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Artigo de Pesquisa

Beachface slope, swash climate and its relationship with the morphodynamic stage

Declividade da face praial, clima de espraiamento da onda e sua relação com o estágio morfodinâmico

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Abstract: The uprush and backwash of a wave (*swash climate*) at the beach face, as well as the duration of this process, depend not only on wave characteristics such as height and period, but also on the beach-face slope, which in turn is partially conditioned by the sediment grain size. As a general trend, the coarser the grain size, the steeper the slope, and faster the uprush and backwash cycle (swash regimen) is completed. This cycle is partially related to the morphodynamic characteristics of a beach, passing through dissipative, intermediate, and reflective stages as the beach face slope increases. Observational data along the beaches of the Doce river delta, Espírito Santo - Brazil, showed a correlation between beachface slope, morphodynamic state and swash regimen, with some variations along the study site. Dissipative and saturated swash regimen were related to beach face slopes lower than 3°, while the reflective stage and more complete swash regimen were related to slopes higher than 5.5°. The flow regimen of extreme states often shifts from dissipative or reflective to intermediate morphodynamic state and vice-versa. The results herein provide an objective physical framework to morphodynamical comparative studies and potential implication for benthic ecological studies.

Keywords: Beachface; wave climate; morphodynamic stage; Doce river delta.

Resumo: A velocidade de espraiamento e refluxo de uma onda na face da praia, assim como a duração desse processo, definido como regime de fluxo (*swash climate*), depende das características da onda, como altura e período, e da declividade da face praial que, por sua vez, é parcialmente condicionada pela granulometria dos sedimentos. Como tendência geral, quanto maior o diâmetro granulométrico, maior a declividade e mais rapidamente se completa o ciclo espraiamento-refluxo (*swash regimen*). Este ciclo se reflete na característica morfodinâmica de uma praia passando pelos estágios dissipativo, intermediário e refletivo de acordo com o aumento da declividade da face praial. Dados observacionais obtidos ao longo do litoral do delta do rio Doce, Espírito Santo, mostram uma relação consistente entre a declividade da face praial, o estágio morfodinâmico e o regime de fluxo, com algumas variações ao longo da área de estudo. Condições dissipativas e saturadas corresponderam às declividades inferiores a 3° enquanto estados refletivos e regimes de fluxo mais completos tiveram declividade superior a 5,5°. Os regimes de fluxo dos estágios extremos, refletivo e dissipativo, ocasionalmente transitaram para o estágio intermediário e vice-versa. Os resultados oferecem uma base física objetiva para comparações morfodinâmicas e potencial implicações para estudos bentônicos.

Palavras-chave: Face praial 1; clima de onda 2; morfodinâmica 3

1. Introduction

The contact of a beach with the ocean occurs along a wave dissipation ramp, the beach face, where the process of wave runoff and backwash (*swash climate*) takes place, with part of the return flow occurring through sub-superficial flow (Huges and Turner, 1999; Hughes and Baldock, 2020). Therefore, the beach face represents one of the most aggressive environments due to its inherent mobility and morpho-sedimentary dynamics, with the entire benthic community controlled by the active physical processes. For McLachlan (1990), it is the swash climate and not the wave climate, responsible for modifications in benthic communities, since the swash climate is the key factor that limits the distribution of species along the morphodynamic gradient of the beach face.

It is assumed that all the fauna is, at some point, subjected to the processes of uprush and backwash at the beachface requiring that all the fauna living in this environment, both on the surface and subsurface, be able to move rapidly up and down according to the rhythm of the tide (McArdle and McLachlan, 1992; Defeo and McLachlan, 2025). The decrease in invertebrate species richness from the dissipative to the reflective morphodynamic stage, stages defined by Wright *et al.* (1985), although recognized, is not adequately understood due to a lack of knowledge of the underlying ecological factors and biological processes (Brazeiro, 2001). According to Brazeiro (2001), the difficulty in understanding the behavior stems from the coexistence of species with distinct habits, such as feeding on suspended materials versus scavengers, different means of reproduction, and occupying different intertidal zones (Brazeiro, 2001). McLachlan *et al*. (1993) suggest that some species are expelled as the swash climate becomes more aggressive, characterized by an increase in the frequency of swash cycles, particularly by an increase in the frequency of exceeding the saturation line. In contrast, according to Brazeiro (2001), this hypothesis does not consider aspects such as sediment grain size and sorting, availability of organic matter, and erosion and accretion processes. That is, part of this variability would be represented by the characterization of the morphodynamic stage. Consequently, the benthic fauna needs to be adapted to the different regimes of wave run-up and backwash, which in turn occur as a function of the slope of the beach face, which determines the speed and distance of the wave run-up, as well as the surface and subsurface flow.

Studies conducted on beaches in Rio de Janeiro sate, (Muehe and Silva, 1998), (Figure 1), show an increase in meiofauna density with a decrease in the mean grain size and an improvement in the degree of sorting, which in turn is reflected in the definition of the morphodynamic stage. The decrease in the dispersion of grain sizes, relative to the mean size, may indicate better drainage and aeration capacity.

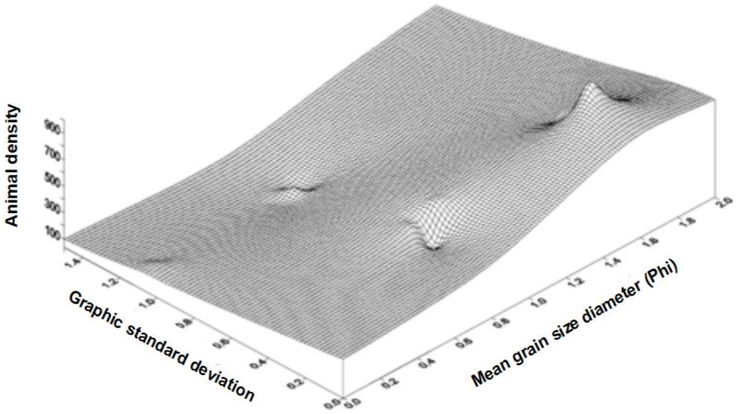

Figure 1. 3D surface showing the relation between animal density, sediment grain size and associated standard deviation, modified from Muehe and Silva (1998).

Statistically, the slope of the beach face depends on the grain size diameter, in the sense that the coarser the grain, the greater the slope Bascom, 1951. This, in turn, represents an important indicator of the morphodynamic stage (Wright and Short, 1984). However, there is a large dispersion in relation to statistical regression, so that the same slope may be associated with more than one morphodynamic stage, which can lead to errors in identifying the morphodynamic environment, as can be seen in Figure 2, where the grain diameter has been replaced by the settling velocity (Muehe, 1998).

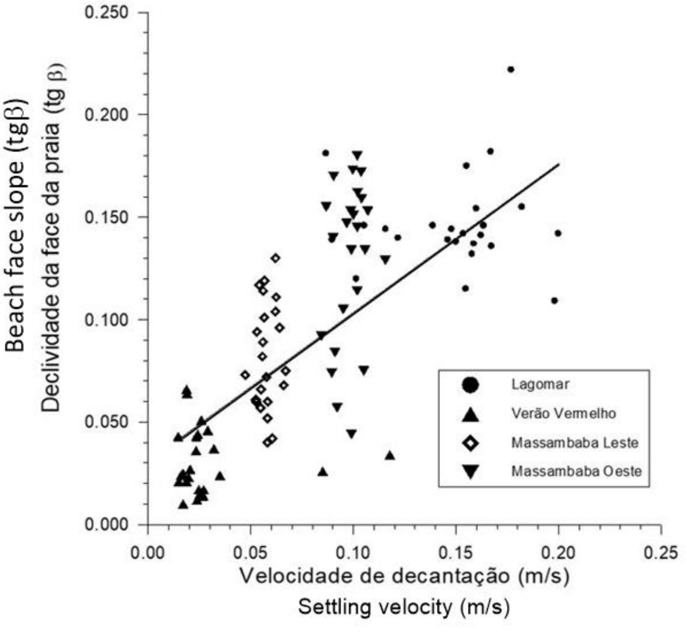

Figure 2. Graphic correlation between sediment settling velocity of beach face sediments and the slope of the beach face, of four exposed beaches on the east coast of the State of Rio de Janeiro (Muehe, 1998).

In determining the swash climate on the beach face, Kemp and Plinston (1968) established the Ts/T relationship to characterize the flow regime through the relation between the duration of the wave upwash (Ts) and the wave period (T) (Table 1). The backwash time was not included, as later proposed by McArdle and McLachlan (1992). This exclusion was made to avoid errors on dissipative beaches where, due to the low slope, the backwash is prevented from completing on the lower part of the beach face due to the arrival of a new wave before the completion of the backwash, leaving this part almost continuously covered with water.

Table 1. Classification of flow regimes on the beach face (*swash climate*)

Ts/T	Flow regime	Description
<0,5	complete	The backwash is completed before the arrival of a new wav
0,5 -1	incomplete	The backwash is not completed due to the arrival of a new
>1	saturated	The backwash is prevented by the arrival of a new wave

This study aims to evaluate the relationship between beach face slope, morphodynamic stage, and associated flow regime, to define slope limits for each stage based on a dataset of beaches with a wide variability of beach face slope and different degrees of wave exposition and orientation. This is a morphodynamic study of a physical nature that may interest ecological studies of meiofauna, even though this study did not include biological sampling and analysis.

2. Study Area

The data analysed in this study were collected between April 2019 and January, 2022, during seven field work campaigns, including winter and summer seasons. The 13 beaches studied are located on the coast of Espírito Santo, encompassing two geomorphological domains: 10 beaches associated with the Rio Doce deltaic plain (S4-N6) and three beaches, to the south, associated with the lateritic terraces (shore platform) of the Barreiras Formation (S1-S3). The grain size of the exposed beaches, associated with the Rio Doce, varies between coarse, medium, and fine sands because of the redistribution of fluvial input along the foreshore and the influence of littoral drift (Albino *et al.*, 2018; Oliveira *et al.*, 2015). They also present diverse typologies, varying between reflective, intermediate, and dissipative domains. The beaches preceded by the terraces, on the other hand, present medium and fine sands, exhibiting intermediate and reflective characteristics due to the distribution of the terraces and greater wave dissipation (Albino et al. 2016). The various morphodynamic stages, typical of the research area, are exemplified in Figure 3.

Reflective (Stage S7) Intermediate (Stage N3) Dissipative (Stage N5)

Figure 3. Examples of the main morphodynamic stages. For location see Figure 4. (Photos: Lucas Bermudes de Castro)

The wave climate in the region is characterized by waves from the E-NE and S-SE, generated, respectively, by the South Atlantic Subtropical Anticyclone and frontal systems originating at higher latitudes (Pianca; Mazzini and Siegle, 2010). In a specific analysis of storm waves, Eguchi and Klumb-Oliveira (2023) found that these waves have heights between 2.5m and 3.0m and periods of 13s to 15 s.

The tidal range is 1.7 m in the port of Vitória, characterizing a micro-tidal regime (CPTEC, INPE, 2025).

3. Materials and Methods

Topographic and bathymetric profiles were carried out during four campaigns, at 3 monitoring stations associated with the coast of the Barreiras Formation (S1, S2 and S3) and 10 stations along the southern and northern plain of the Rio Doce delta (S4 to N6), comprising 191 km of coastline (Figure 4).

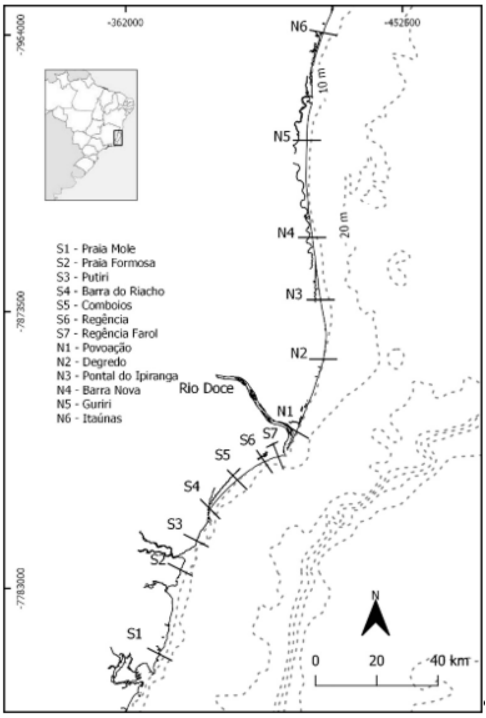

Figure 4. Location of the study area with the monitoring stations

Topographic profiles, transverse to the beach, were made to determine the slope of the beach face (β) The topographic profiles were extended to the foreshore using an echo sounder coupled with satellite positioning (GPS). Wave period (T) and wave height at the breaking point (Hb) were measured. The extent (D_{up}) and duration (T_s) of the wave run-up at the beach face were also measured. The bathymetric data were reduced to the tidal level and coupled to the beach profile. However, the slopes of the beach face and foreshore were calculated separately, considering the topography and bathymetry. The slopes, in degrees, were calculated from the arctangent function of the ratio between the maximum difference in level and the greatest horizontal distance.

The topographic profiles were surveyed during the spring low tide, with the beach face slope expressed in degrees, defined by the arctangent of the ratio between the altitude of the contact of the beach face with the beach berm and the horizontal distance from that point to the wave backwash. Each field survey extended over approximately ten consecutive days, during which the team successively traversed different sectors of the coast. As the low tide time is delayed daily, the first surveys in the sequence were generally carried out at morning low tide, while the profiles further north tended to be measured at afternoon low tide. The beachface was considered as the segment of the beach between the maximum wave retreat and the contact with the berm. On beaches with low slope, the terraces formed at low tide were included.

Wave height, as the difference between wave crest and wave trough, was measured *in situ* using a surveying rod. The intuitive tendency of the person taking the measurement is to choose the wave that is closest in height to the significant wave height, disregarding the lowest and highest waves. The wave height was calculated as a mean of at least 3 significative wave heights while the period was measured by averaging the time it took for eleven wave-crests to pass over the observer positioned at a fixed point. Alternatively, the height at the breaking point, under conditions of greater agitation, was measured by placing the surveying rod at the position of maximum wave back-wash on the beach face and projecting an imaginary line connecting the horizon line with the wave height and its extension to the rod, where the reading is taken, considering the mean value of 3 waves. The period, alternatively was also measured by counting the time of a sequence of 11 breaking waves. The distance and duration of wave run-up on the beach face were measured with a measuring tape from the point of maximum backwash of the preceding wave to the arrival of a new wave, following its displacement to the point of maximum run-up, and measuring the time spent on this path. From these data, the ratio Ts/T was calculated, which, according to Kemp and Plinston (1968), expresses the flow regime on the beach face adopted here as an operational descriptor of the swash climate on the beach face.

The morphodynamic stage was determined using the Δ equation (Muehe, 1998).

$$\mathit{\Delta} = \frac{(\sin\beta \cdot D_{up})/H_b}{T_s/T} \tag{1}$$

The classification of the morphodynamic stage as dissipative, intermediate, and reflective has the limits depicted in (Table 2), whereas in the Intermediate Stage the subdivisions, already well known, of low tide terrace, transverse bar and beach, rhythmic bar and beach and longshore bar and trough, so well individualized by Wright and Short (1984) and Wright et al. (1985), was not discretized, to allow comparison with the 3 flow regimes on the beach face.

Table 2. Classification of the morphodynamic stage by the Δ parameter

Δ	Stage
<0,5	Dissipative
0,5 -2	Intermediate
>2	Reflective

4. Results

The occurrence of various morphodynamic domains identified throughout the study area is shown in Figure 5, with red representing reflective beaches, blue representing intermediate beaches, and green representing dissipative beaches.

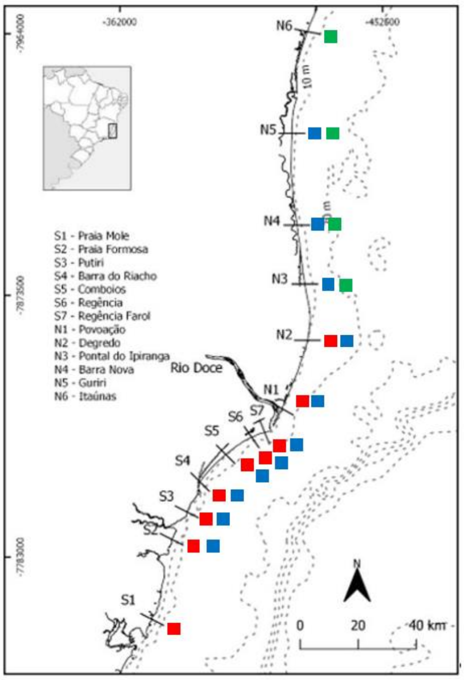

Figure 5. Morphodynamic stages identified throughout the study area. The red squares represent reflective stages, the blue squares, intermediate stages and the green square the dissipative stage.

The waves measured during the surveys showed maximum heights at the surf zone of 1.5m, a minimum of 0.1m and an average of 0.5m, and maximum periods of 13s, a minimum of 4s and an average of 9s (Figure 6).

The bathymetric profiles, represented by linear adjustment, reflect the southeast exposure on the southern flank and the east exposure on the northern flank of the deltaic plain, with steeper profiles on the southern flank and gentler profiles on the northern flank (Figure 6). The profiles N1, N3, N5 and N6, of the North sector, presented a lower declivity compared to the profiles from the South, with exception of profiles N2 and N4 which showed profiles of higher declivity, more like the profiles from beaches with terraces of the South (S1, S2 and S3). The profiles from the South flank of the Rio Doce plain (S4, S5, S6 and S7) showed steepest profiles.

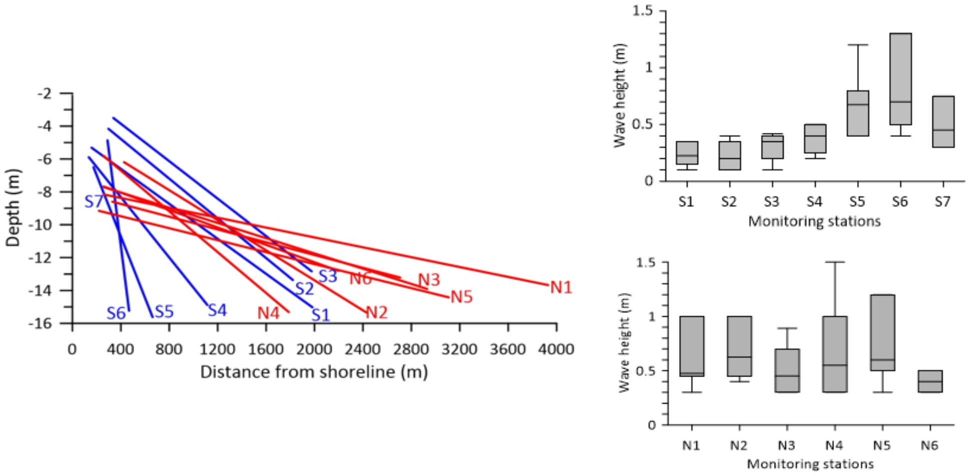

Figure 6. Bathymetric profiles of the shoreface and wave heights measured during the fieldwork. The bathymetric profiles were grouped according their location, with blue lines for the South of the Rio Doce outlet, and red lines for the North sector of the river mouth. The graphic of the right side (box diagram) represent the median and the first and third quartile and the standard deviation of the wave heights of the North (upper diagram) and South sector (lower diagram).

Contrary to expectations, the bathymetric profiles of the southern flank of the deltaic plain, with its steeper slope, should show the highest wave heights when compared to the northern flank, which has gentler profiles and a wider inner shelf. This apparent discrepancy can be explained, on the one hand, by the campaigns having been carried out predominantly under good weather conditions, with calm to moderate seas and incident waves from the East-Northeast, and, on the other hand, by the temporal organization of the surveys.

As the profiles were acquired on successive days, the low tide progressively shifted to the afternoon period, so that part of the profiles on the northern flank was measured at afternoon low tide, under a more well-established East-Northeast breeze. In this situation, the combination of wind and incident wave in the same quadrant tends to increase the breaking wave height, causing the northern flank to register episodes of slightly more energetic seas. On the southern flank, the lower wave height was partly due to the diffraction of NE-E wave incidence as well as the rugosity of the shoreface substratum. Nevertheless, despite the lower wave height, compared to the north flank, an increase in wave height from south to north, from S1 to S6, was observed, while position S7, already in the estuary area, oriented towards the SSE, represents a distinct pattern of wave incidence and morphological adjustments associated with fluvial influence. The lowest heights were observed on beaches with lateritic terraces of the Barreiras formation (S1, S2 and S3) whose rugosity during low tide affect the wave high, and reduce the extension of the surf zone.

The relationship between the morphodynamic stage and the slope of the beach face is represented in Figure 7, where a clear, and expected, positive correlation is observed between the increase in slope and the increase in reflectivity; with low slopes indicating a dissipative regime and an increase in slope towards a reflective regime. However, the definition of limits for the intermediate morphodynamic stage is diffuse, and in terms of slope, it can belong to both the dissipative regime, mainly for slopes less than 3°, and the reflective regime, for slopes greater than 3° and less than 4.5°. Based on the data collected, the different stages can be individualized according to the limits presented in Table 3. It is worth noting that the limits were obtained based on observational data from the 13 monitored beaches on the coast of Espírito Santo and should be seen as operational ranges, not as universal values. The low occurrence of observations of dissipative stages must be considered with caution. It is possible that the limits for the declivity for the reflective domain (> 4.5°) are better established, while the range of declivities of the dissipative domain (< 3°) is less precise due to the low number of observations.

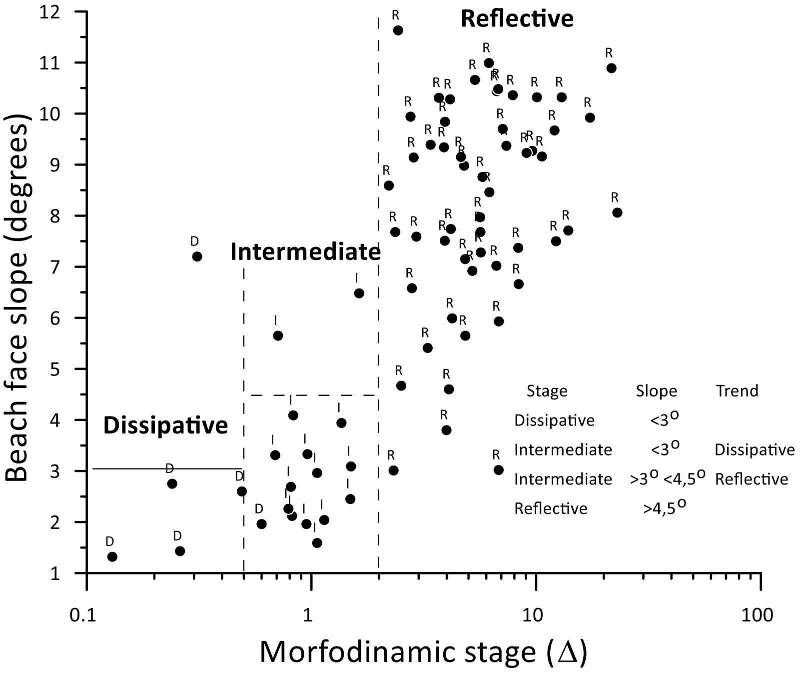

Figure 7. Relationship between morphodynamic stage and beachface slope. Labels represent the morphodynamic stage

Table 3. Limits of the beach face slope for different morphodynamic stages.

Stage (D)	Slope	Trend
Dissipative	<3º	
Intermediate to Dissipative	<3º	Dissipative
Intermediate to Reflective	>3º <4.5	Reflective
Reflective	>4,5º	

As already noted above (Figure 5), most monitoring stations show variations between two stages, either between intermediate and reflective or intermediate and dissipative, but not between one extreme and the other. This observation is highlighted in Figure 8, where the relative occurrence of each morphodynamic stage is represented. Only the two stations at the two extremes of the study area, S1 (reflective) and N6 (dissipative), did not show stage changes. All the others presented an intermediate stage at some point.

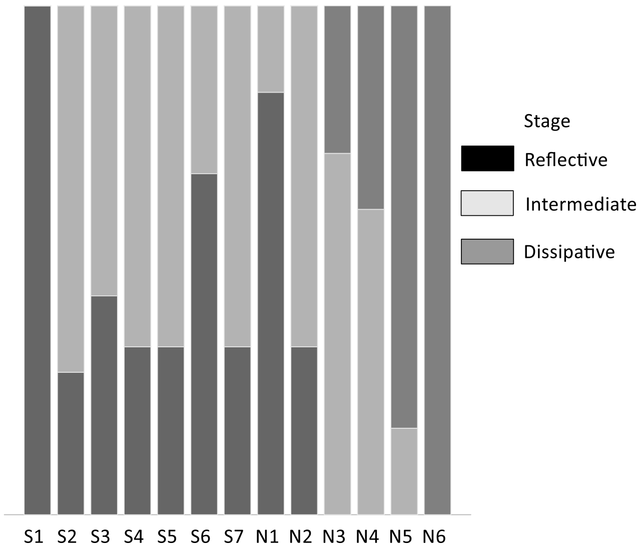

Figure 8. Relative occurrence of morphodynamic stages in each Station

An additional aspect of morphological variability is presented in Figure 9, which relates the slope of the beach face to the horizontal variability of the profile. This variability was estimated based on the amplitude of horizontal displacement of the beach profiles between the sampling campaigns. A tendency towards greater mobility is observed in the intermediate and dissipative states, and a reduction in this mobility towards the reflective state. Samples near the mouth of the Rio Doce constitute an exception, as the influence of river load and discharge imparts a unique dynamic to the system. However, the morphodynamic classification associated with slopes remains the same.

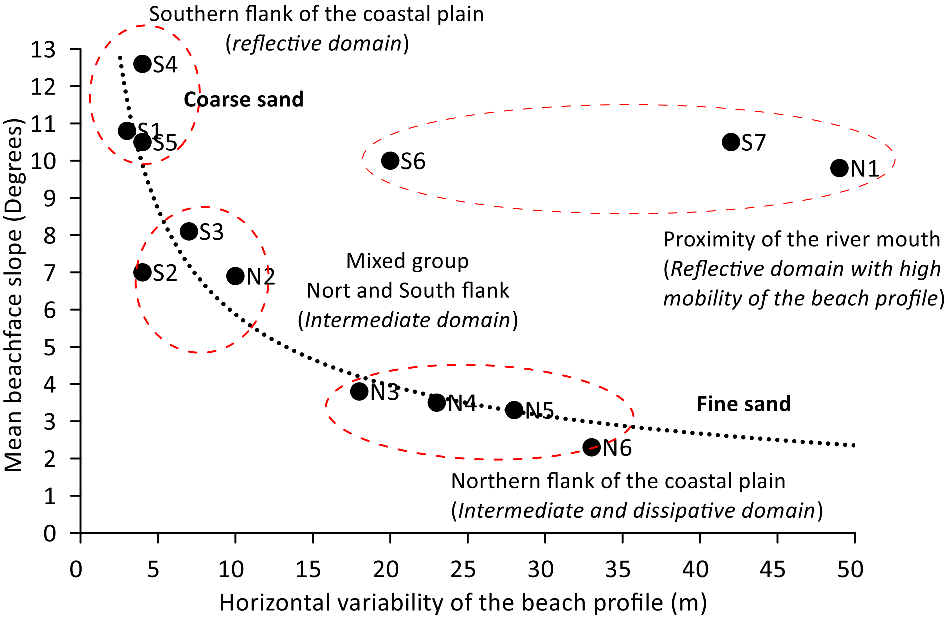

Figure 9. Relationship between the slope of the beach face and the horizontal variability of the beach profile.

The variation in the morphodynamic stage, according to the wave climate, and the consequent response in the slope of the beachface, are also reflected, as could not be otherwise, in the flow regime, but with slope limits slightly different from those found in the relationship between slope and the morphodynamic stage. These limits could be better defined by considering the wave period, with the reflective state being characterized not only by the greater slope, but also by a tendency of slightly higher wave period, as represented in Figure 10.

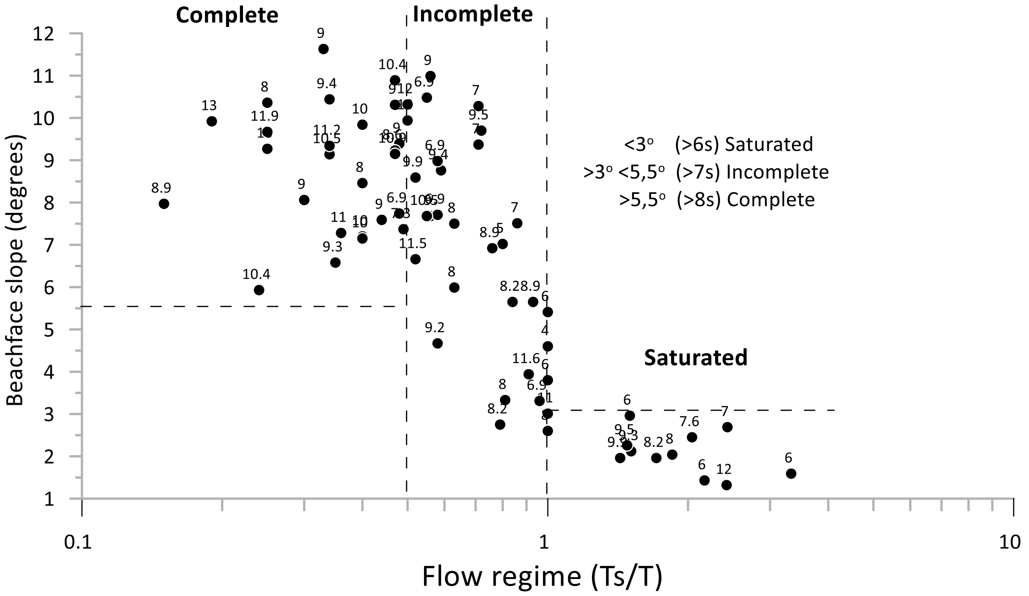

Figure 10. Relationship between flow regime and beach face slope. Labels represent wave period

Table 4 presents the slope limits of the beachface for the various flow regimes, and their approximate correspondence to the respective morphodynamic stage.

Table 4. Relationship between the slope of the beach face, the flow regime, and the probable associated morphodynamic stage

Flow regime **T_s/T**	**Slope** **(wave period)**	**Morphodynamic stage** **(Trend)**
Saturated	<3° (>6s)	Dissipative
Incomplete	>3° <5,5° (>7s)	Intermediate
Complete	>5,5° (>8s)	Reflective

In Summary, the results show a consistent relationship between beachface slope, morphodynamic stage, and swash climate, although spatial and temporal variations occur across the study area. These patterns are physically relevant and may have implications for the benthic habitat.

5. Discussions

The slope of the beach face is an intrinsic variable to the morphodynamic stage of a beach and to the wave flow regime on the beach face. While the morphodynamic stage represents the morphological configuration of a beach, including the surf and breaker zones, the flow regime describes the dynamics of a very specific and extremely dynamic segment of the beach, the beach face. In this area, the cycles of up-rush and back-wash directly affect the meiofauna, which needs to adapt to the wave flow velocity at the surface and subsurface, conditioned by the slope and permeability, and directly associated with the grain size. However, in addition to this very localized dynamic, there is also a topographic variability of the beach that is wide in the intermediate stage and relatively stable in the reflective and dissipative stages.

The combination of slope limits by morphodynamic stage and Ts/T intervals observed in this study suggests that physically similar beaches may alternate between more or less stressful flow regimes over time, which, depending on the frequency of these changes, may require adaptations in mobility, vertical distribution, and possibly the composition of assemblages. Finally, slope limits and Ts/T intervals constitute a framework that summarizes the interaction between swash climate, beach morphology, and flow regime in different sectors of the same coastal system. This framework can be used in future studies to test how changes in wave climate, sediment supply, or morphodynamics are reflected in adjustments to habitat structure and in the mobility, distribution, and composition of fauna along the gradient of morphodynamic stages.

6. Conclusions

The results show that the slope of the beach face is an important variable for interpreting, in a synthetic way, both the morphodynamic stage and the swash regime. For the monitored beaches, slopes less than 3° were predominantly associated with dissipative and saturated conditions, while slopes greater than 4.5° tended towards reflective states and more complete flow regimes. However, there are variations in the flow regime within the same morphodynamic stage. Thus, a reflective beach, with coarse grain size and a steep slope of the beachface, tends to complete the flow regime, without interruption of the wave reflux. However, for a short- wave-period, the time to complete the wave run-up and back-wash cycle may become too long to complete the reflux before the arrival of a new wave. Thus, what is observed is that the two extreme stages, reflective and dissipative, present flow regimes that occasionally transition to the intermediate stage and vice versa. Nevertheless, the framework presented consistently summarizes the interaction between wave climate, beach face morphology, and flow regime, offering an objective physical basis for morphodynamic comparisons and future studies, with possible integration into benthic processes.

Autor contributions: Conception, data analysis, writing the article, D.M.; topography and beach processes, L.B.C., DM; bathymetry and manuscript review; L.H.S; laboratory analysis, L.B.C.; manuscript review, acquisition of funding, J.A. All authors have read and agreed with the published version of the manuscript.

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Conflict of Interest: The authors declare no conflict of interest. The funders had no interference in the development of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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