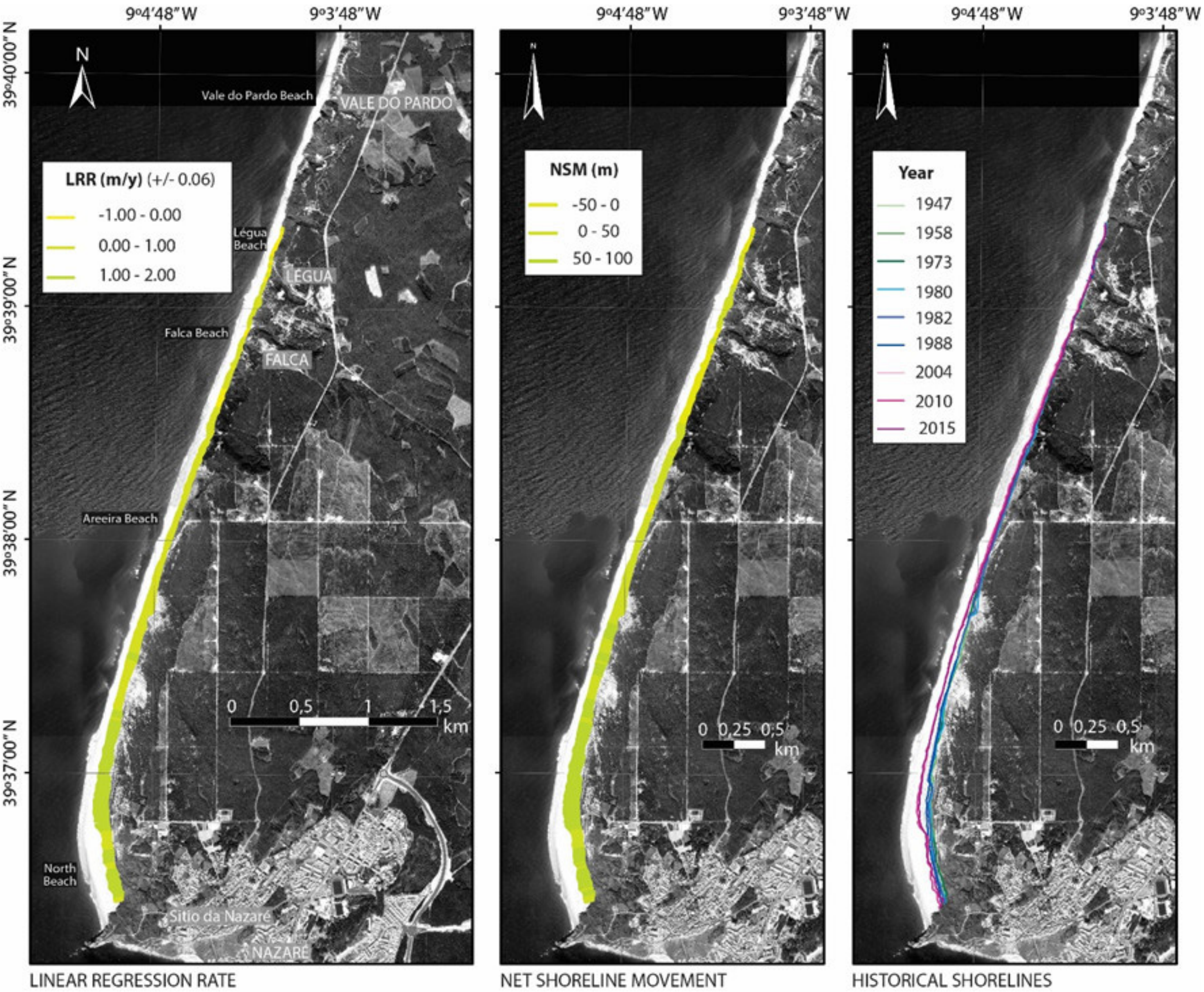

Figure 12. Historical coastline position, Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) for *Vale do Pardo - Nazaré* coastal sector, between 1947 and 2015. Background photo is the 2010 ortophotomap. Map produced using ArcMap, a module from ArcGIS© Desktop 10.6.1 of ArcGIS® software by Esri.

an average coastline retreat (NSM), most of it prior to the defence constructions, of 55 m, with a maximum of 88,6 m, and an average LRR of 0.75 my^{-1}. In contrast, the next 720 m suffered an average coastline retreat (NSM) of 130.5 m, with a maximum of 145.7 m, and an average LRR of 1.89 my^{-1}. Taking in consideration the overall eroding coast, approximately with 5400 m of length, the analysis shows that the average coastline retreat (NSM) is -68 m, with an average rate of erosion (LRR) of 0.92 my^{-1}. The maximum value of retreat, -145.7 m, is located approximately 270 m southward of the last *Cova Gala* groin, and the erosion tends to diminish southwards.

As previously mentioned, a small accretion area is observed at the southern limit of this sector. Along this 500 m end-stretch, a tenuous average accretion (NSM) of 10.6 m, and an average progadation rate of 0.12 my^{-1} is measured. This accretion is related with the *Costa de Lavos* groin, built between 1973 and 1980 with the aim to stop the prevailing erosion.

Human interference induced in coastal dynamics through the introduction of rigid constructions was not able to stop erosion completely and, as a consequence, beach and dune nourishment was carried out. Between 1973 and 1976, 294 020 m^3 of sand were deposited on *Cabedelo* beach (table 3). The reinforcement, with a later nourishment, in 2014, at *Cova Gala* and *Lavos* beach (table 3) had also a negligible effect on 2015 coastline position which is still inland displaced, when comparing to the 2010 position, as it is visible southward *Cova Gala* area.

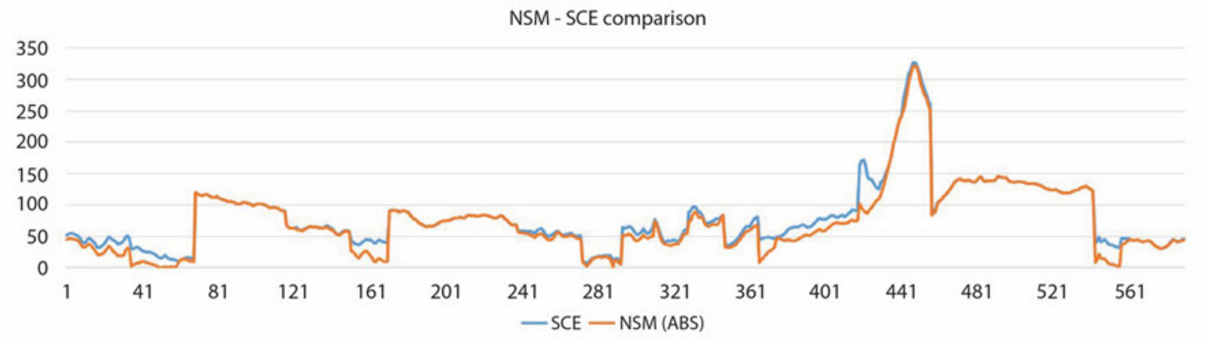

Figure 13. SCE and absolute value of NSM comparison for the *Figueira da Foz* – Costa de *Lavos* coastal sector, showing similarity between both indexes. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

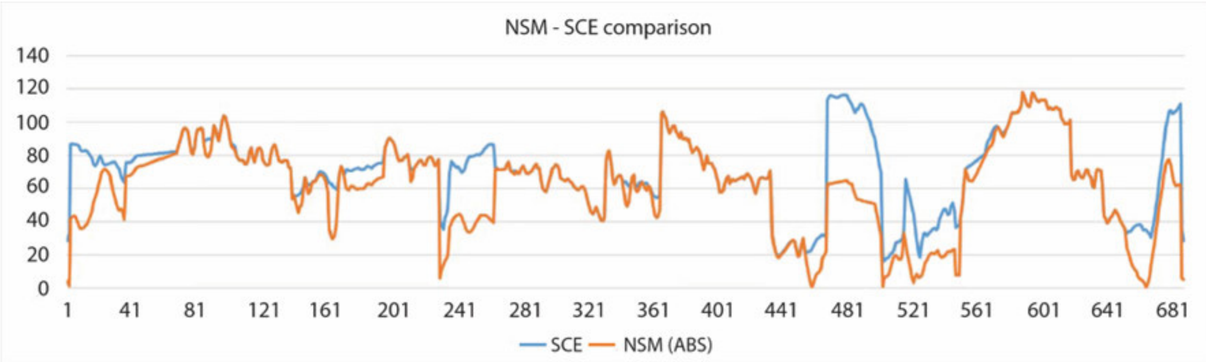

Figure 14. Absolute value of NSM and SCE comparison for the Costa de *Lavos* - *Osso da Baleia* coastal sector, showing similarity between both indexes. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

Regarding the Coastal Oscillation index, [Abs (NSM)/SCE], (table 2), the value of 0.9 for this sector indicates that NSM gives a good indication of the coastal evolution behaviour during the period of analysis (figure 13), since both lines are almost coincident.

5.2.2 Costa de Lavos – Osso da Baleia (N) coastal sector

This segment (figure 5) is a good example of the effect of perpendicular coastal defences deployment in a longshore drift coastal environment exposed to a negative sedimentary budget. As N-S longshore drift prevails in the study area, groins deployed perpendicular to the coast promote accumulation of sand updrift (in the present case, towards the north of the structures) and erosion downdrift (to the south of the structures).

Therefore, southwards of *Costa de Lavos* groin, erosion is intense (higher value of NSM of -117.8 m, with a LRR of -1.68 my^{-1}), diminishing gradually in the direction of the *Leirosa* groin, where progradation occurs (higher value of NSM of 77.6 m, with a LRR of 0.9 my^{-1}). South of this groin, erosion occurs again (higher value of NSM of -103.7 m, with a LRR of -1.37 my^{-1}) (figure 5).

It is also important to stress that, despite the deployment of coastal defences, erosion continued to occur. To mitigate the erosion effect, an artificial nourishment of sand was done in 2014 at *Leirosa* beach (table 3), but it was not enough to overcome the erosional trend, as the 2015 coastline position is still the one placed at a more inland position (figure 5).

Regarding the CO index, [Abs (NSM)/SCE], (table 2), the value of 0.9 for this sector indicates, like in the previous sector, that NSM is a good indicator of the coastal evolution behaviour during the time period analysed (figure 14).

5.2.3 Osso da Baleia coastal sector

Erosion prevails in the *Osso da Baleia* sector (approximately in 94 % of its length), extending the trend described in the southern part of the preceding sector. Although having an average coastline retreat of -47 m (and an average LRR of -0.51 my^{-1}), no intervention has been made on the coast, since there is no human occupation to protect. Accretion is solely present in the last 400 m of the sector.

The observed erosion is likely the result of the diminishing of the longshore sediment drift (Santos *et al*., 2014). In fact, if we consider a larger area than this sector, from *Leirosa* (in the precedent sector) and Pedrogão (a natural rocky outcrop, in the next sector), the process is similar as it happens between groins: Erosion in the updrift side (north), changing gradually to accretion (which happens in this sector), to a more notorious accretion environment in the southern part, near the natural sand trap obstacle, the *Pedrogão* promontory.

Regarding the CO index, [Abs (NSM)/SCE], (table 2), the 0.8 value indicates, like in the previous sector, that the NSM gives a good indication of the coastal evolution behaviour during the period of analysis. However, a decoupling occurs at the end of this segment (figure 15).

5.2.4 Pedrogão coastal sector

The accretion tendency observed from the southward area of *Osso da Baleia* beach continues to the *Pedrogão* sector (figure 7), being present in 73 % of its length.

From the comparison of SCE and the absolute value of NSM (figure 16), it is noticeable that the two variables differ substantially, being the distance from the oldest (1947) and the most recent (2015) coastline (average of 12.3 m), significantly smaller than the shoreline envelope, SCE (average of 50.0 m). Analysing the coastline positions, an offshore displacement tendency is observed from 1947 until the 70's and 80's, followed by a more recent onshore displacement.

Although the *Pedrogão* promontory, acting like a natural groin, may be seen as responsible for the observed updrift sand accumulation, the coastline instability near that natural structure is significant and erosion is dominant. A road and

Table 3. Beach nourishments, and corresponding characteristics, between 1950 and 2017 for the study area (from Pinto *et al.*, 2018).

Location	County	Date	Volume (m^3)	Deposition type	Loan spot	Device	Objetive
Cabedelo beach (South)	*Figueira da Foz*	1973	50,110	emerged beach	Dredging of the *Coxim* dock	Dredge	Enhancement of the coastline stability conditions
Cabedelo beach (South)	*Figueira da Foz*	1974	69,830	emerged beach	Dredging of the *Coxim* dock	Dredge	Enhancement of the coastline stability conditions
Cabedelo beach (South)	*Figueira da Foz*	1975	88,640	emerged beach	Dredging of the *Coxim* dock	Dredge	Enhancement of the coastline stability conditions
Cabedelo beach (South)	*Figueira da Foz*	1976	85,440	emerged beach	Dredging of the *Coxim* dock	Dredge	Enhancement of the coastline stability conditions
Nazaré harbour beach (southward)	*Nazaré*	2009	28,000	emerged beach	Dredging of the *Nazaré* harbour	Dredge	Enhancement of the coastline stability conditions
Cova Gala beach, *Lavos* beach and *Leirosa* beach	*Figueira da Foz*	2012	100,000	Immersed beach (-2m ZH/-8m ZH)	Maintenance dredging of the *Figueira da Foz* harbour inlet	Dredge	Enhancement of the coastline stability conditions
Cova Gala beach, *Lavos* beach and *Leirosa* beach	*Figueira da Foz*	2013	90,000	Immersed beach (-2m ZH/-8m ZH)	Maintenance dredging of the *Figueira da Foz* harbour inlet	Dredge	Enhancement of the coastline stability conditions
Cova Gala beach, *Lavos* beach and *Leirosa* beach	*Figueira da Foz*	2013	165,630	Immersed beach (-2m ZH/-8m ZH)	Maintenance dredging of the *Figueira da Foz* harbour inlet	Dredge	Enhancement of the coastline stability conditions
Cova Gala beach, *Lavos* beach and *Leirosa* beach	*Figueira da Foz*	2014	110,000	Immersed beach (-2m ZH/-8m ZH)	Maintenance dredging of the *Figueira da Foz* harbour inlet	Dredge	Enhancement of the coastline stability conditions

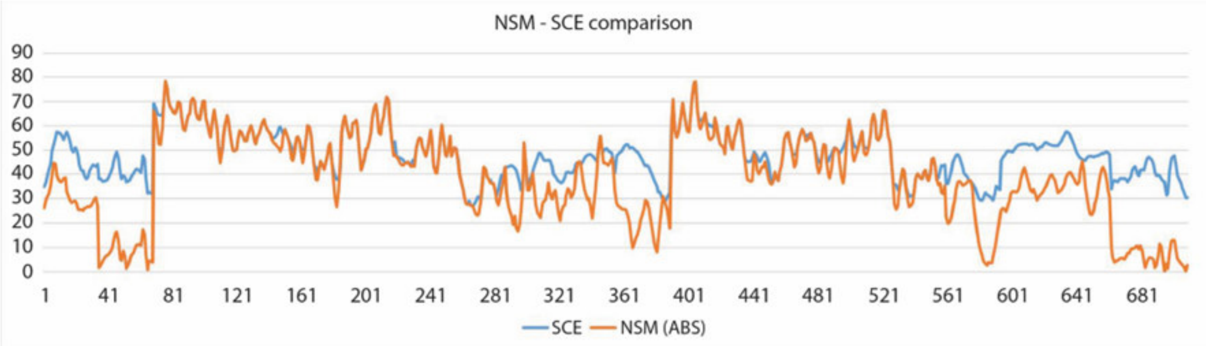

Figure 15. Absolute value of NSM and SCE comparison for the *Osso da Baleia* coastal sector, showing similarity between both indexes, although with a strong decoupling in the beginning and in the ending of the sector. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

housing were built on top of the foredune and, due to the dune erosion and associated overwash events, a seawall had to be built to protect those structures. Human activity and hard coastal stabilization may have contributed to the unrecovered state of the dune in that particular area.

Southward of *Pedrogão* erosion prevails. This may be interpreted as a result of the littoral drift diminishment during the analysis period.

Regarding the CO index, [Abs (NSM)/SCE] (table 2), the 0.2 value indicates that the NSM has to be used carefully when analysing the coastal evolution behaviour during the analysed time period. SCE is consistently higher than NSM which means that coastline oscillation is significant, playing an important role in this sector (figure 16).

5.2.5 *Praia da Vieira* coastal sector

The most notorious changes in this sector are related with the Liz River mouth, which has been artificially fixed, with two jetties, between 1947 and 1958. These structures induced coastal changes, being that the intensity of the variations diminish with the distance to the inlet.

As previously mentioned, this sector reverts gradually from erosion (related with the *Pedrogão* promontory) to accretion, as we move south in the direction of the Liz River north jetty. The sand accumulation against the jetty starts to be noticeable approximately 1700 m north of the structure. Near the north jetty, accretion reaches 154.2 m in contrast with 26,3 m average of the progradation values observed in the sub-sector, showing the importance of the structure in the longshore drift retention.

Southward of the jetties, as often happens, the erosion reappears, occurring in 3130 of the 3440 m remaining sector length. Immediately south of the second jetty, the erosion reaches -84.2 m in contrast with the sub-sector average, which is -17.1 m, illustrating, once again, the erosional effect of these structures in a longshore drift coastal sand transport.

Erosion values southward of the jetty could be even higher than the ones obtained with the DSAS analysis. *Praia da Vieira* is protected by a seawall and artificial nourishment was already applied to minimize and prevent the coastline inland displacement.

As previously mentioned, the CO index, [Abs (NSM)/SCE], for this sector is 0.5 (table 2). This is a consequence of SCE being 1.9 times higher than the Abs (NSM). However, in the present case, oscillation shouldn't be regarded with great concern once that the CO index values are significantly smaller. Although the ratio is high, the SCE average is only 37.7 m and the average for the absolute value of NSM is 19.8 m, for the last 68 years. Looking to figure 17, it may be concluded that this is a relatively stable coastline, and the oscillation is only more significant in the last 300 m of the sector.

5.2.6 *Samouco* coastal sector

The *Samouco* littoral sector (figure 9), with slight erosion prevailing in the northern part and progradation in the southern part, is the steadiest sector of the study area, with mean LLR of 0.06 my$^{-1.}$

This sector is influenced by two features that lies outside its boundaries: to the north, the *Liz* River jetties and, to the south, the *São Pedro de Moel* promontory. As seen in similar northern sectors, also influenced by hard structures, erosion tends to occur downdrift and sand accumulation tends to occur updrift those structures. This sector, being located between those two hard structures, is in the transition zone, what may explain its stability.

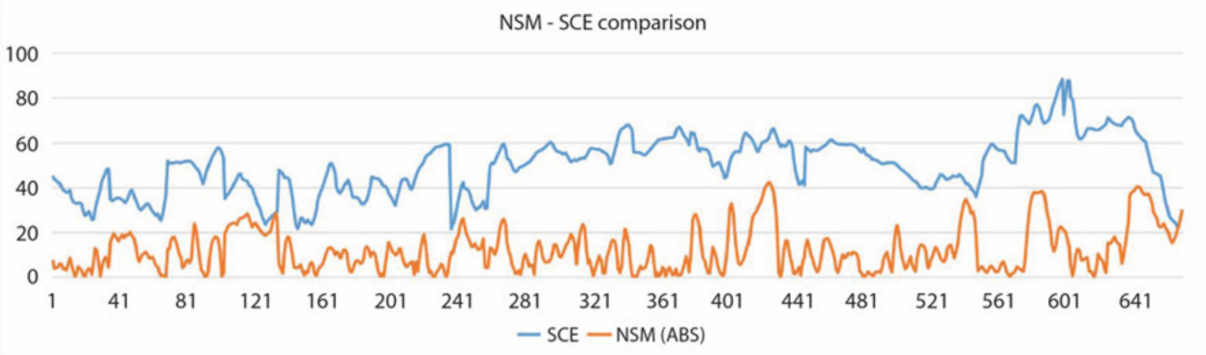

Figure 16. Absolute value of NSM and SCE comparison for the *Pedrogão* coastal sector, showing a strong decoupling from both indexes, with NSM being significantly smaller than SCE. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

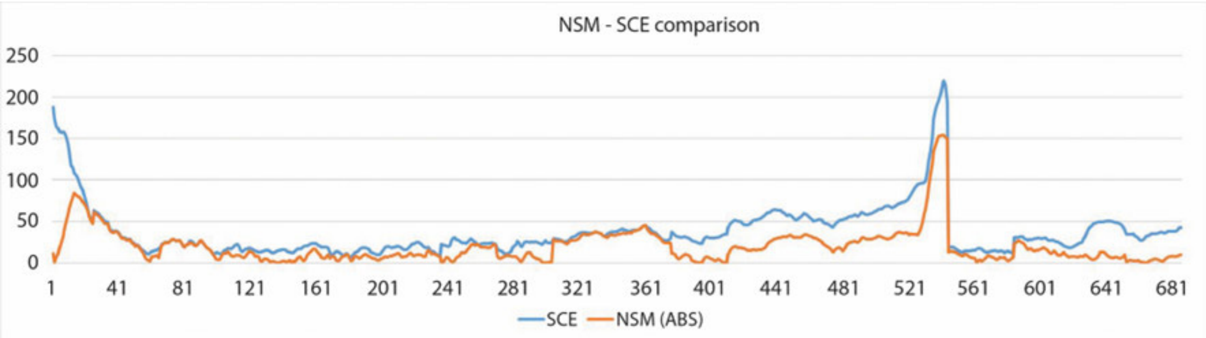

Figure 17. Absolute value of NSM and SCE comparison for the *Praia da Vieira* coastal sector, showing similarity between both indexes, although with a decoupling in the beginning and in the second half of the sector. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

In this segment, the coastline oscillation follows the same pattern as the one of the southern limit of the predecessor sector, with a slightly decoupling of the SCE and Abs (NSM) indexes (figure 18). With a CO ratio of 2.1, caution should be taken in the analysis of coastline displacement, based solely in the NSM values. However, as coastal changes absolute values are small, with an average NSM of 10.4 m and an average SCE of 21.9 m, the ratio shouldn't be regarded with great concern.

5.2.7 São Pedro de Moel coastal sector

An SCE value approximately 2.5 times larger than the NSM (table 2) is an indication that we are in presence of a coastal stretch where oscillation plays, through time, an important role in the characterization of coastal evolution. The *São Pedro de Moel* rocky shore, already eroded and aligned with the general coastal orientation (figure 10), act as a natural groin, resulting in the updrift accumulation of sand, and establishing a maximum seaward coastline position prior to bypassing occur.

In a finer analysis, the S. Pedro stream also plays an important role in local coastal behaviour. To the north of the stream mouth, nearby *Praia Velha* (located around the 161 (m x 10), in figure 19), the mean SCE value is 19.1 m, while southwards of this beach, the SCE average value is 57.7 m. This higher value is likely related with the observed shift of the mouth stream from 1947 to 2015.

Although the observed coastline oscillation is important in terms of coastal evolution analysis for this sector [Abs (NSM)/ SCE ratio of 0.4, table 2], the LRR value of 0.29 my^{-1}, with shifts between eroding and accretion coastal stretches, indicates that this sector is relatively stable, and the occurred changes may be regarded as part of the natural coastal evolution process in a longshore drift, high energetic coast.

South of *São Pedro de Moel*, the *Valeiras* beach, with 570 m length, has an average NSM value of -3.7 m, showing a slight erosional trend (LRR of 0.08 my^{-1}). However, coastline oscillation has also to be considered, since the average SCE is 16.2 m.

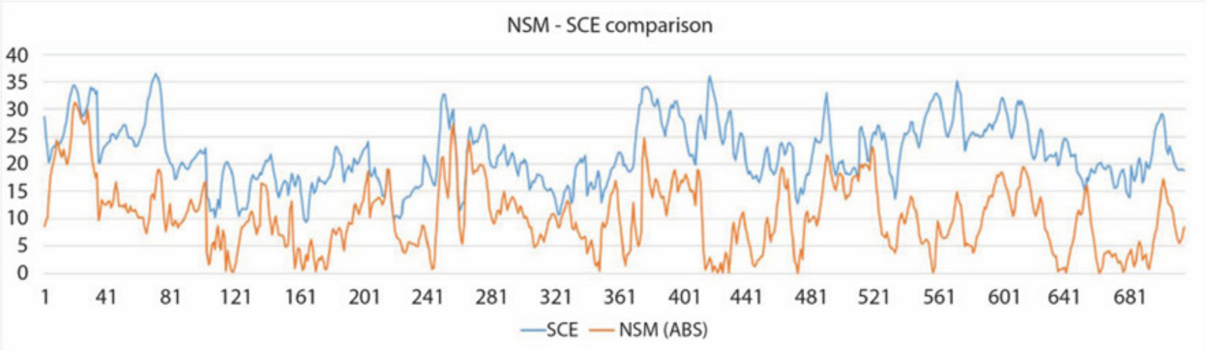

Figure 18. Absolute value of NSM and SCE comparison for the *Samouco* coastal sector, showing some decoupling between both indexes. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

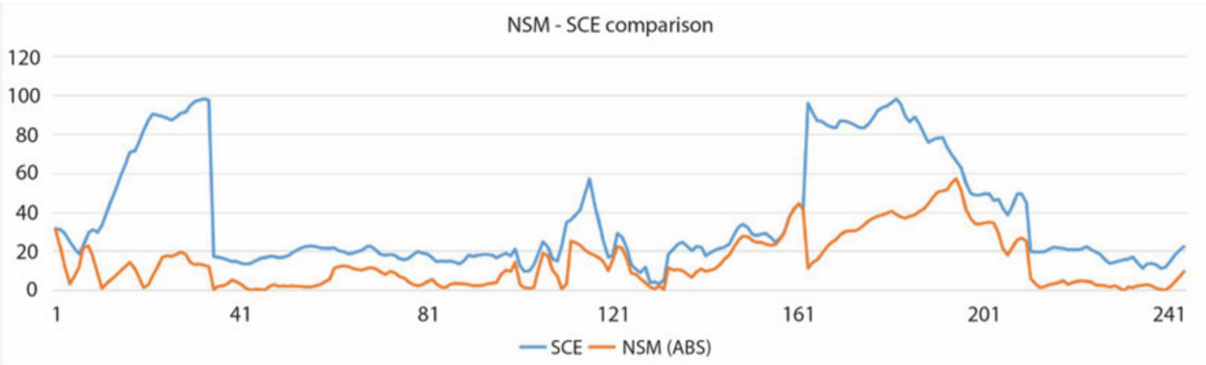

Figure 19. Absolute value of NSM and SCE comparison, north of *São Pedro de Moel*, showing a significant decoupling between both indexes. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

5.2.8 *Paredes da Vitória* coastal sector

With an SCE value approximately 3 times larger than the NSM, oscillation plays, as in the preceding sector, an important role in the characterization of coastal evolution. Progradation values (NSM average of 7.3 m and LRR average of 0.15 my^{-1}) should, thereby, be valued within this context.

5.2.9 *Vale do Pardo - Nazaré* coastal sector

Although the slightly northward orientation of the coast at these sectors may induce a small increase in the potential of the coastal drift (Santos *et al*., 2014), sand accumulation occurs, confirmed by the presence of wide beaches and well developed dunes (especially in the southern part), where, due to the existence of an aeolian ramp, a sand continuity between the beach/dune system and top-cliff dunes are observed.

Like in the several existent rocky promontories in the coast northward this sector, the *Nazaré* headland has an important role in sand accumulation due to the littoral drift, being the North beach a good example. However, in this sector, the coastline has a peculiar shape (figure 12), drawing a curve and extending seaward, approximately 1 km to the north of the promontory, surpassing what was expected to be the natural coastline orientation. This singular shape of the coastline is due to the effect of the *Nazaré* canyon which tends to rotate the waves orientation anticlockwise (Forone, 2014), promoting a higher accumulation in that area.

This sector, where accretion prevails, may be divided in two subsectors in terms of evolutionary trend. In the first 2470 m of coast, NSM values reflects an oscillation between erosion and accretion. Also in this first subsector, the CO index, [Abs (NSM)/SCE], has a value of 0.3, which reflects a very strong oscillation/instability of the coastal position. In the following 3090 m, accretion is dominant and the Abs (NSM)/SCE ratio has a value of 0.7. However, although ratios are very different, the average difference between the SCE and Abs (NSM) is approximately the

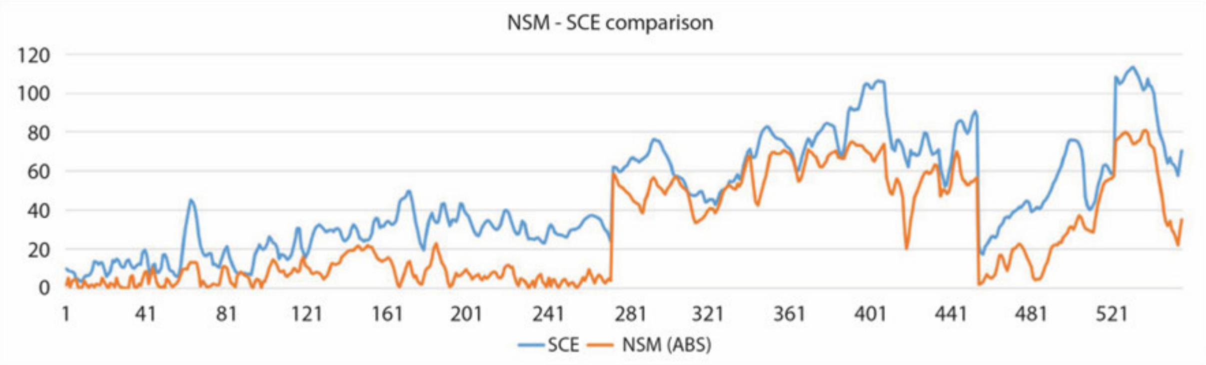

Figure 20. Absolute value of NSM and SCE comparison for the *Vale do Pardo - Nazaré* coastal sector. In the first 2470 meters, coastline oscillation is 3.3 times larger than NSM, whereas in the remaining part of the sector the oscillation is only 1.4 times larger than the NSM. Vertical axis: Coastal displacement, in meters; Horizontal axis: Coastal sector distance, from the most northern point (in meter x 10).

same (16.5 m in the north part and 20 m in the south) (figure 20), showing the precaution that has to be taken when using this ratio alone for coastal displacement analysis: depending on the NSM and SCE absolute values involved, very different ratios may be obtained.

5.3 Land loss by coastal erosion

The obtained data may also be used to quantify the lost and gain of territory due to the coastline shift during the 68-year period of analysis. Considering the positive and negative coastline shifts from 1947 to 2015, data shows that 1 164 888 m^2 of land were lost, along 30 470 m of coast, and 462 330 m^2 were gained, along 21 010 m of coast. The overall result may be expressed as a loss of territory of 702 558 m^2.

Table 4. Land loss and land growth for each sector, based on the NSM values.

Coastal sector	Net Area – land loss/land growth (m^2)
Figueira da Foz-Costa de Lavos	-272097
Costa de Lavos-Osso da Baleia	-347886
Osso da Baleia	-265663
Pedrogão	24632
Praia da Vieira	-29558
Samouco	9722
São Pedro de Moel	24065
Paredes da Vitória	17326
Vale do Pardo-Nazaré	136899
Resultant	**-702558**

The analysis may also be made by sectors, as shown in Table 4. As a result, 4 of the 9 sectors show erosion, while 5 show accretion. Table 4 also displays a clear predominance of erosion in the northern sectors, despite the artificial beach nourishment performed in the northern part, versus a clear tendency for accretion in the southern sectors, during the time-period of analysis.

6. CONCLUSIONS

The current work brings new and detailed insights on the historical evolution trend of the western Portuguese littoral, occupied by beaches with dunes, from *Figueira da Foz* to *Nazaré*. Being part of a broader national programme at LNEG [https://geoportal.lneg.pt/mapa/?escala=4000000&mapa=geologiacosteira#], this study achieves, for the first time, a long-term (nearly 7 decades, from 1947 to 2015), high-resolution (10 m spaced), systematic (with an approximately 10-year analysis interval) and continuous coastline evolution analyses, using different sources of aerial imagery and USGS DSAS software to calculate coastline displacement.

The applied DSAS methodology, widely used and recognized to be appropriated for the current propose, makes the presented dataset easily comparable to other previously acquired datasets, with the advantage of, being a continuous and a high-resolution dataset, becoming more adequate to support the planning and efficacious implementation of adaptive measures, not only in a regional, but also on a local scale. Thus, the current results are valuable, in a scientific perspective, but also, and perhaps most importantly, in an applied context, as the understanding of long-term and mesoscale shore evolution of the Portuguese western coast, is needed for the planning and implementation of effective adaptive measures on the climate change scenarios, in particular in this region, significantly endangered by erosion.

Coastline evolution results for the 68 years' time window, obtained in the coastal stretch comprising beach and dunes (51 480 m of the total 63 408 m coastline extension from *Figueira da Foz* to *Nazaré*), reveals an erosional trend, with an average retreat of -13.6 m, despite the artificial beach nourishments deployed in the area as presented in table 3 (759 650 m3). This erosional trend is also shown by the 702 558 m^2 net land loss area during the analysed period. However, and looking only for the coastal sectors where erosion occurred, a total of 1 164 888 m^2 of land loss was observed.

Erosion, that is more severe in the northern part, reaching a maximum coastal retreat of -145 m and an erosion rate of 2.46 my^{-1} south of *Cova Gala*, is due to a negative sedimentary budget that affects this sector (Santos *et al*., 2014). The erosional pattern seems to be induced by human interference in coastal dynamics, namely by the introduction and enlargement of the original rigid constructions at *Figueira da Foz* harbour and by the *Cova Gala,* Costa de *Lavos* and *Leirosa* groins installation. In these later, the slight updrift accumulation is followed by a much expressive downdrift erosion, the typical pattern of coastal areas subjected to a negative sediment budget littoral drift, with maximum retreats of, respectively, -145, -118 and -103 m.

Seaward displacement of the coastline, occupying approximately 40.8% of the studied area, are mainly present in the southern part, reaching a maximum of 81 m of progradation at *Praia do Norte*, near *Nazaré*, although they are also associated with updrift accumulation against the installed protection groins in the north and central part of the study area (maximum values of 322 m between the *Mondego* jetties, 18 m at *Costa de Lavos*, 78 m at *Leirosa* and 154 m at *Praia da Vieira*).

The importance of coastline evolution trend evaluation, at a high-resolution scale, was somehow evidenced by the current work. The advantage of the achievement of continuous updated and reinterpreted high-resolution data at a regional scale, likely favour successful application of the needed mitigation measures (as sand nourishment, and others) at the exact key target locations.

REFERENCES

Andrade C, Freitas MC (2002) Coastal Zones. In: Santos F. D. F, K., and Moita, R. (ed) Climate Change in Portugal. Scenarios, Impacts and Adaptation Measures - SIAM project. Lisboa, Portugal, pp 173-219.

André, J., & Cordeiro, M. (2013). *Alteração da linha de costa entre a Figueira da Foz e São Pedro de Moel após o prolongamento do molhe norte do Mondego.* Paper presented at the VI Congresso Nacional de Geomorfologia, Coimbra.

Beach to Canyon (2013) . Relatório de campo n.º 6, available at http://beachtocanyon.fc.ul.pt//Fieldwork/FieldReport_VI.pdf

Coelho, C., Silva, R., Veloso-Gomes, F., and Taveira-Pinto, F. (2009). Potential effects of climate change on northwest Portuguese coastal zones. – ICES Journal of Marine Science, 66: 1497 – 1507

Commission E. (2004) Living with coastal erosion in Europe – Sediment and space for sustainability. Luxembourg office for official publications of the European Commission. Retrieved from http://www.eurosion.org/reports-online/reports.html

Dias JMA, Ferreira Ó, Pereira AR (1994) Estudo sintético de diagnóstico da geomorfologia e da dinâmica sedimentar dos troços costeiros entre Espinho e *Nazaré*. Relatório para o ICN, 303 pp.

Ferreira O, Matias A (2013) Portugal. In: Enzo Pranzini, Williams A (eds) Coastal Erosion and Protection in Europe. Routledge, London, 488 pp. doi:10.4324/9780203128558.

Fletcher, C., Rooney, J., Barbeeh, M., Lim, S.-C., & Richmond, B. (2003). Mapping Shoreline Change Using Digital Orthophotogrammetry on Maui, Hawaii. *Journal of Coastal Research, SI 38*, 106-124.

Fletcher CH *et al*. (2012) National Assessment of Shoreline Change: Historical Shoreline Change in the Hawaiian Islands. U.S. Geological Survey.Retrieved from http://pubs.usgs.gov/of/2011/1051.

Forone, E. (2014). Evaluation of the *Nazaré* canyon's influence in the maritime agitation of the region through the SWAN model application. Tese para obtenção de grau de Mestre. Universidade de Aveiro. Departamento de Ambiente e Ordenamento.

Himmelstoss EA, Henderson RE, Kratzmann MG, Farris AS (2018) Digital Shoreline Analysis System (DSAS) version 5.0 user guide. Reston, VA. doi:10.3133/ofr20181179.

Masson DG, Huvenne VAI, de Stigter HC, Arzola RG, LeBas TP (2011) Sedimentary processes in the middle *Nazaré* Canyon Deep Sea Research Part II: Topical Studies in Oceanography 58:2369-2387 doi:10.1016/j.dsr2.2011.04.003

Nave S, Rebêlo L. (2018). High-resolution geological cartography and coastal evolution assessment at Armação de Pêra – Galé sector: a prototype for a national coastal mapping. *Journal of Coastal Conservation, 22*(6), 1031-1043. doi:10.1007/s11852-018-0612-2.

Nave S, Rebêlo L (2021) Coastline evolution of the Portuguese south eastern coast: a high-resolution approach in a 65 years' time-window Journal of Coastal Conservation 25:7 doi:10.1007/s11852-020-00791-3.

Oliveira IM, Valle AF, Miranda F Littoral problems in the portuguese west coast (1982). In: Eng. C (ed) Proceedings, 1982. pp 1951-1969.

Pinto CA, Silveira TM, Teixeira SB (2018) Alimentação artificial de praias na faixa costeira de Portugal continental: enquadramento e retrospetiva das intervenções realizadas (1950-2017). Agência Portuguesa do Ambiente, 65 pp.

Lira, C., Nobre Silva, A., Taborda, R., & Freire de Andrade, C. (2016). Coastline evolution of Portuguese low-lying sandy coast in the last 50 years: an integrated approach. *Earth Syst. Sci. Data, 8*, 265-278. doi:https://doi.org/10.5194/essd-8-265-2016.

Rebêlo L, Nave S (2019) Manual de Utilizador para Execução da Determinação da Perigosidade Costeira à Escala 1: 3.000 vol Versão: 1. 7 pp. Procedimentos Técnicos, LNEG. Alfragide, Portugal.

Santos, FD. and Miranda P. (Editors) (2006). *Alterações Climáticas em Portugal, Cenários, Impactos e Medidas de Adaptação - Projecto SIAM II*. Lisbon, Portugal: Gradiva, 500pp.

Santos FD, Lopes AM, Moniz G, Ramos L, Taborda R (2014) Relatório do Grupo de Trabalho do Litoral: Gestão da Zona Costeira , O Desafio da Mudança. 260 pp.

Schmidt L, Prista P, Saraiva T, O'Riordan T, Gomes C (2013) Adapting governance for coastal change in Portugal Land Use Policy 31:314-325 doi:http://dx.doi.org/10.1016/j.landusepol.2012.07.012.

Taveira-Pinto, F., Rosa-Santos, P. e Fazeres-Ferradosa, T. (2021). Integrated coastal zone management: Preservation, adaptation and monitoring. Journal of Integrated Coastal Zone Management, 21(1): 5-9. DOI 10.5894/rgci-n442

Veloso-Gomes, F., Taveira-Pinto, F., das Neves, L. *et al*. (2004). Erosion risk levels at the NW Portuguese coast: the Douro mouth—Cape *Mondego* stretch. J Coast Conserv 10, 43–52. https://doi.org/10.1652/1400-0350(2004)010[0043:ERLATN]2.0.CO;2

Vousdoukas, M. I., Ranasinghe, R., Mentaschi, L., Plomaritis, T. A., Athanasiou, P., Luijendijk, A., & Feyen, L. (2020). Sandy coastlines under threat of erosion. *Nature Climate Change, 10*(3), 260-263. doi:10.1038/s41558-020-0697-0.

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Conflicts of interest

The authors declare that they have no conflict of interest

Availability of data and material

Data is available at LNEG GeoPortal:

https://geoportal.lneg.pt/mapa/?escala=4000000&mapa=geologiacosteira#

Authors' contributions

Both authors have been involved with the work, namely in the conception and design of the project, data interpretation and manuscript writing

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