Longshore Sediment Transport Along a Sandy Coast with Hard Rock Outcrops

By

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ABSTRACT

This study aims to characterize the longshore sediment dynamics at Buarcos Beach, located in the central part of the west coast of Portugal, based on the analysis of previous studies and numerical results newly obtained by application of a numerical model. The annual and seasonal cross-shore distribution of the longshore sediment transport and associated beach characterization parameters were calculated for beach profiles representative of the length of Buarcos Beach, containing sections with hard rock outcrops and sandy bays. Based on wave data of 12 consecutive years, the average annual gross transport is approximately 1,000 m³/year, always directed southwards in this stretch of the Portuguese west coast. Most of the annual longshore transport, 87%, occurs during the local maritime winter (October to March). The influence of the sea level variation on the annual and seasonal longshore transport was estimated. The effect of extensive sectors of hard rock outcrops along the beach on the longshore sediment transport was analyzed for different sea levels and seasonal wave regimes. In contrast to sectors of sandy bottom sea, the sea level variation plays a major role on the variation of the longshore sediment transport in the beach sectors of hard rock outcrops. Annual longshore transport contributions as functions of wave direction and wave height were investigated. Waves incident from the sector N265-285 deg generate more than 80% of the annual transport, and waves with root-mean-square height within the range 1.0-2.5 m give the greatest contribution to the annual longshore transport. Discretization of the longshore transport in terms of wave direction and wave height contributions allows prediction of inter-annual and seasonal changes of wave climate on the longshore sediment transport.

Additional Keywords: Numerical model, beach, erosion, sea level variation, Buarcos Beach, Portugal

INTRODUCTION

The objective of this study was to characterize the dynamics of Buarcos Beach, located on the Atlantic west Coast of Portugal. This beach contains sectors of hard rock outcrops among smaller sectors of sandy bottom (Figure 1). The methodology applied was based on analysis of previous studies and calculations performed in this study by application of a numerical model. Buarcos Beach is an important seaside summer resort and downtown seafront. An avenue along its perimeter followed by other urban infrastructures vital to the local population limits the backshore. During the summer, the beach is mainly used for bathing (Figure 2) and leisure activities, not only by the local residents, but also by a large number of tourists that exceeds the local population. Important erosion episodes occurred between 1996 and 1998 that brought attention to this stretch of the Portuguese west coast. The erosion was associated with extreme and unusual meteorological conditions and sediment starvation (Andrade, Teles, and Barata 1997; Cunha and Dinis 1998; Vicente and Clímaco 1998). However, although understanding of the beach dynamics was acquired in these studies, a quantitative analysis of the local processes and the governing parameters was still lacking.
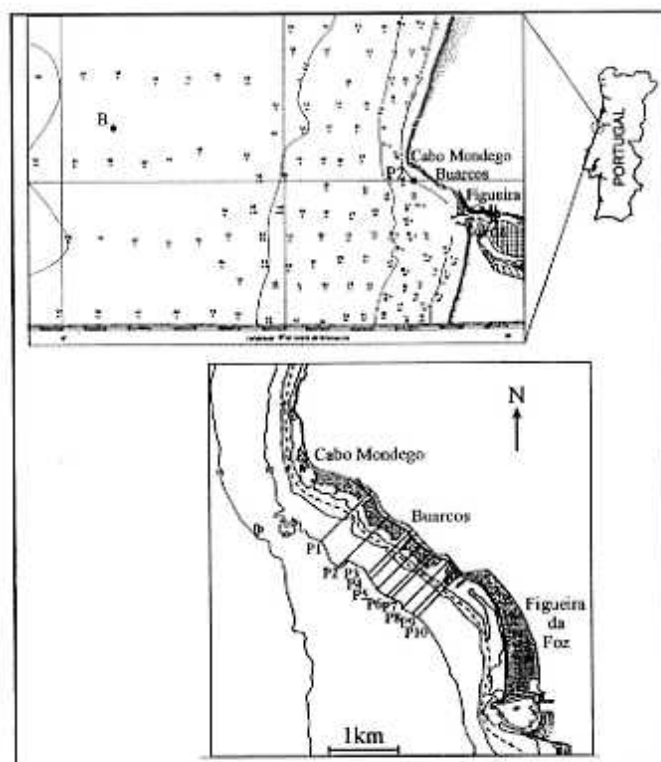

Figure 1. Location of Buarcos Beach and cross-shore profiles (based on IH Chart No. 64, 4th edition, 1985).

STUDY SITE

Buarcos Beach has a N126 deg general orientation and a length of 2.8 km. It is confined to the north by Cabo Mondego, a natural headland, and to the south by Figueira da Foz Beach, which has a N-S (N180 deg) general orientation and a slight curvilinear shape (Figure 1). Further north and south, the shoreline takes a rectilinear shape with NNE-SSW orientation. Besides its orientation, the other distinct feature of Buarcos is the existence of hard rock outcrops that cover almost the total length of the beach, with the exception of discontinuities of three small sandy bays. The hard rock outcrops (Figure 3) constitute an irregular solid platform, located between 2 m depth above chart datum (CD) and 1 m depth below CD, which is almost totally submerged at mean high sea level. These natural irregular structures have an onshore-offshore orientation and a maximum length of about 200 m. Beach sediments are predominantly

Figure 2. Buarcos Beach.

Figure 3. Outcrops sector of Buarcos Beach.

medium and coarse sands. The mean sea level (MSL) is 2 m above 0 m CD. The tide observed in Buarcos is semidiurnal with mean range 2.2 m, and maximum tidal level above the CD 3.6 m.

The historical evolution analysis of Buarcos Beach (Bettencourt and Ângelo 1992) based mainly in the study of charts and aerial photographs shows that, despite some interannual oscillations, between 1871 and 1985, the shoreline position at MSL was relatively stable. Based on surveys of the shoreline position between 1954 and 1984, Vicente and Clímaco (1998) reached the same conclusions. The only exception to this behavior was observed in the southern sector of the beach, as an enlargement that started in the 1960s as a result of construction of jetties in the Mondego estuary mouth (2 km further south). This led to the advance of new infrastructures (an avenue along the perimeter) over the beach. More recently, in January of 1996, the occurrence of an extreme storm initiated erosion that lasted until 1998.

Several authors (Ferreira, Gilbert, and Cordeiro 1961; Consulmar 1988; Bettencourt and Ângelo 1992; Andrade, Teles, and Barata 1997; Cunha and Dinis 1998) have estimated the net longshore transport to be directed to the south and to vary between 200 and 1.500 x 10³ m³/year. Such a wide range of estimated values reveals the difficulty of analyzing the Buarcos Beach dynamics and points to the necessity of applying other methodologies, such as numerical modelling, to obtain a detailed description of the longshore transport.

Capitão, Fortes, and Carvalho (1997) characterized the annual wave climate in the nearshore region of Buarcos based on wave records covering January 1984 to December 1996 that had been obtained from a wave rider buoy located at 89 m depth CD, labelled as "B" in Figure 1. In this study, the annual wave climate was transferred, based on mathematical modelling of wave propagation at MSL, to a location in front of the beach, at 10 m depth CD, location P2 in Figure 1. The transference of the wave climate was done for three time periods as: (1) the average annual regime observed, (2) average maritime winter (October to March), and (3) average maritime summer (April to September). The results are presented in Figure 4a-b.

METHODOLOGY

Ten parallel cross-shore profiles along Buarcos Beach, P1-P10 in Figure 1, were extracted from a sea chart at scale 1:2000, dated 1987. The location of the cross-shore profiles was selected strategically in order to obtain a good representation of the beach. Profiles P1, P3, and P8 are located in the small bays of
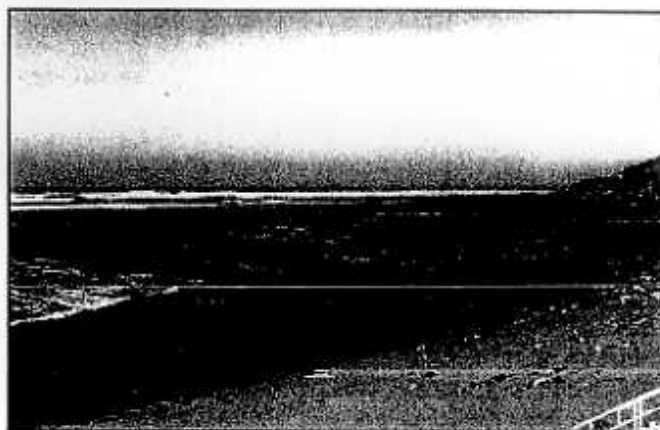
sandy bottom sea existent within the hard rock outcrops discontinuities. The remaining profiles intercept the irregular hard rock outcrops and are therefore representative of beach profiles of a partial solid bottom sea. The cross-shore distribution of the average annual and seasonal longshore sediment transport corresponding to the wave data available were estimated for each beach profile.

The numerical model applied was LITPACK (DHI 2000). The model is well known in the coastal engineering scientific community, so a description of its formulation is omitted. The three sea levels of 2.0, 0.5, and 3.5 m above CD were implemented in the model to simulate the beach dynamics at MSL, low sea level (LSL), and high sea level (HSL), respectively. The sedimentological characteristics of the beach obtained from local surveys was based on the parameters median grain diameter, $D_{50} = 0.71$ mm, and diameter spreading, $(D_{84}/D_{16})^{1/2} = 1.38$.
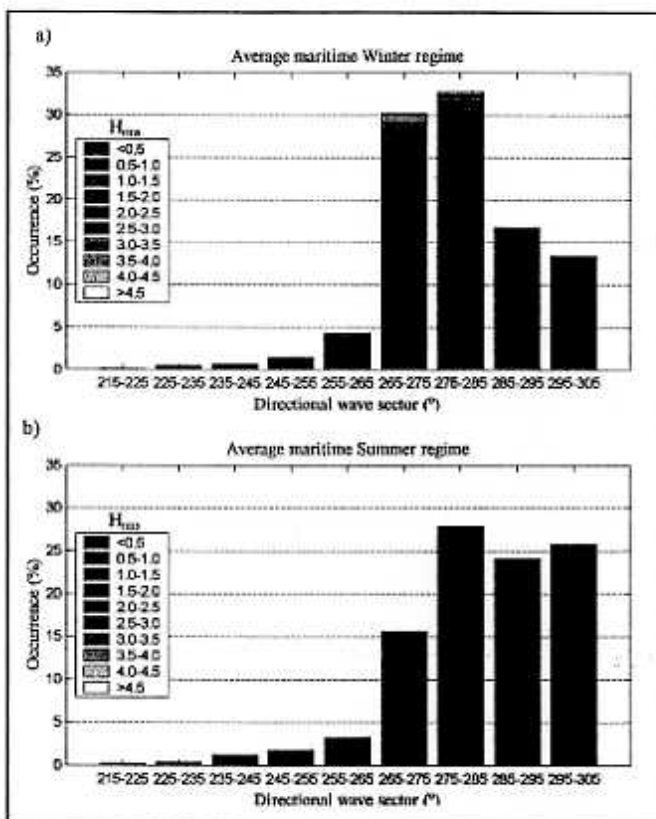

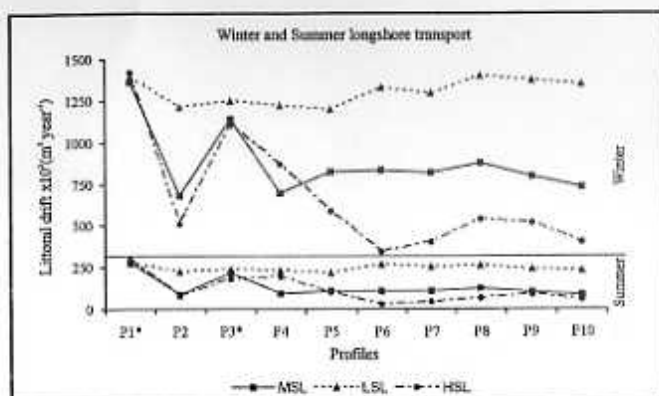Figure 4. Wave regime: (a) Maritime winter, and (b) Maritime summer.

Figure 5. Seasonal longshore sediment transport at MSL, LSL, and HSL for profiles P1-P10.

ANALYSIS AND DISCUSSION

Annual Longshore Transport at Different Sea Levels

Due to the alignment of the shoreline, it was found that the net and gross transport rates are equal and directed southwards, independent of the seasonal wave climate, which in both cases presents a wide spread of wave direction distribution. The average seasonal longshore transport obtained for the three sea levels, MSL, LSL, and HSL, at each beach profile P1-P10 (Figure 1), is presented in Figure 5.

At MSL, the hard rock outcrops are partially submerged. The average annual longshore transport along the total extension of the beach is 1.008×10^3 m^3/year. On average, the transport is 868 $\times 10^3$ m^3/year in the beach sectors of hard rock outcrops and 1.501×10^3 m^3/year in the sandy bays (Figure 5). The longshore transport at the hard rock outcrops sectors might be underestimated because the model neglects both bed load and suspended sediment transport over the solid bottom sea.

At MSL, in the sectors of hard rock outcrops, the majority of the longshore transport occurs seaward of the outcrops. Only about 2% of the average annual longshore transport occurs shoreward of the outcrops (Figure 7a). At both types of profiles (with and without outcrops), the presence of an offshore bar generates a second peak in the cross-shore distribution of the longshore transport, as can be seen for profiles P3 and P10 in Figures 6a and 7a, respectively. The existence of an offshore bar reduces the magnitude of the peak of the longshore transport closer to the shoreline as result of previous wave breaking.

At LSL, the hard rock outcrops are almost completely emergent. The average longshore transport along the total extension of the beach is 1.545×10^3 m^3/year. On average, the transport is 1.519×10^3 m^3/year in the beach sectors of hard rock outcrops and 1.579×10^3 m^3/year in the sandy bays. Comparing these values with the corresponding values at MSL, it is observed that the longshore transport is 75% and 5% greater for the beach sectors of rocky bottom and sandy bottom, respectively.
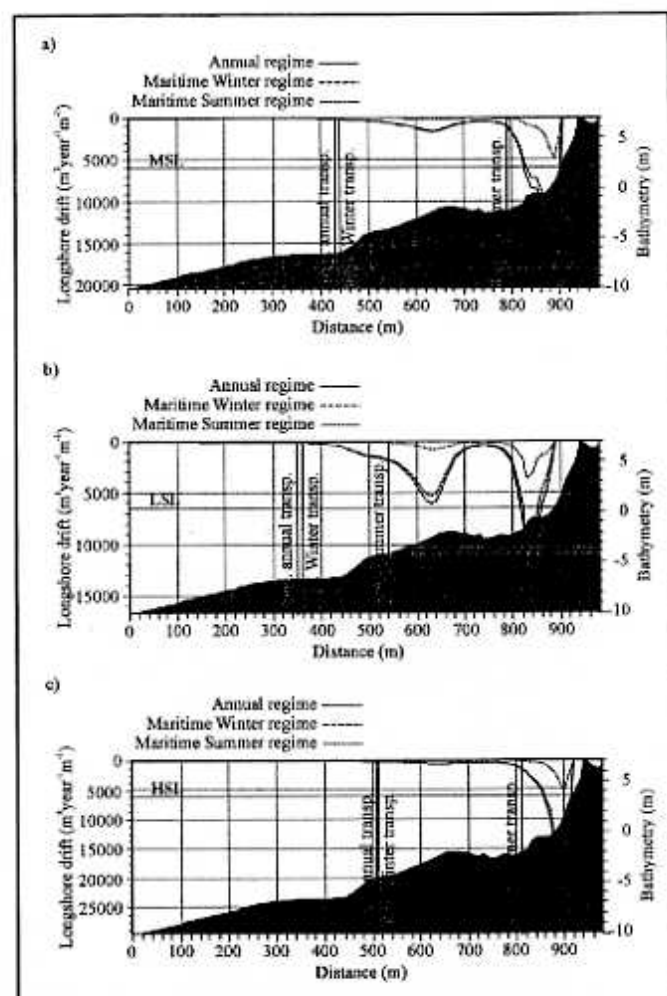

Figure 6. Cross-shore distribution of the longshore sediment transport at P3 at: (a) MSL, (b) LSL, (c) HSL.
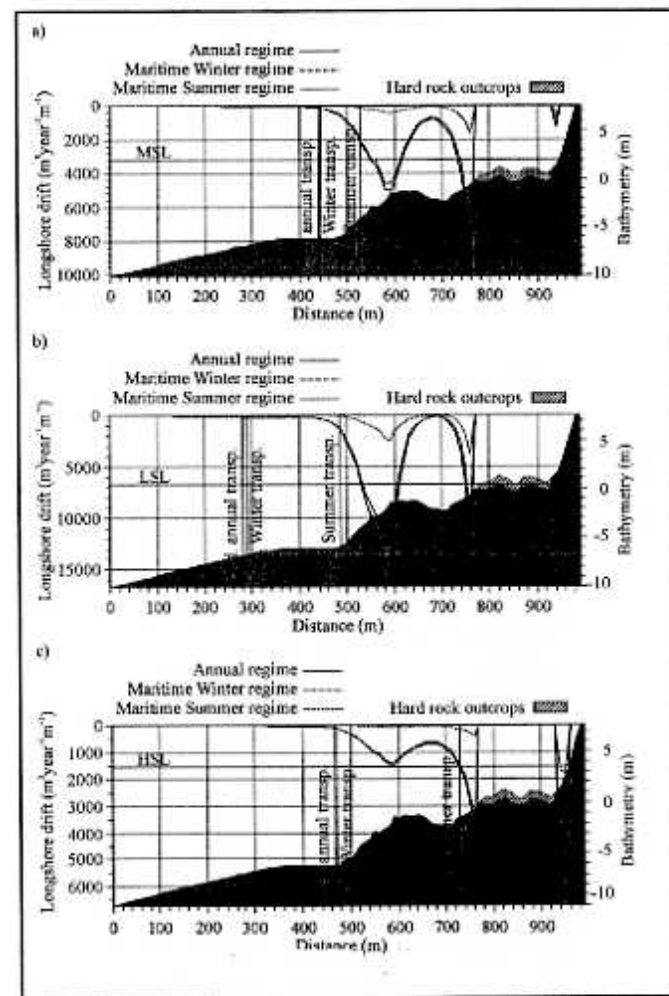

Figure 7. Cross-shore distribution of the longshore sediment transport at P10 at: (a) MSL, (b) LSL, (c) HSL.
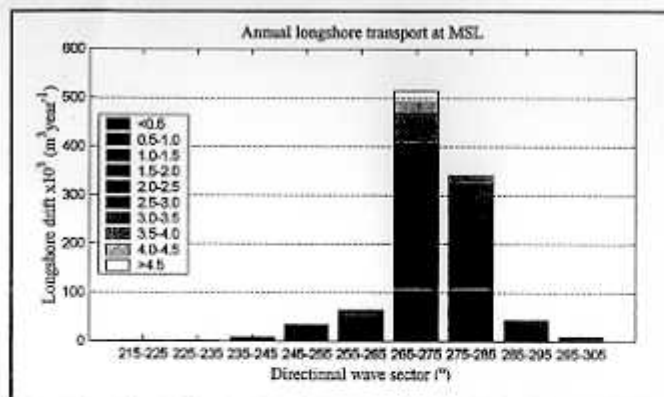
Figure 8. Discretised annual longshore sediment transport at MSL.

At LSL, for both types of profiles with and without outcrops, the offshore bar has a larger contribution to the longshore transport than at MSL. No longshore transport occurs shoreward of the outcrops because the shoreline intercepts the hard rock bottom. The increase of the overall transport is mainly due to the bar contribution and, therefore, is localized (Figures 6b and 7b).

At HSL, the hard rock outcrops are almost completely submerged. The average longshore transport along the total extension of the beach is 783 x 10³ m³/year. On average, the transport is 604 x 10³ m³/year in the beach sectors of hard rock outcrops and 1.496 x 10³ m³/year in the sandy bays (Figure 5). Comparing these values with those at MSL, it is observed that the longshore transport is 30% and 5% lower at HSL for the beach sectors of rocky bottom and of sandy bottom, respectively. The difference between the longshore transport for both types of beach sectors is 1.4 times greater at HSL than at MSL. It is again remarked that such a value might be an underestimate because the model neglects sediment transport over the outcrops.

Comparing the cross-shore distribution of the longshore transport at HSL and MSL for the outcrops sectors, an increase in longshore transport was observed closer to the shoreline (reaching 76% of the total transport for profile P4), and a considerable decrease seaward of the outcrops, as result of the reduction of the transport at the offshore bar (Figures 6c and 7c). The overall transport decrease at HSL results from the reduction of the contribution of the offshore bar and simultaneous increase in width of the surf zone over the rocky bottom. Concluding, the numerical results show that sea level variation has greater influence in the longshore transport for the rock outcrops sectors than for the sandy bays (P1 and P3 in Figure 5) because, as the sea level rises, the average transport along the beach decreases due to advance of the surf zone over the outcrops.

The role of sea level variation in calculation of the average annual longshore transport was assessed. Because the tide in Buarcos is semidiurnal, it is represented as three sea levels occurring daily and that the duration of MSL is twice the duration of LSL and HSL. The average annual longshore transport obtained along the total extension of Buarcos Beach was 1.086 x 10³ m³/year. The average annual longshore transport, considering that the MSL is constant during the day, is 93% of that value. Thus, the importance of considering sea level variation in calculating the average longshore transport rate is demonstrated.

Seasonal Longshore Transport at Different Sea Levels

During the maritime winter, the longshore transport is on average, at MSL, LSL, and HSL, 877 x 10³ m³/year, 1.302 x 10³

m³/year, and 670 x 10³ m³/year, respectively. These values correspond to 87, 84, and 86% of the annual transport, for each respective sea level. For this seasonal wave regime, the transport in the outcrops sectors is, for LSL, equal to the transport at the sandy bays, and it is about 1.6 and 2.4 times lower at MSL and HSL. During the maritime summer, the transport in the outcrops sectors is, at MSL, LSL, and HSL, about 2.5, 1.1, and 2.8 times lower than in the bays.

The differences between the longshore transport found for the two maritime regimes (outcrops sectors and sandy bays) are due to the variation of the position of the breaker line. During the maritime winter, the wave breaking process starts at higher depths than in the summer, generating a more pronounced offshore peak of the cross-shore transport distribution. Because during the maritime summer the surf zone is narrower, a higher percentage of waves break over the outcrops, and the differences between the longshore transport for both types of beach sectors are greater.

Beach Parameters: Active Length and Active Depth

The parameters of active depth and active length were used to evaluate the dynamic beach behavior based on analysis of the numerical results. Such parameters allow quantification of the cross-shore extent of the longshore transport. The extension of predominant annual and seasonal transport is marked for profiles P3 and P10 in Figures 6 and 7. For the total length of the beach, during the maritime summer at MSL, the average active depth and length are 7.8 and 507 m, respectively. These values correspond to 68 and 61% of the average values obtained for the maritime winter.

Wave Height and Wave Direction Contributions to the Annual Longshore Transport

In this section, the contribution to annual longshore for each directional sector and associated wave height is quantified. The numerical results at MSL are presented in Figure 8. The longshore sediment transport induced by waves incident from the sector N265-285 deg is, at MSL, LSL, and HSL, about 85, 80, and 83% of the annual drift. For the three sea levels, waves with root-mean-square wave height H_{rms} in the range 1.0-2.5 m have the greatest contribution to the annual longshore transport. At MSL and HSL, the contribution is about 60%, and at LSL it is about 64%. Waves from N265-285 deg and within the height class 1.0-2.5 m generate about 50% of the annual drift at all sea levels.

Wave height was found to be more important than wave duration in the longshore transport. Waves with H_{rms} greater than 2.0 m, which always break seaward of the rock outcrops independent of the sea level, account for only for 13% of the annual duration, but they generate at MSL, LSL, and HSL, about 71, 59, and 67% of the annual longshore transport. Waves with H_{rms} lower than 2 m generate a longshore transport that not only depends on wave height, but also on the position of the breaker line, which moves over the outcrops according to the level of the sea.

Although the directional sector N275-285 deg has the longest duration, the largest contribution to the annual longshore transport is in sector N265-275 deg, about 51% at MSL, 46% at LSL, and 50% at HSL. The explanation is that: (1) the highest waves are associated with this directional sector, and (2) the angle between the bisecting line of this wave sector and the normal to the coastline, which orientation is N216 deg, is the closest to 45 deg and maximum possible transport.

CONCLUSIONS AND RECOMMENDATIONS

The longshore sediment transport along a sandy coast with hard rock outcrops was analyzed based on an innovative methodology that can be applied to coasts with similar morphologic features. Due to the wide range of longshore sediment transport values resultant from previous studies and consequent difficulty in characterizing the beach dynamics, a detailed quantitative analysis was conducted. This analysis was achieved through the application of a numerical model based on a 12-year time series of wave observations. The beach was divided into ten parallel cross-shore profiles representative of the two types of beach sectors, hard rock outcrops, which are predominant, and sandy bottom sea. The simulations were conducted for the average annual wave climate and the average seasonal wave climate (maritime winter and summer) and for three sea levels (MSL, LSL, and HSL).

The average annual longshore transport obtained along the total length of the beach was 1.008×10^3 m³/year at MSL, 1.545×10^3 m³/year at LSL, and 783×10^3 m³/year at HSL. For the hard rock outcrops sectors, the annual longshore transport was found to be 42% (at MSL), equal (at LSL), and 60% (at HSL) of the transport in the sandy bays. At LSL, the longshore transport shows a low variability along the beach because the surf zone is generally located over sandy bottom and the outcrops are almost completely emerged. As the sea level rises, the results show an overall reduction in the transport due to the shoreward advance of the surf zone and subsequent increase of its extension over the outcrops.

At MSL, the average longshore transport in the maritime winter is 87% of the annual transport. The differences of the longshore transport for both types of beach sectors between the two maritime wave regimes were analyzed. They were found more pronounced during the maritime summer because the surf zone is mainly located over the hard rock outcrops, unlike during the maritime winter when the waves break further offshore due to the occurrence of higher waves. During the maritime summer, the active depth and length are 7.8 and 507 m, which correspond to 68 and 61% of the values found for the maritime winter.

The annual longshore transport was examined as function of wave height and wave direction. Waves with H_{ms} above 2 m account only for 13% of the annual duration, but they generate between approximately 60 and 70% of the annual littoral transport for the three sea levels. Waves incident from the directional sector N265-285 deg generate between approximately 80 and 85% of the average annual drift for the three sea levels. The directional sector N265-275 deg is particularly important because, although it accounts only for 25% of the annual duration, it generates about 50% of the annual longshore transport for the three sea levels. The reason is because it contains the highest percentage of waves with H_{ms} above 2 m and because the angle between its bisecting line and the profile is the closest to 45 deg, which corresponds to the incident direction that induces the greatest longshore transport.

Waves with H_{ms} higher than 2 m always break seaward of the outcrops, independent of sea level, and therefore, their contribution to the longshore transport rate is not affected by the presence of the hard rock material. In contrast, the contribution of waves with H_{ms} lower than 2 m depends on sea level because the the breaker line moves over the hard rock outcrops.

The existence of the irregular rock outcrops implies the occurrence of several three-dimensional local phenomena, such as turbulence and vorticity, which are neglected in the numerical model applied. Suspended sediment transport over the outcrops was also not represented in the model. In future work, these physical processes should be considered through a three-dimensional simulation instead of the cross-shore two-dimensional approach here applied.

ACKNOWLEGMENTS

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