



Potential vulnerability to climate change of the beach-dune system of the Però coastal plain - Cabo Frio, Rio de Janeiro state, Brazil

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Abstract. The Però coastal plain is one of the three morphological compartments located between Búzios and Arraial do Cabo, on the east coast of Rio de Janeiro State, characterized by the occurrence of dune fields, driven by northeasterly winds, obliquely oriented in relation to the coastline. In order to evaluate the stability of the coastline as well as of the dune system a topographical and sedimentological characterization of the different morphodynamic units was made, consisting of topographic and bathymetric profiling, evaluation of eolian sediment transport through sediment traps, sediment sampling for grain size analysis and comparison of aerial photographs. The results indicate that during the period of investigation sediment transport from the beach-foredune to the main dune field was largely inhibited by the presence of vegetation, and that sediment transport was limited to the reworking of its own sediment stock. Climatic oscillation toward drier periods, whether the result of global climate change or local variation in the duration of the dry period, will probably trigger the eolian sediment transport due to the reduction of the vegetation cover resulting in the migration of the main dune field towards urban areas. No coastal erosion was observed, whether through comparison of aerial photographs of 1970 and 2000 or during one year of monthly topographic profiling. Nevertheless, a rise in sea level might result in an erosive adjustment of the shoreline as well as in an increase in the flooding of the low lying areas.

Key words: Eolian transport, dune stability, beach profile, shoreface profile

Resumo: Vulnerabilidade potencial às mudanças climáticas do sistema duna-praia da planície costeira do Però - Cabo Frio, Rio de Janeiro, Brasil. A planície costeira do Però é um dos três compartimentos costeiros localizados entre Armação dos Búzios e Arraial do Cabo, no litoral leste do Rio de Janeiro, que se caracterizam pela presença de campos de dunas dispostas obliquamente à linha de costa por efeito do transporte induzido pelo vento nordeste. Para a avaliação da estabilidade da linha de costa e do sistema de dunas foi efetuada uma caracterização topográfica e sedimentológica das diversas unidades morfológicas. Os levantamentos consistiram de perfis topográficos e batimétricos, avaliação do transporte eólico por meio de armadilhas de areia durante doze meses consecutivos, coleta de sedimentos para análise granulométrica e análise de fotos aéreas. Os resultados mostram que no momento atual o sistema de dunas se alimenta do seu próprio estoque sedimentar, sem aporte significativo do sistema praia-duna frontal. Oscilações do clima para o mais seco, independentemente de mudanças globais, podem reativar o transporte eólico em função da redução do recobrimento vegetal reiniciando a migração das dunas em direção a áreas urbanizadas. A linha de costa não apresentou tendência de erosão, no entanto uma elevação do nível do mar implicará num ajuste erosivo através de retrogradação da mesma, e aumento da dificuldade de escoamento com resultante inundação das áreas baixas à retaguarda das dunas frontais.

Palavras-chave: Transporte eólico, duna, perfil de praia, antepraia

Introduction

The Però coastal plain constitutes, together with Tucuns and Cabo Frio coastal plains, one of the three geomorphological compartments that stretch from Cape Búzios, herein called Búzios, to Arraial do Cabo, characterized by the presence of sandy dunes, which lie obliquely to the coastline, driven by the prevailing northeasterly wind (Fig. 1). As this is an area of environmental protection, it is still relatively well preserved thus being suitable for a representative case study of the coastal processes operating in the region as related to its present and potential vulnerability to climate change.

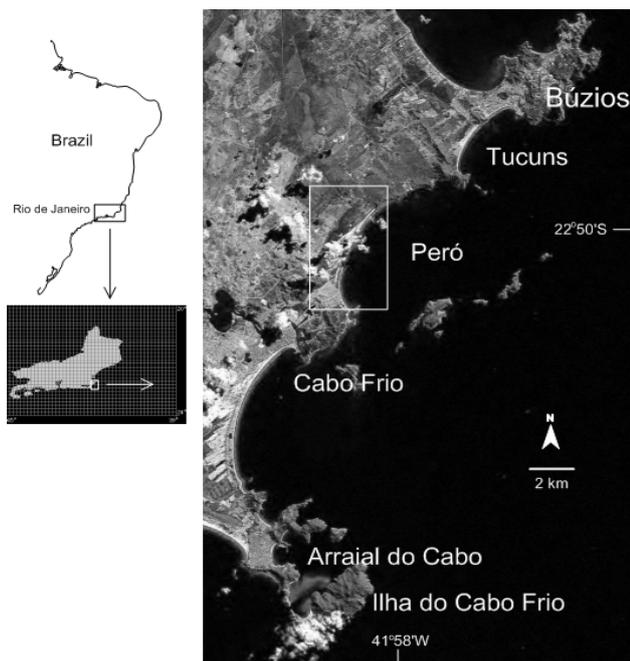


Figure 1. The dune fields of Tucuns, Però and Cabo Frio, between Búzios and Arraial do Cabo, with location of the study area (white rectangle).

Three distinct geomorphologic units characterize the study area (Fig. 2):

- i. The beach-foredune ridge system in front of a deflation plain;
- ii. The deflation plain with isolated parabolic dunes;
- iii. The active dune field which intercepts and overlaps a paleo-lagoon, currently filled with sediments.

The foredune ridge extends behind the beach from which it receives the sediments. It represents, when depleted of vegetation, a source of sediment for the dune field, which is developing behind it and forms a considerable barrier, with its 7 m high dunes, to the erosion of the coast whose stability depends on its vegetation cover and sediment budget.

The deflation plain is located between the foredune ridge and the active dune field and it

presents a few semi-active parabolic dunes.

The active dune field consists of NE-SW trending transgressive dunes and is located in the distal sector of the sandy terrace. Its starting point is located in the northern extremity of the beach and it extends obliquely to the coastline, partially intercepting a paleo-lagoon forming the western limit of the deflation plain. As the dune field moves away from the coastline it becomes wider and encroaches on the lower slope of the coastal range assuming the characteristics of a climbing dune (Rangel & Castro 2005), while its western slip face precipitates towards an urban zone, having already led to the abandonment of a residential estate (Rangel & Castro 2005). The mobility of this dune field has been studied by Dourado & Silva (2005) who estimated a displacement of 125 m between 1965 and 2001 and an average displacement rate of 3.5 m/year, with great variation in the different sectors of the dune field. Because the sediment input from the foredune field, has been almost completely interrupted by the vegetation cover of the foredunes and of the deflation plain, the mobility of the dune field results essentially from the reworking of its own sediment stock. Sediment stability therefore depends essentially on the rainfall regime for the maintenance of the vegetation cover and the consequent inhibition of the wind transport as does the stability of the coastline in terms of coastal erosion.

Local climate, according to Barbière (1975, 1984), is warm and semi-arid (BSh), with mean temperatures between 25.2 °C in February and 20.5 °C in August; mean monthly rainfall of is 60 mm, except in December when it stays above 100 mm; mean monthly evaporation rate is 60 mm. The dry period, when the monthly precipitation drops below



Figure 2. Geomorphologic units of the Però coastal plain with the location of the foredune ridge, the deflation plain and the active dune field. The dotted line represents the inferred contours of a former lagoon partially intercepted by the active dune field. Image Google Earth.

60 mm, occurs between June and September while the rainy season starts in December, with decreasing amounts of rain up to March. Winds are predominantly from northeast during the whole year alternating with short periods of winds from southeast and southwest associated to the arrival of cold fronts. Wind velocities usually stay between 4 and 6m/s; higher values are observed during the winter.

The present study seeks to identify present-day morphodynamic processes and the possible effects of climate change on them.

Methodology

Monthly topo-bathymetric profiles were measured over twelve months in three positions along the beach arc and along the longitudinal axis of three parabolic dunes; the main goal was to characterize the topography of the foredunes and to assess the mobility of the beach and shoreface as well as that of the parabolic dunes of the deflation plain (Fig. 3).

Topo-bathymetric profiles were measured at positions P2, P5 and P7 (Fig. 3), and adjusted to the average sea-level on the basis of the predicted tides for the Porto do Forno (Arraial do Cabo), following the methodology described by Muehe *et al.* (2003) and Muehe (2004). The profiles extended from the back of the foredune field (profiles P5 and P7) and from the public walk (profile P2), up to the outer limit of the surf zone through conventional topographic leveling. The profiles were extended to greater depths, for the determination of the depth of closure and sediment sampling, with a kayak, a portable echo sounder a hand-held GPS, in accordance with the methodology developed by Belligotti & Muehe (2007).

In accordance with the studies undertaken by Belligotti (2009), the depth of inflection of the bathymetric profile was considered for the determination of the depth of closure, the depth at which vertical variations of topography are negligible (Hallermeier 1981), as a more practical alternative in view of the enormous discrepancy between the values obtained with the different equations proposed in the literature (Hallermeier 1981, Birkemeier 1985, Houston 1995, Wang & Davis Jr 2007) which are, in their turn, greatly influenced by the wave parameters adopted.

The determination of the shoreface equilibrium profile, for purposes of comparison with the measured profile, was obtained with the use of Dean's equation (1991) expressed by the relation:

$$z_x = Ax^{2/3}$$

where the depth "z" at a distance "x" from the

coastline is defined as a function of the median diameter of the sediments or of the corresponding settling velocity of (ω_s), expressed by the scale parameter "A", determined in its turn by the relation:

$$A = 0,0067 \cdot \omega_s^{0,44}$$

For a rough assessment of a potential retreat of the coastline corresponding to a given rise in sea-level the equation of Bruun (Bruun, 1962, 1988) was employed:

$$R = \frac{SLG}{h}$$

where:

R = erosive retreat of the coastline due to rise in sea-level (m)

S = rise in sea-level (m)

L = length of the active profile (m)

h = height of the active profile (m)

G = proportion of eroded material which is maintained on the active profile

The height of the active profile is determined by the sum of the land height (sand barrier, terrace, foredune) and the depth of closure, and the active length is the horizontal distance between the land height and h. The proportion of material retained on the profile (G) is considered to be 1, because of the difficulty of assessing the quantity of material made available by erosion and retained on the submerged profile. This is certainly one of the sources of error in the assessment of the amplitude of the retreat.

Sediment traps were installed at a few selected locations (Fig. 3) for the assessment of sediment transport from the foredunes to the deflation plain and were monitored during the period of the surveys. The traps were constructed in accordance with Leatherman (1978) and consisted of a 100 cm long PVC tube whose upper half was provided with two openings on each side, one of them being closed with a silk-screen in order to retain the sediments but still allowing the passage of the wind. The lower part was buried and served as support for an acetate cylinder in which the grains collected by the trap were retained. The traps were placed with the opening in the direction of the prevailing wind, of about 60°, well defined in satellite images by the tracks of the trajectory of the sedimentary transport.

Sediment samples were collected for grain size analysis at each of the traps and along the beachface (Fig. 3), where the sampling was carried out at 500 m intervals on the top of the foredune, of the berm and on the beachface. For an adequate representation of the berm sediments 30 cm deep

trenches were dug, and one side of the trench was scraped to obtain compound representative samples. Thirteen sediment samples were obtained from the dune field and its associated deflation plain and a further 27 samples were collected from the dune-beach system. Grain size analysis was made through dry sieving according the method described by Folk & Ward (1957).

The stability of the coastline was assessed by means of a comparison between aerial photographs from 1970 with orthophotocharts from 2000/2002.

Climatic data for Arraial do Cabo/Cabo Frio were obtained at following sources: Corpo de Bombeiros Militar do Estado do Rio de Janeiro (CBMRJ) for rain, Centro de Previsão do Tempo e Estudos Climáticos (CPTEC) for cold fronts, and Rede de Meteorologia do Comando da Aeronáutica (REDEMET) for hourly wind direction and speed.

Results

Sediment characterization

Samples collected on the beach (beach face and berm) and on the top of the foredunes, along the beach arc, indicate an increase in median grain size diameter from the southern end toward the center of the beach arc, and a decrease towards the northern



Figure 3. Location of the sediment traps (o), of the topobathymetric profiles (Pn) and of the beach-foredune sediment samples (Δ). Image Google Earth.

end. The median grain size is coarsest in the vicinity of the center of the beach arc (P5), and decreases towards both extremities of the beach. This suggests that the region near the center of the beach is a dispersal center for the finer sedimentary fractions which are displaced preferentially towards the north, possibly being the result of an increase in wave energy under storm conditions (waves from the SE) due to the more exposed position of this segment. The localized increase in the grain size of the beach sediments is not so clearly reflected in the sediments of the foredunes because of the inability of the wind to transport sediments greater than 0.2 mm (2.3 phi) (dashed horizontal line in Fig. 4).

The finer sands that are more easily transported by wind are found in the final third of the northern extremity of the beach arc (Profile P7), precisely where the beginning of the active dune field is located.

In figure 5 it is presented a correlation between the median diameter and the respective standard deviation of the sediment samples collected on the berm, foredune and on the deflation plain with associated parabolic dunes. The area delineated on the graph by a broken ellipse indicates the grain size characteristics of the foredunes whose sediments present a median diameter equal to or less than 0.2 mm (2.3 phi) and a standard deviation of less than 0.7 mm (0.5 phi). The occurrence of sediments of larger median grain size and higher standard deviation in the dunes of the deflation plain suggests the occurrence of residual deposits resulting from the winnowing of the finer fractions or even a mixture with the sediments of the deflation surface.

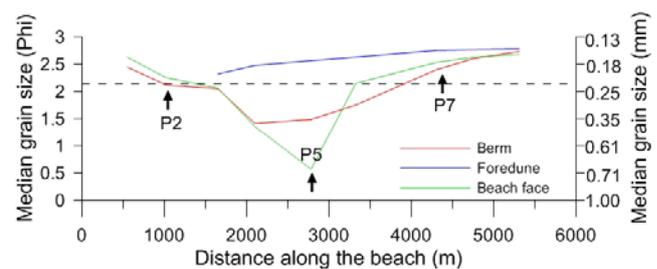


Figure 4. Median grain size distribution along the beach and foredune field. The dashed horizontal line represents the local grain size threshold for eolian sediment transport as depicted in figure 5 indicating a convergence in grain size between beach and foredune sediments toward the northern sector (profile P7) of the beach.

Sediment traps

Through out the monitoring period only three traps, 7, 11 and 14, registered a significant capture of sand. The first two were located on the windward side of parabolic dunes of the deflation

plain and the last on the flank of the active dune field. At the other traps, sediment capture was nil or very small. Therefore the few areas of significant wind transport are associated to places without vegetation cover at the inner or lateral flank of the dunes resulting in remobilization of their own sediment stock, suggesting that there is no continuous transport from the foredunes to the deflation plain. This becomes clearer when the traps are grouped by location. Trap 7 presented significant sediment capture while at traps 5 and 4 located, respectively, outside the trailing ridge of the parabolic dune and at the deflation plain upwind from the dune, sediment trapping varied from nil to very small. Trap 11 was also located on the windward side of a reactivated parabolic dune. Trap 14 was located on the flank of the active dune field where sediment transport is active because of a complete absence of vegetation. Trap 12 was placed in a similar position, though closer to the beach, in order to assess the flow of sediment which fed this dune field from the beach. Surprisingly, this trap captured no sediment, suggesting that the main dune field is also largely being fed by its own sediment reservoir without receiving any significant contribution from the beach.

Our results strongly suggest that the maintenance of the vegetation cover is fundamental to inhibit the transport of sand, which is extremely

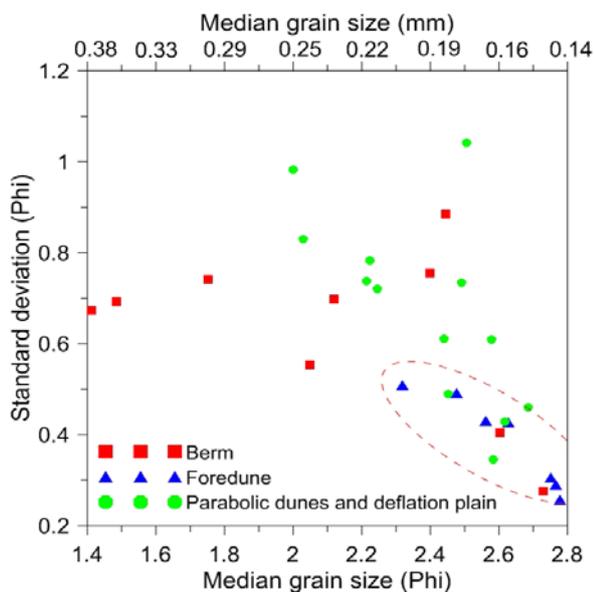


Figure 5. Graphic correlation between median grain size and standard deviation of the beach, foredune and deflation plain sediments. The samples inside the ellipse represent the grain size characteristics of the source sediments that feed the parabolic dune and the active dune field; these sediments are characterized by low standard deviation (well to very well sorted) and median grain size finer than 2.3 phi (0.2 mm).

sensitive to the water balance as illustrated by the sediment mobility that occurred in the areas with no vegetation cover (traps 7 and 14). The observed pattern reflects a strong seasonality with expansion of vegetation cover and decrease of eolian sediment transport (Fig. 6).

During the period of investigation the rainy season, with monthly rainfall above 60 mm, extended from November 2007 to April 2008 with the highest levels of precipitation in January and March (Fig. 7) while, according to Barbière (1975), there is normally a decrease in precipitation after December. The expected relationship between high precipitation and low eolian sediment transport was not found in November, January or August. As shown in figure 7, the number of rainy days in each month was fewer than five, mainly associated with the passage of cold fronts. After the rain the sands deprived of vegetation became once again susceptible to transport by winds. Thus, for the eolian sediment transport, frequency of rainfall is more important than the amount, whereas for the maintenance of vegetation the amount of monthly precipitation is still important.

A better explanation for the observed pattern of eolian sediment transport was found when the monthly duration of the highest wind speeds was taken into consideration. During the period of investigation mean monthly wind speed varied between 7 m/s and 9 m/s, with a constant standard deviation of ± 2 m/s, while the highest values ranged between 9 m/s and 14 m/s. When considering only winds from 50° to 70° , which represent the main direction of transport, and velocities \geq than 9 m/s the relation with eolian sediment transport is significantly higher (Fig. 8). The 9 m/s wind velocity threshold was chosen as being the highest mean monthly wind velocity.

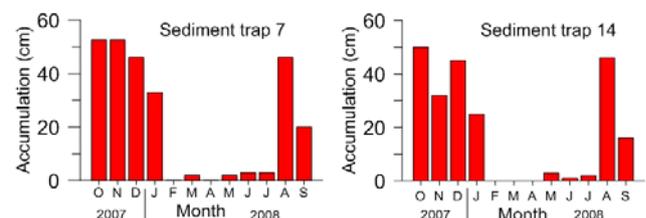


Figure 6. Sediment accumulated in the traps reflects alternating humid and dry weather conditions.

In the light of the preliminary results the importance of the vegetation cover is clear, both in inhibiting sediment mobility and in producing the opposite effect when removed. During the monitoring period it became apparent that the activity of off-road vehicles (buggies and motorcycles) also triggered the remobilization of sediments by dama-

ging the vegetation cover, and resulting in blowouts and modification of the topography (Fig. 9).

Mobility of the Parabolic Dunes of the Deflation Plain

The comparison of the topographic profiles of three parabolic dunes did not indicate any net displacement, despite the intense mobilization of sediments on the windward side of the depositional lobe. This mobilization is reflected in the greater morphodynamic variability of this face as compared to that on the slip face (Fig. 10).

Considering the present climate conditions, the parabolic dunes are reasonably stable, with no input of sediments from the foredune-beach system, due to the, even sparse, vegetation cover of the foredune ridge as also of the deflation plain; in contrast, there is intense sediment remobilization on the windward, vegetation depleted side of the dunes,

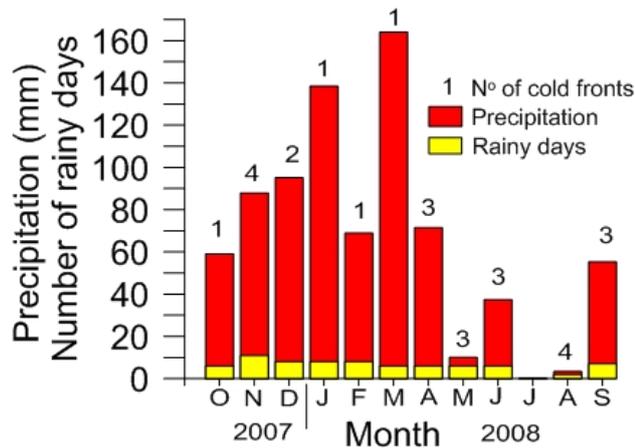


Figure 7. Monthly precipitation and indication of the number of rainy days and number of cold fronts.

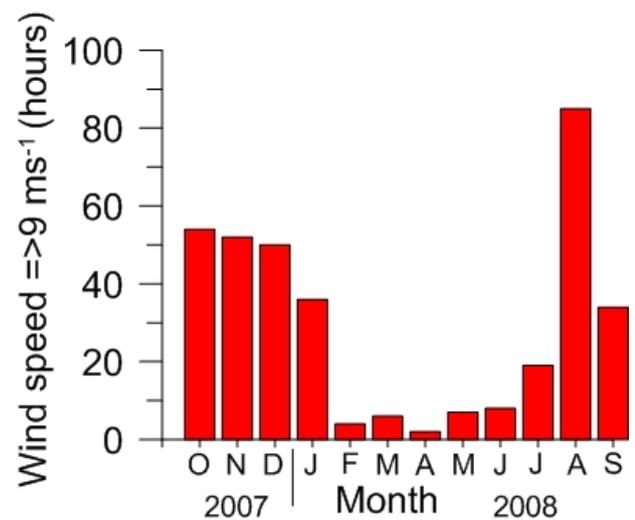


Figure 8. Duration of wind velocities over 9 m/s indicating the close relationship between sediment transport (Fig. 6) and duration of strongest winds from 50-70°.

due to the reworking of their own sediments. The maintenance of the vegetation cover is, however, extremely dependent on the water balance, with longer dry periods leading to the destabilization of the system due to the intensification of the wind transport. This is well exemplified by the 1959 aerial photograph, which indicates sediment transport from the foredunes in the direction of the active dune field, through transgression over the deflation plain (Fig. 11).

When the annual rainfall rates measured in Cabo Frio (from 1921 to 1968) and Arraial do Cabo between (1969 and 1986) are compared with the average rainfall of the same period (Fig. 12) large



Figure 9. Destruction of the vegetation cover and subsequent incision of the terrain due to the traffic of off-road vehicles. Location landward from position P6, figure 3.

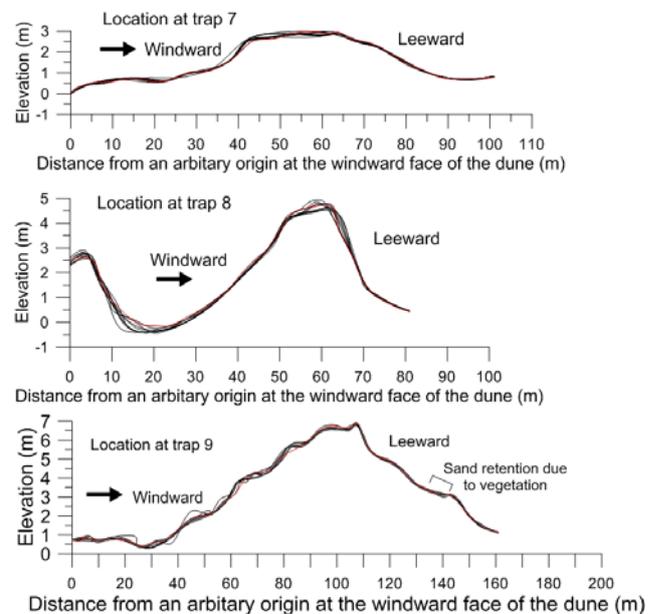


Figure 10. Overlay of the 12 monthly topographic profiles along the longitudinal axes of three parabolic dunes located on the deflation plain (see Fig. 3). No net advances of the base of the slip face of the dunes were detected. The last profile of each dune is represented by a red line. Location of profiles in figure 3.

oscillations are observed, with the occurrence of alternating dry and rainy periods. In the 1950's the monthly rainfall fell far below the average during five successive years what might explain the reactivation of the wind transport as indicated by the 1959 photograph (Fig. 11). This phenomenon may be recurrent during occasions of water deficit: an aerial photograph from 1976 shows some sediment transport in the direction of the active dune field, though less evident than that seen in the 1959 photograph. It must be borne in mind that in 1975 the annual rainfall was above the average value and so the effects of the water deficit were not so remarkable.

Erosion and Coastal Flooding

In the study area, the georeferencing of older aerial photographs is extremely difficult due to the sparse land occupation and the consequent lack of points of reference. Images from 1970 and 2000 were compared by drawing the position of the internal limit of the berm in each image; no evidence of significant change in the position of the coastline was found. Dias *et al.* (2007) had found a different result by inferring erosion of the coastline based on satellite images and a digital terrain model. However, in a later study, Dias *et al.* (2009) reappraised this interpretation as they had then identified a period of coastal advance of some 30m between 1959 and 1976, and of retreat, also of 30m, between 1976 and 2003. This result should be accepted with caution because these analyses were based on aerial photographs by taking the limits of the vegetation cover as points of reference, besides a few roads and buildings, what may lead to significant errors. Beyond that, it is possible that changes may have occurred in the vegetation cover at the foredune-beach interface which could lead to an equivocal interpretation of the position of the coastline. Assuming however, that the amplitude of the erosive process was compensated by progradation of equal extent, the final result does not disagree with the findings of the present study.

The analysis of the time series of the topographic profiles of the foredune-beach system (Fig. 13) did not identify the occurrence of erosion, apart from the morphodynamic variability of the beach with periods of gains and losses typical of beaches of the intermediate morphodynamic stage (Short 1999, Calliari *et al.* 2003). A similar result was obtained by Pereira *et al.* (2008).

The bathymetric profiles present significant landward increase in slope at 9 and 10 m depth. Equilibrium profiles (Dean 1991) despite indicating equilibrium of the upper shoreface are not adjusted

to the remaining measured profiles, with "excess" of sand in profile P7 and lack in profiles P2 and P5 (Fig. 14). This may indicate a lack of sediments tending to an erosive adjustment of the profile or a compound profile in which the intermediate shoreface presents a profile with equilibrium of its own, as proposed by Inman *et al.* (1993).



Figure 11. Aerial photograph taken in 1959, by the Cruzeiro do Sul company. The bright white areas at the center and at the northern edge of the beach show sediment transport from the foredunes to the active dune field.

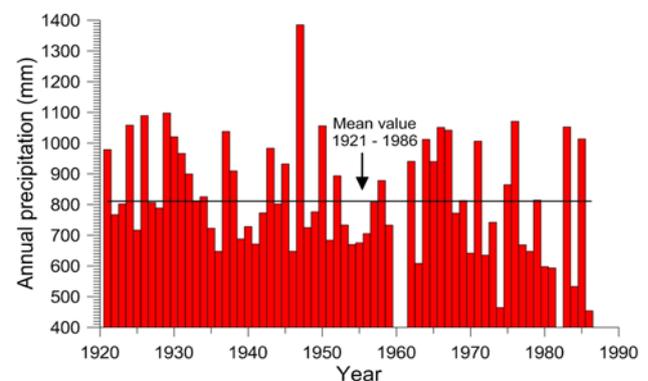


Figure 12. Annual rainfall in Cabo Frio/Arraial do Cabo showing significant deviations from the average of the 1921-1986 period, represented by the black line parallel to the x-axis. No data were collected during the period of 1960 to 1961. In 1982 registered rainfall was only 91.8 mm.

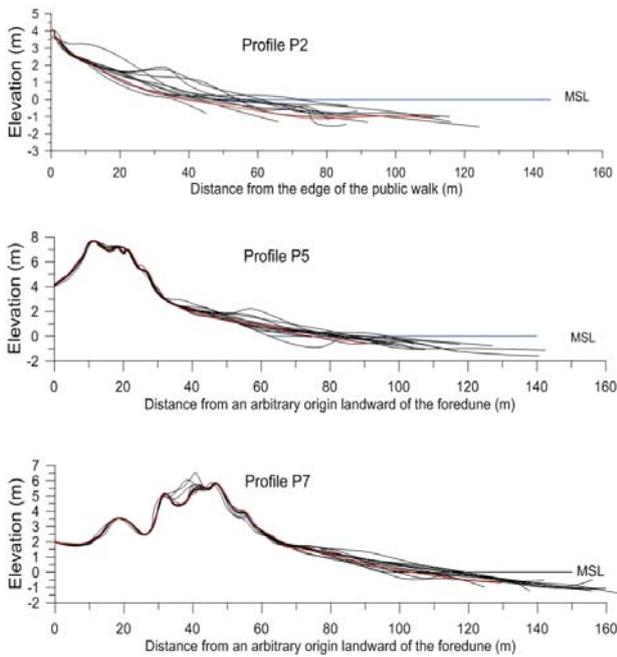


Figure 13. Overlay of the 12 monthly topographic profiles of the foredune-beach system indicating the absence of net erosion during the period of observation. The last profile is represented by a red line. Location of profiles in figure 3.

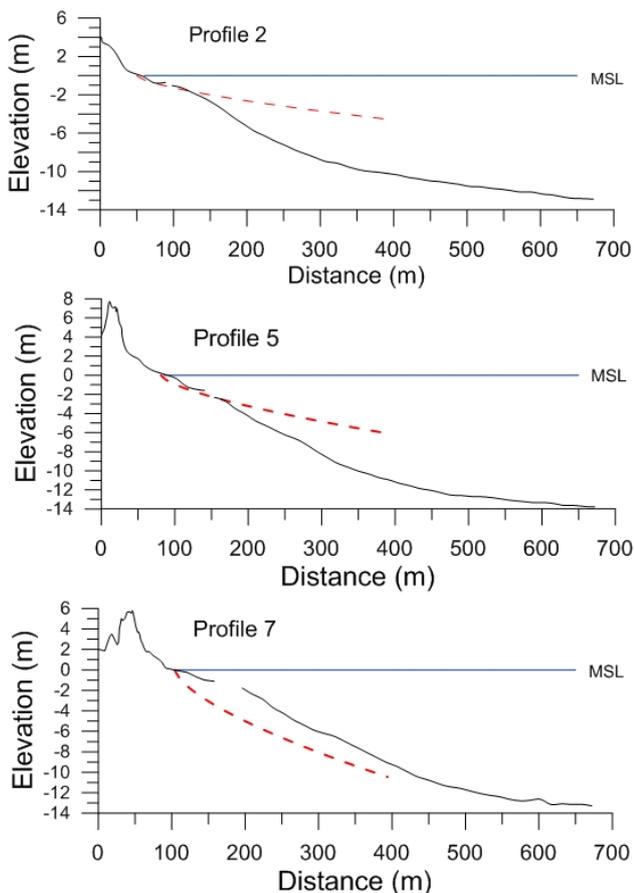


Figure 14. Topo-bathymetric profiles of the foredune-beach-shoreface system compared to the equilibrium profile (broken line) according to the model proposed by Dean (1991).

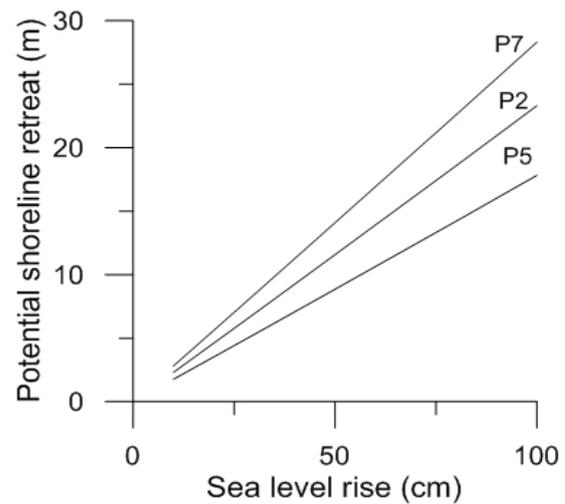


Figure 15. Estimated erosive adjustment of different sectors of the coastline to distinct sea level rise scenarios according to the Bruun rule. Profile locations in figure 3.

The non-identification of an erosive trend of the coastline (not taking into account the possible lack of sediments in the middle shoreface) is auspicious in the sense that it indicates a certain robustness of the coast in the face of the variability of the coastal processes.

However, a rise in sea-level will tend to result in an erosive adaptation of the coastline as there are no sediment sources to compensate for this rise. The application of Bruun’s model (1962, 1988), as described above, to provide a rough estimate of the amplitude of this response to different scenarios of sea level rise, is presented in figure 15; the model predicts an increase in the amplitude of the retreat from the center to the extremities of the beach arc a result that stems essentially from the lower gradient of the shoreface, associated with a smaller grain size in the northern and southern sectors of Perú beach.

For the urban area, behind profile P2, this erosive adaptation will mean the destruction of the public walk in front of the urban area, unless the beach is preserved by means of artificial landfill. Another vulnerability factor arises from the shallow depth of the water table and the poor drainage of the deflation plain with the consequent renewed flooding of the low-lying areas that were extensively flooded during a period of intense rainfall that occurred in the period from January to May 2008.

Conclusion

The Perú coastal plain, with its system of sandy dunes, presents a highly sensitive environmental equilibrium, as climatic oscillations tending to drier weather, independently of global changes, can disturb its delicate morpho-sedimentary balance. Alterations in the water balance, whether by dimini-

shed rainfall or increased evaporation, may lead to a reduction of the vegetation cover of the foredunes and of the deflation plain, thus re-starting sediment transport from the foredunes to the active dune field that, in turn, will resume its displacement towards the urban areas. Sea level rise and increased storminess will lead to both, an erosive adjustment of the coastline by means of its retreat and to increased flooding of the low-lying areas of the deflation plain and of the paleo-lagoon located behind the active dune field. Other consequences include the landward displacement of the foredunes and the transference of sediments as blowouts and parabolic dunes towards the deflation plain and the active dune field, as described by Psuty & Silveira (2010).

The observations made on the Peró coastal plain may also be applied to other coastal dune fields that occur in Rio de Janeiro State in areas with higher rainfall rates such as those observed to the

north, in the Paraíba do Sul river plain, and to the south, in the beach barriers found in front of Araruama and Saquarema lagoons as well as of Sepetiba bay (Marambaia beach barrier) where localized active blowouts already indicate occasional eolian sediment transport. As some of these areas are experiencing increased occupation adequate setback lines should be established in order to avoid future loss of propriety.

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