LITTORAL DRIFT GRADIENTS ON THE PORTUGUESE COASTAL SECTOR ESMORIZ-NAZARÉ: PAST AND FUTURE TRENDS

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The Northwest Portuguese coastal sector Esmoriz-Nazaré is exposed to a very energetic wave climate that promotes a net littoral drift estimated to be around $1.1x10^6$ m^3/year. This study aimed to characterize the littoral drift in the coastal sector Esmoriz-Nazaré, discussing past and future trends by applying two bulk longshore sediment transport formulas: CERC (1984) and Mil-Homens *et al.* (2013). Generically, the results present a longshore sediment transport variability at the study area. In spite of the differences between the considered formulas, both of them present similar trends along the coastal sector and for the past and future wave climates. In the future, mainly due to changes in the projected waves direction, the net littoral drift is expected to decrease.

Keywords: wave climate; sediment transport; climate changes; coastal erosion; Portugal

INTRODUCTION

The Northwest Portuguese coast, where the coastal sector Esmoriz-Nazaré is located, is characterized by continuous sandy beaches with foredune systems which have been developed from rivers sediment supply and wave action (Figure 1). The sector is exposed to a very energetic wave climate with mean values of significant wave height (*Hs*) between 2 m and 2.5 m (Andrade *et al*., 2002; Coelho, 2005).

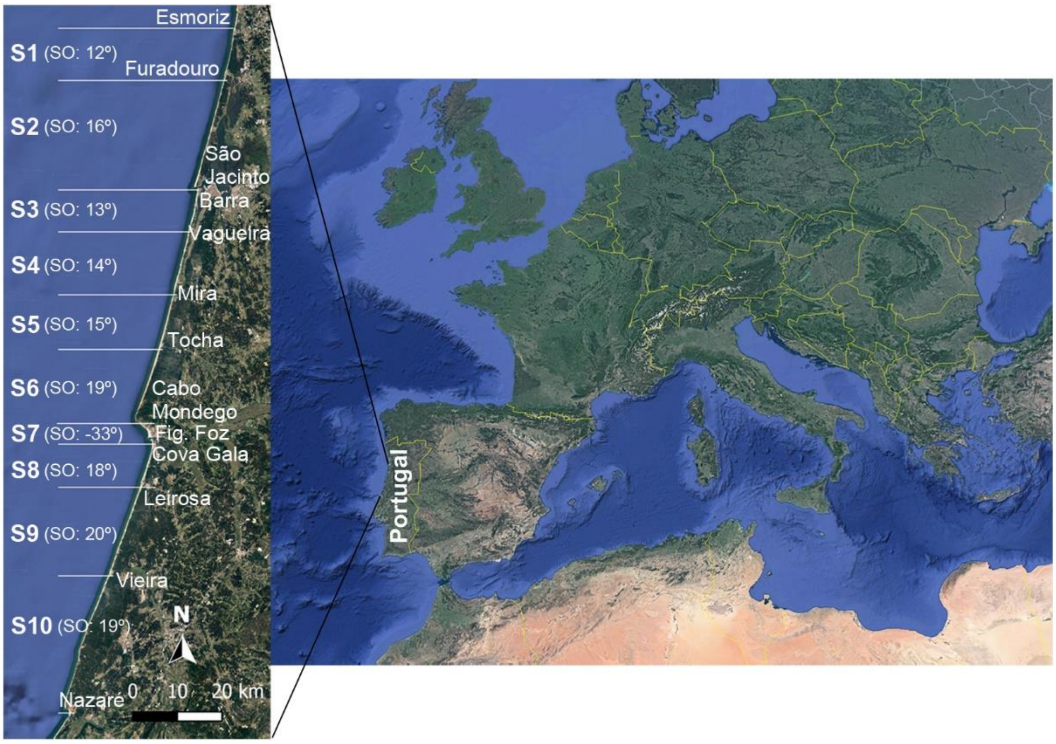

Figure 1. Study area location, considered coastal stretches and their shoreline orientations (SO), defined anticlockwise.

According to Santos *et al*. (2014), the wave climate at the West Portuguese coast promotes a North to South directed net littoral drift estimated to be around $1.1x10^6$ m^3/year. This high energetic wave capacity to transport sediments combined with anthropogenic actions (dams, sand extraction, dredging activities, coastal protection works, etc.), that over the years reduced the sediment volume in the coastal

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extension between Esmoriz and Nazaré, had consequences on the shoreline evolution. Presently a large extension of the Portuguese West coast shows erosion problems related to sedimentary deficit (Coelho *et al*., 2011; Costa and Coelho, 2013; Santos *et al*., 2014; Ferreira *et al*. 2021). Based on the analysis of the shoreline evolution in the Portuguese low-lying sandy coasts between 1958 and 2015, Lira *et al.* (2016) pointed that approximately 50% of the coastal extension between Esmoriz and Nazaré is under erosion, presenting shoreline retreat rates that reaches 8 m/year in some locations.

This study aimed to estimate the potential littoral drift along the coastal sector Esmoriz-Nazaré for different wave climates (past and future trends), discuss the uncertainties on longshore sediment volumes estimates, and to identify the stretches that are most susceptible to negative sediment balances and therefore, to erosion. For that, the study area that compromises a shoreline extension of approximately 160 km was divided in 10 stretches (Figure 1), being the sediment transport in each coastal stretch obtained by applying two bulk longshore sediment transport formulas: CERC (1984) and Mil-Homens *et al*. (2013). The division of the study area in 10 stretches was based on the existence of coastal structures and/or morphological singularities.

METHODOLOGY

The potential longshore sediment transport was characterized considering the wave series produced in the scope of the MarRisk (2017) research project. These wave series represent the deep-water wave regime at offshore of the study area for different past and future periods. The past wave regime, designated as Historical, contemplates 46 years of records (1960-2005) and the future wave regime characterizes the waves actions considering climate change effects, for two greenhouse concentration pathways (RCP4.5 and RCP8.5) and two time periods of twenty years: near future (2026-2045) and end of the century (2081-2100).

The different components of the potential longshore sediment transport were evaluated for each coastal stretch, namely the sediment transport both in the North-South (N-S) and South-North (S-N) directions, the net sediment transport (difference between the N-S and S-N components) and the total longshore sediment transport (sum of the N-S and S-N components). The potential sediment transport was quantified through the longshore sediment transport formulas CERC (1984) and Mil-Homens *et al.* (2013).

CERC formulation (Eq. 1) was introduced several decades ago but it is still widely used in both practice and fundamental research (Shaeri *et al*., 2020). Eq. 1, is dependent on: an empirical coefficient (k); the water volume mass (ρ); the sediment's volume mass (ρ_s); the gravity acceleration (g); the sediment's porosity (n); the breaking wave coefficient (γ_b); the significant wave height at breaking (H_b); and the wave direction at breaking (α_b).

$$Q_S = k \frac{\rho\sqrt{\frac{g}{\gamma_b}}}{16(\rho_S-\rho)(1-n)} H_b^{\frac{5}{2}} sen(2\alpha_b) \quad (1)$$

Mil-Homens *et al*. (2013) presented an equation to estimate the *k* value of the CERC formula, Eq. 2, depending on the wave height at breaking (H_b) and the offshore wave length (L_0).

$$k_{MH,CERC} = \left[2232.7\left(\frac{H_b}{L_0}\right)^{1.45} + 4.505\right]^{-1} \quad (2)$$

Table 1 presents the water and sediments characteristics adopted for the parameters required by the formulas.

Table 1. Adopted values for the parameters in the equations related to water and sediments.

ρ	***g***	***ρ_s***	***n***
(kg/m^3)	(m/s^2)	(kg/m^3)	(-)
1027	9.81	2650	0.4

To characterize the sediment transport in the study area, three main steps were considered:

1. Identification of the most representative value for the *k* parameter in CERC formula:
   CERC formula requires the knowledge about the calibration coefficient *k*, and thus, the first part of the study focused on obtaining its adequate value. For that, a mean shoreline orientation representative of the all coastal sector Esmoriz-Nazaré was adopted, equal to 17 degrees (clockwise angle with the North). Then, the sediment transport was quantified by propagating the historical wave time series, under the linear wave theory of Airy assumptions. Based on the performed analysis, it was concluded that a *k* coefficient of 0.041 reproduces a net littoral drift close to the littoral drift referred in the bibliography (1.1×10^6 m^3/year, Santos *et al.*, 2014).

2. Characterization of the representative shoreline orientation of each of the ten coastal stretches:
   For each coastal stretch was defined the shoreline orientation and the adopted representative values are presented in Figure 1 (angle with North positive in the clockwise direction).

3. Quantification of the potential longshore sediment transport in each coastal stretch, by applying both formulas (CERC, 1984 and Mil-Homens *et al*., 2013):
   Considering the shoreline orientation representative of each coastal stretch, the waves were propagated (Airy wave theory assumptions) and the potential longitudinal sediment transport was quantified for past and future wave climate series.

RESULTS

The overall results show a variability of the potential longshore sediment transport along the study area and the sediment transport volumes obtained through the two formulas present differences on the order of magnitude. However, despite these differences, the observed main trends are similar, both for past and future wave climate series. In all the coastal stretches, the sediment transport occurs predominantly from North to South, being the N-S component significantly higher than the S-N component (Table 2 and Table 3).

Table 2. Net, N-S and S-N components of the longitudinal sediment transport, considering CERC (1984) formula ($\times 10^6$ m^3/year).

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Historical	**Net**	1.33	1.15	1.29	1.25	1.20	1.00	1.34	1.05	0.95	1.00
	N-S	1.60	1.49	1.57	1.55	1.52	1.41	1.38	1.44	1.38	1.41
	S-N	0.27	0.34	0.28	0.30	0.32	0.40	0.04	0.38	0.43	0.40
RCP4.5 (2026-2045)	**Net**	1.27	1.12	1.24	1.20	1.16	0.99	1.21	1.04	0.95	0.99
	N-S	1.53	1.45	1.51	1.49	1.47	1.38	1.24	1.40	1.35	1.38
	S-N	0.26	0.33	0.28	0.29	0.31	0.38	0.03	0.36	0.40	0.38
RCP4.5 (2081-2100)	**Net**	1.07	0.93	1.04	1.00	0.97	0.81	1.13	0.85	0.77	0.81
	N-S	1.33	1.25	1.31	1.29	1.27	1.19	1.16	1.21	1.16	1.19
	S-N	0.26	0.32	0.27	0.29	0.30	0.38	0.03	0.36	0.40	0.38
RCP8.5 (2026-2045)	**Net**	1.26	1.11	1.22	1.19	1.15	0.98	1.20	1.02	0.93	0.98
	N-S	1.50	1.41	1.48	1.45	1.43	1.33	1.22	1.36	1.31	1.33
	S-N	0.24	0.30	0.25	0.27	0.28	0.36	0.03	0.34	0.38	0.36
RCP8.5 (2081-2100)	**Net**	0.97	0.80	0.93	0.89	0.85	0.66	1.29	0.71	0.61	0.66
	N-S	1.25	1.15	1.23	1.20	1.18	1.08	1.32	1.10	1.05	1.08
	S-N	0.28	0.35	0.30	0.31	0.33	0.42	0.03	0.40	0.44	0.42

Table 3. Net, N-S and S-N components of the longitudinal sediment transport, considering Mil-Homens *et al.* (2013) formula (x10^6 m^3/year).

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Historical	**Net**	3.03	2.57	2.92	2.80	2.69	2.20	3.49	2.32	2.07	2.20
	N-S	3.50	3.21	3.43	3.36	3.28	2.98	3.53	3.06	2.90	2.98
	S-N	0.48	0.64	0.51	0.55	0.59	0.78	0.04	0.73	0.83	0.78
RCP4.5 (2026-2045)	**Net**	2.83	2.43	2.73	2.63	2.53	2.10	3.15	2.21	1.98	2.10
	N-S	3.30	3.05	3.23	3.17	3.11	2.85	3.19	2.92	2.78	2.85
	S-N	0.47	0.62	0.50	0.54	0.58	0.75	0.04	0.71	0.80	0.75
RCP4.5 (2081-2100)	**Net**	2.39	2.03	2.31	2.22	2.12	1.73	2.87	1.83	1.63	1.73
	N-S	2.85	2.62	2.79	2.74	2.68	2.45	2.90	2.51	2.38	2.45
	S-N	0.45	0.59	0.48	0.52	0.56	0.72	0.03	0.67	0.76	0.72
RCP8.5 (2026-2045)	**Net**	2.79	2.39	2.69	2.60	2.49	2.06	3.11	2.17	1.95	2.06
	N-S	3.21	0.42	3.21	0.42	3.21	0.42	3.21	0.42	3.21	0.42
	S-N	2.96	0.57	2.96	0.57	2.96	0.57	2.96	0.57	2.96	0.57
RCP8.5 (2081-2100)	**Net**	2.17	1.77	2.07	1.97	1.87	1.44	3.16	1.55	1.33	1.44
	N-S	2.65	2.40	2.58	2.52	2.46	2.21	3.19	2.27	2.14	2.21
	S-N	0.47	0.63	0.51	0.55	0.59	0.77	0.03	0.72	0.82	0.77

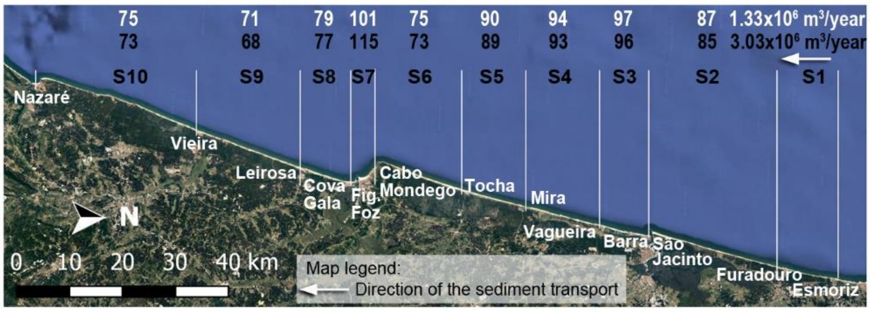
Based on the results presented in Table 2 and Table 3, considering CERC (1984) formula and the Historical period, the majority of the coastal stretches present a N-S longitudinal sediment transport higher than 1x10^6 m^3/year and a S-N annual volume lower than 5x10^5 m^3. The potential sediment transport resulting from Mil-Homens *et al*. (2013) formula, are higher than the results obtained with CERC (1984), as all coastal stretches present a net sediment transport higher than 2.5x10^6 m^3/year. Generically, independently of the wave series and the alongshore position, the potential sediment transport estimated through Mil-Homens *et al*. (2013) is approximately twice the one obtained with CERC (1984). This difference is due to the empirical coefficients of the formulations that in Mil-Homens *et al*. (2013) is dependent on the wave characteristics and were not tuned.

Figure 2 presents the percentage of the net littoral drift in each coastal stretch in relation to the stretch S1 for the different wave series considered in the study. The coastal extension between Esmoriz and Tocha (stretches S1 to S5) and Cabo Mondego and Figueira da Foz (S7) are the ones that present the highest net sediment transport values. The net littoral drift decreases in the coastal extension between Tocha and Cabo Mondego and at South of Figueira da Foz.

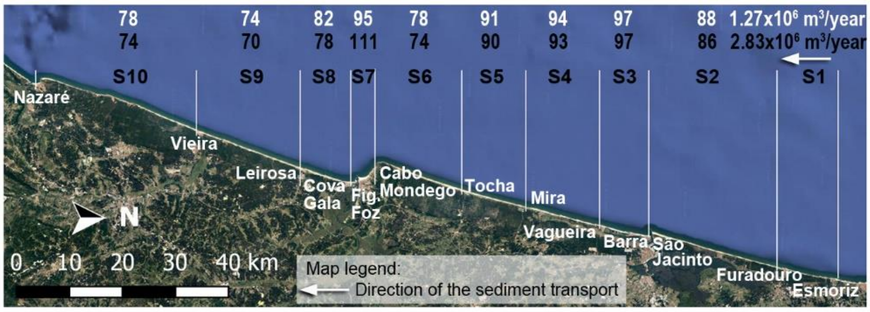
To evaluate the variability of the net longshore sediment transport in the study area and to understand why the highest values occur in the coastal stretches S1 to S5 and S7, the offshore wave direction that promotes higher sediment transport rates was estimated, based on the relationship between sediment transport and shoreline orientation (Table 4).

Table 4. Wave direction that promotes higher longitudinal sediment transport (angle in degrees, from N, anti-clockwise).

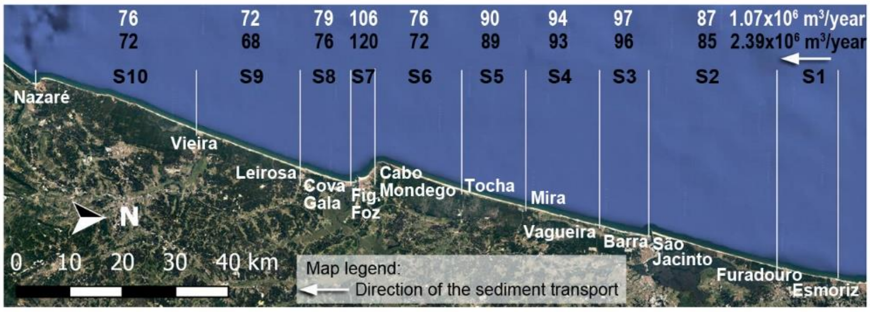
Stretch	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
CERC (1984)	36	32	35	34	33	29	81	30	28	29
Mil-Homens *et al.* (2013)	29	25	28	27	26	22	74	23	21	22



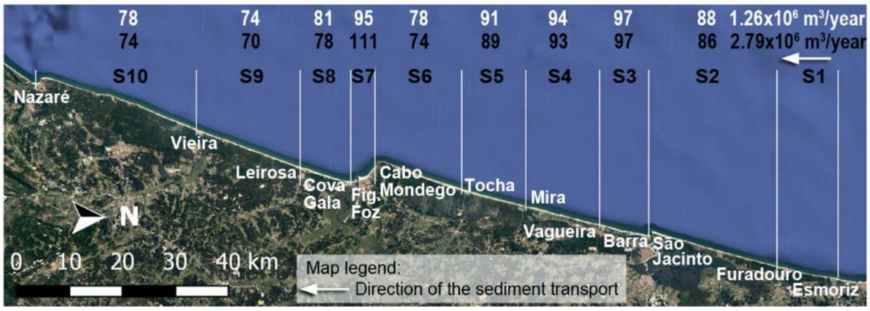
a) Historical



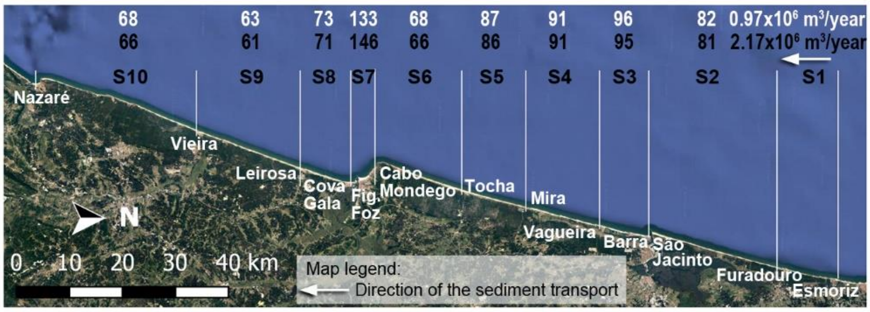
b) RCP4.5 2026-2045



c) RCP4.5 2081-2100



d) RCP8.5 2026-2045



e) RCP8.5 2081-2100

Figure 2. Percentage of the net littoral drift in relation to the stretch S1. The white values are the percentages according to CERC (1984) and the black values according to Mil-Homens *et al*. (2013).

The stretches that exhibit greater net sediment transport are those where the wave direction that promotes higher sediment transport falls within the waves directions that occur more frequently in the study area. As example, in Figure 3 is shown the wave roses of the coastal stretches (historical period) that presents higher net longshore sediment transport (stretch S1) and the stretch that presents lower net sediment transport (stretch S9). The wave direction that presents higher sediment transport in each coastal stretch is represented in the wave roses of significant wave height, by a red and blue lines according to CERC (1984) and Mil-Homens *et al.* (2013) formulas, respectively. Through the comparison of Figure 3a and Figure 3c it can be observed that the wave direction that promotes higher sediment transport in the stretch S1 intersects or is quite close of the waves that occurs more frequently on this coastal stretch and thus, the stretch S1 presents a higher sediment transport than the stretch S9.

Generically, the NW and NNW wave directions promote higher sediment transport, except in the stretch S7, where due to the shoreline orientation of the coastal stretch, the highest sediment transport is induced by WNW waves (Figure 3b).

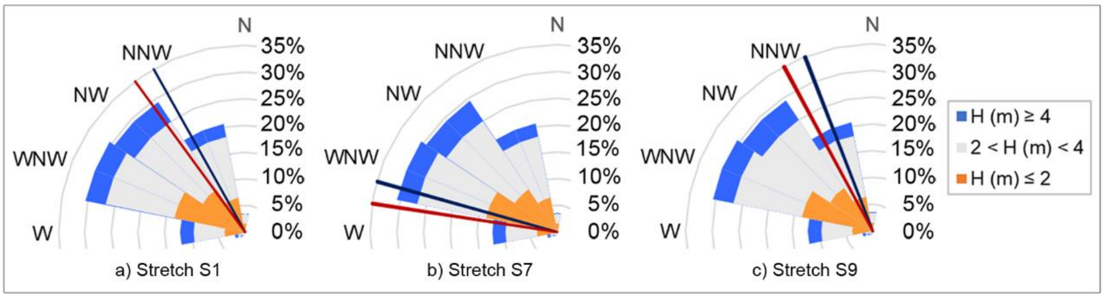


Figure 3. Wave direction that promotes higher longitudinal sediment transport overlapping the historical roses of significant wave height at offshore - red line is the direction according to CERC (1984) formula and blue line is the direction according to Mil-Homens *et al.* (2013) formula.

Based on the ratios of the net sediment transport for the future wave climate in relation to the Historical wave series (Figure 4), it is expected a slight decrease of the net sediment transport in the near future (2026-2045). Independently of the RCP scenario and the sediment transport formula, in this period, the ratio of the net littoral drift considering future and Historical wave series varies approximately from 0.9 to 1. At the end of the century, 2081-2100, the net littoral drift decrease is more evident and the ratios vary approximately between 0.6 and 0.8. Stretch S7 is the exception, where the net sediment transport decrease in RCP8.5 scenario is not so evident, due to the WNW frequency similarity in both future and historical wave series.

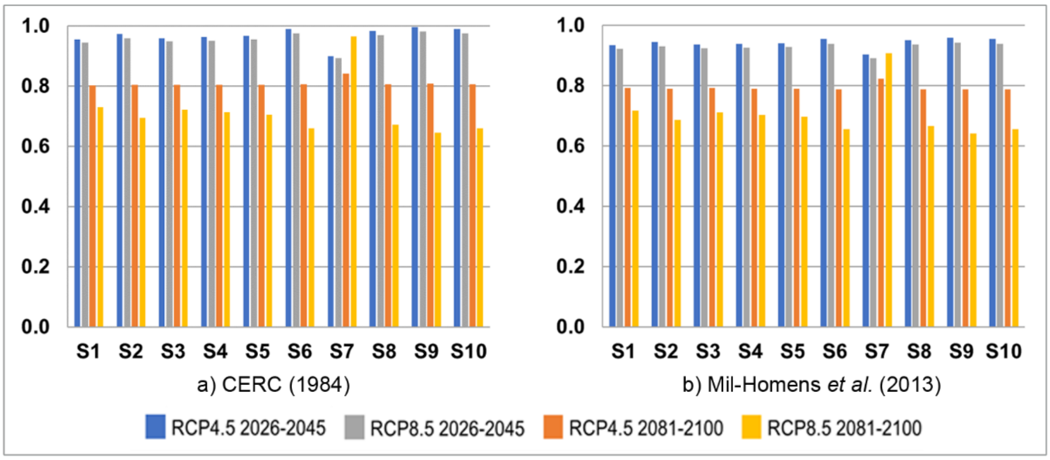


Figure 4. Ratio of the net littoral drift for future wave series, in relation to the Historical wave series.

The expected decrease in the net sediment transport observed in the majority of the stretches is related to changes in the wave directions. The future wave climate depicts a higher dispersion of the wave's directions, Figure 5, decreasing the frequency of the higher waves that promote higher sediment transport rates in the N-S direction, which are the waves from NW-NNW in the majority of the stretches (Table 4).

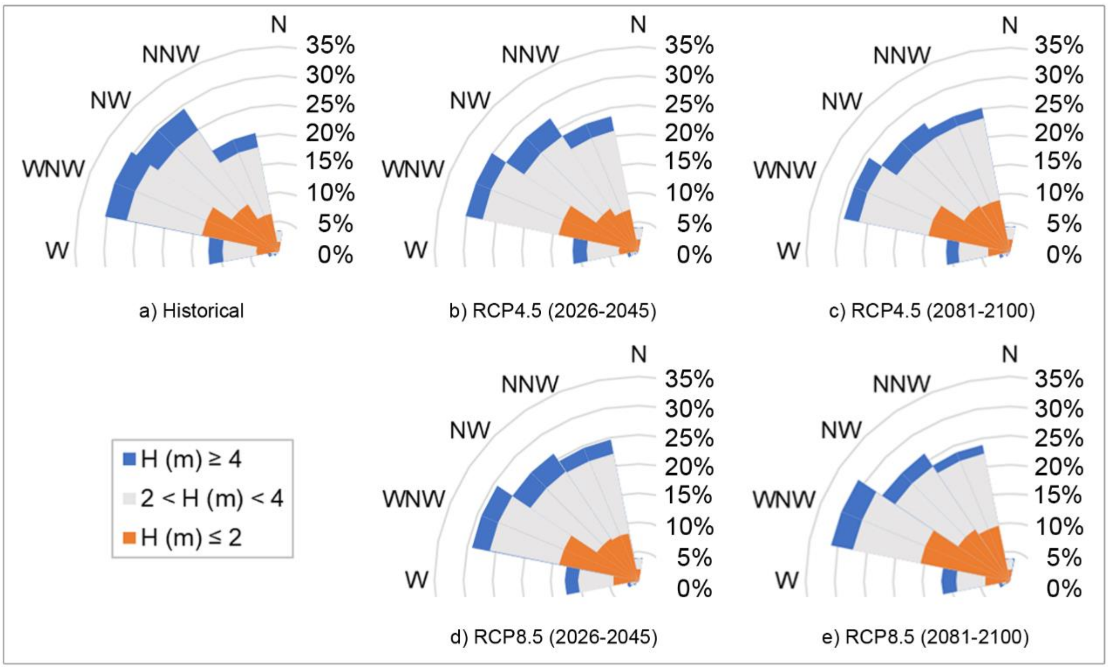


Figure 5. Wave roses and related offshore significant wave height distribution.

Sediment transport gradients were also obtained, resulting of the difference between the net sediment transport in the northern and southern consecutive coastal stretches. Independently of the wave climate, the highest values of transport gradients, occur where the shoreline presents larger changes in the shoreline orientation. Figure 6 presents the gradients for the historical wave series. The highest value occurs between stretches S6 and S7 - Cabo Mondego, followed by S7 and S8 - Cova Gala, S5 and S6 - Tocha and S1 and S2 - Furadouro.

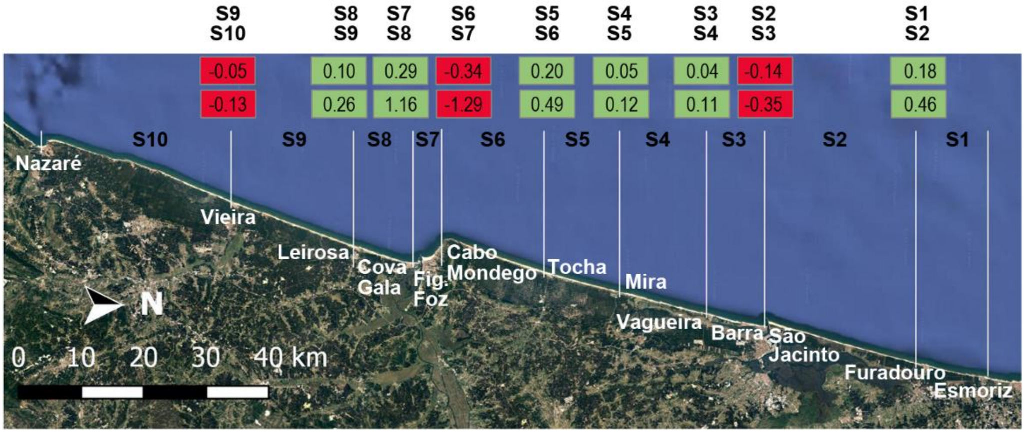


Figure 6. Sediment transport gradients, considering the Historical wave series (x10^6 m^3/year). Top line gradients by CERC (1984) and lower line by Mil-Homens *et al.* (2013).

Figure 7 summarizes the ratio of the net sediment transport gradients for future wave series in relation to the Historical wave series. Generically, it is predicted a slight decrease in the future net sediment transport gradients, with ratios varying from 0.79 to 0.98. The exceptions are the sediment transport gradients between Cabo Mondego and Cova Gala, where the sediment transport gradients increase. This results from the decrease of the net sediment transport for future periods in the coastal stretches S6 and S8 and the maintenance of the potential sediment transport in the stretch S7, previously mentioned.

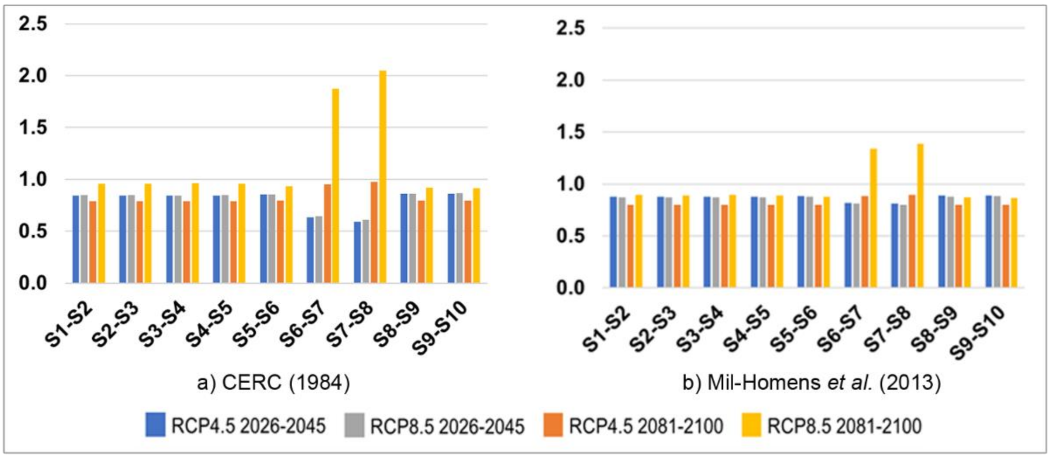


Figure 7. Ratio of the net sediment transport gradients for future wave climate series, in relation to the Historical wave series.

DISCUSSION

The Portuguese West coast present erosion problems related to sedimentary deficit that leads to shoreline retreat and put people, infrastructures and goods at risk. Currently, to improve the stability of the shoreline position, the Portuguese coastal management guidelines are oriented to mitigate the sedimentary deficit, trying to reestablish the sediment transport that occurs naturally in the coastal zone (Pinto *et al*., 2020). Ferreira *et al.* (2021), based on the discussion of coastal erosion mitigation strategies to mitigate coastal erosion risk stated that measures that allow to reduce the sedimentary deficit are the ones that reduce the risk of erosion. Therefore, the study of the potential longshore sediment transport in the coastal sector Esmoriz-Nazaré aimed to contribute to the understanding of the sediment transport patterns in the study area, since the longshore sediment transport is one of the main agents of the beach morphology evolution and a key parameter required for purposes related to coastal management (Mil-Homens, 2016; Silva *et al.* 2021).

In this study, CERC (1984) and Mil-Homens *et al.* (2013) formulas were applied to characterize the longshore sediment transport in the coastal sector Esmoriz-Nazaré, considering past and future wave climate series. According to Shaeri *et al.* (2020), despite CERC (1984) formulation have been introduced several years ago, the formula is still widely used in both practice and fundamental research. The longshore sediment transport according to CERC formula is mainly dependent on the wave parameters at breaking and the calibration coefficient *k*. Mil-Homens *et al*. (2013) enhanced the performance of the CERC formula through an equation to estimate the value for the coefficient *k*. The present results show that the magnitude of the longshore sediment transport is dependent on the sediment transport formula. This result is in line with Shaeri *et al.* (2020) that stated that, despite the several formulas to estimate the longshore sediment transport rates available in the literature, the estimation of the longshore sediment transport is still complicated. Furthermore, the difference in the results obtained for each formulation highlights the recommendation presented by Mil-Homens (2016), that indicates that longshore sediment transport data is needed to improve the accuracy of the formulas projections.

Despite the difference of the values obtained between the two longshore sediment transport formulas, the general findings show that the coastal sector Esmoriz-Nazaré presents a variability on the littoral drift caused by the relationship between the wave directions and the shoreline orientation. This variability is in accordance with Ferreira and Coelho (2021), that showed the impacts of the relationship between the shoreline orientation and the wave directions on the longshore sediment transport. For future wave series it is expected that climate change effects result in a decrease in the net longshore sediment transport, due to changes in the wave direction. Similar results related to future changes in the longshore sediment transport due to climate change effects on the wave characteristics were reported by Vieira da Silva *et al*. (2021) for the Gold Coast, Australia.

Generically the results of the potential longshore sediment transport gradients are aligned with the main features of the shoreline evolution observed in the Portuguese West coast, from 1950 to 2010, and presented by Lira *et al.* (2006). The potential sediment transport in the stretch S1 is higher than in S2, which indicates that Esmoriz-Furadouro coastal extension (S1) is one of the most affected by the erosion phenomena in the North of Portugal, due to the lack of sediments. The positive gradient shows that if sediments are available, there are potential to some deposition at S2.

Updrift São Jacinto, the shoreline position between 1950 to 2010 moved seaward. This behavior can be explained by the relationship between the high sediment transport capacity and the sedimentary retention that occurs at São Jacinto, due to the existence of the Aveiro harbor breakwaters, which produces a barrier effect to the longshore sediment transport. Thus, between the stretches S2 and S3 the longshore gradient is negative, as the potential longshore sediment transport is higher in the stretch S3 than in the stretch S2. This high sediment transport capacity in the stretch S3, combined with the sediment retention in the stretch S2, previously indicated, allows to correlate the negative sediment transport gradient with the high shoreline retreat rates reported by Lira *et al.* (2016) between Barra and Vagueira (reaching 8 m/year).

The longshore sediment transport gradients between the consecutive stretches S3 to S6 are similar, and slightly positive, being related with the reduction of the potential longshore sediment transport capacity estimated in South direction. Considering the lack of sediments along this coastal stretch, this result is in accordance with the shoreline change rates presented by Lira *et al.* (2016), that refer retreat rates between Barra and Tocha. At South of Figueira da Foz, the potential sediment transport is higher in the stretch S8 and Lira *et al.* (2016) results also evidence that the shoreline retreat is more intense in the coastal extension between Cova Gala and Leirosa, decreasing in South direction, considering the lack of sediments available to feed this potential transport capacity.

CONCLUSIONS

This study discussed the potential sediment transport on the coastal sector Esmoriz-Nazaré, since the understanding of the sediment transport is crucial for planning coastal management, as well to predict the performance and longevity of measures to mitigate coastal erosion, namely, the artificial sand nourishments.

The results provided by two longitudinal sediment transport formulas allowed to identify the spots that present high potential littoral drift gradients and to discuss future trends. The findings show that the study area presents spatial variability on the littoral drift, but, in spite of the different magnitude, both of the applied formulas present similar trends along the coastal sector and for all the considered wave climates.

In a large extension of the study area, it is expected a future decrease of the net littoral drift due to changes in the wave directions. The highest littoral drift gradients are observed at Cabo Mondego, Cova Gala and Furadouro, corresponding to locations where important dynamics of shoreline evolution were verified. Therefore, this analysis when combined with the availability of sediments and existing coastal structures could help to identify the territories most susceptible to erosion, supporting future coastal management.

The results support the viability of the methodology to achieve the objectives defined for the study, but further research is needed to discuss uncertainties associated with wave propagation assumptions, sediment transport formulas and future wave climates. The simplified linear wave theory of Airy was applied, being important to discuss or compare with more robust numerical models its suitability to reproduce the wave parameters at breaking. Other future wave climate series must be analyzed and compared to discuss uncertainties related to the impact of climate change on wave characteristics and consequent sediment transport patterns.

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