Beach morphodynamics: a tool for coastal habitat managers. A case study: Praia de Fora, Itapuã State Park, RS.[1]

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ABSTRACT

Of the thousands of protected areas worldwide, few include coastal and marine components, contrasting strongly with the global importance of these ecosystems. In this study, the morpho- and hydro-dynamics of beach of Praia de Fora near the Lagoa dos Patos, Itapuã State Park, Rio Grande do Sul, Brazil, were examined to inform management decisions for this beach, including adjacent submerged areas that may be important for beach maintenance. Various morphodynamical models, those held sacred in the worldwide literature, were studied from 1978- 2001: equilibrium profile models; longitudinal and perpendicular sediment transport models; external limits; closure depth; and temporal analysis of beach line variation. Results indicate that this beach is characterized by large annual energetic variation while classified as a beach of low to moderate energy. Thus, the beach is often similar to lacustrine beaches yet, in some circumstances, the high energy levels result in the beach becoming very similar to open ocean beaches. Recommendations for management based on this research are in the following areas: security risks for bathers, dune management, sand removal restrictions at the mouth of the Lagoa dos Patos, underwater delineation of the Itapuã State Park at a depth of 6m near the Praia de Fora.
Key words: beach morphodynamics, Itapuã State Park management, protected areas

INTRODUCTION

Coastal zones, due to strong and diversified pressures for their use, may be considered to be zones of contrasts that present very difficult challenges for environmental management. In these zones many, at times contradictory, forces meet: intense urbanization, port activities, industrial exploitation and tourism on large scales. Thus, the challenges to management are varied due to these varied usage demands.

"Coastal zone" is defined in a variety of ways, based on physical, geographical and demographical characteristics as well as ecological function. Perhaps the most accepted definition defines the coastal zone as that space delimited by the interface between the ocean and land: the strip of land that receives strong marine influence and the strip of ocean that receives a strong terrestrial influence (Rodríguez & Windevoxhel, 1998). Also, it is the region between the Economic Exclusive Zone (EEZ) and the terrestrial limit affected by marine climate (Clark 1996).

In Brazil, the Interministerial Commission for Marine Resources (CIRM) considers the coastal zone that geographical region with interactions between the air, sea and land, including its natural resources, that includes the following:

- Marine Strip: the region of ocean that extends to 12 nautical miles from shore, established by the United Nations Convention on the Law of the Sea.
- Terrestrial Strip: is the land bordering the sea including municipalities that suffer direct influence of marine phenomena (CIRM 2001).

The study of geomorphology is fundamental for planning and integrated management in the coastal zone. This study allows the understanding of watershed delimitation and behavior, soil use capacity, surface and subsurface water resource maintenance and of geomorphological processes in motion. In this context, we include the study of beach morphodynamics, a tool for the understanding of morpho- and hydro-dynamic processes in coastal environments.

Understanding morpho- and hydro-dynamics of beaches is a great advantage for public planners or protected areas managers that include beaches in their jurisdictions. Several important uses of beaches and coastal zones, such as security for swimmers, dune management, sand mining, beach recuperation, underwater delimitation of protected areas and others are intimately linked to this area of study.

Along with these needs, morphodynamical understanding of beaches becomes fundamental for the development of ecological studies in this environment. Long considered large and sterile sand deposits, today we understand that beaches are important ecosystems with a complex animal community including echinoderms, mollusks, crustaceans and arthropods (McLachlan & Erasmus, 1983).

This importance of beaches became more evident when studied by Australian researchers, who, by demonstrating the beach's importance, also showed its fundamental importance in ecological studies (diversity, species richness, abundance and so on;

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Borzone 2000).
Here, we report on an analysis of the principal morphodynamical characteristics of the beaches at Praia de Fora in the Itapuã State Park, Rio Grande do Sul, southern Brazil. Specific objectives were to increase knowledge of this environment, to contribute to the understanding of morphodynamical parameters and to provide recommendations for the management of this protected area.

Itapuã State Park

The State Environmental Protection Foundation (Fundação Estadual de Proteção Ambiental, FEPAM) included the Itapuã State Park in the Midwestern Littoral Region, as part of the Coastal Zone of Rio Grande do Sul. The park is situated in the Guaíba Watershed, which contains 28 protected areas and encompasses a great diversity of ecosystems. Together with Lake Guaíba are two parks: Jacui Delta State Park (at the confluence of the Jacui, Sinos, Gravatai and Cai rivers) in the north; Itapuã State Park at the edge of the Lagoa dos Patos in the south (Figure 1), comprising a mosaic of ecosystems such as open grassland, *restingas*, islands, beaches and hills that shelter a variety of fauna native to Rio Grande do Sul. Some of these species are in danger of exctinction, such as the Otter, Yellow-throated Caiman and the Red Howler Monkey.
Located in the Viamão municipality (50° 50' to 51° 05' W and 30° 20' to 30° 27' S) Itapuã State Park was created in 1973 by the state and included 1,535 ha. The park was enlarged in 1976, 1991 and finally in 1996, and now totals 5,560 ha. These lands were originally owned by the Portuguese Priest, Father José dos Reis, and part of a ranch that was established in 1733 and was fragmented by successive sales up until the year 1973, the year the park was created.
Around 1970 tourism in the area began to grow, along with abuse. The local press began to publish stories of granite and sand mining, depredation of the local flora and fauna, and clandestine division and sale of lots in Praia de Fora (Fujimoto, 1994). In March 1991 the park was closed to visitation because of a general degradation of the ecosystem due to intensive use, tourism, burning and cattle grazing. At that time the only activities permitted in the park were maintenance and scientific studies. In April 2002 the park was finally re-opened with restrictions placed on the number of visitors and the areas that were accessible to visitation.

"Praia de Fora" Beach

Itapuã State Park includes eight beaches, seven of which are oriented towards Lake Guaíba, and the last and largest is Praia de Fora, oriented towards Lagoa dos Patos (**FIGURE 1**). Praia de Fora is a long sandy beach that extends approximately 14 km to the extreme southeast to the Pontal das Desertas.
The conservation importance of this beach contrasts strongly with the depredations it has suffered over the years. Berte *et al* (1991) state that "...transformations due to the occupation of the Park interfered strongly with the landscape that is characterized by different environments." Those authors state that the principal impacts on the Praia de Fora were sand dune release caused by plant destruction and the removal or leveling of the protective frontal dunes, the disorderly human occupation due to illegal subdividing of the area for real estate and associated garbage production and groundwater pollution.
The genesis of this beach is associated with the growth of Pontal das Desertas, which is a submersed source of sand. According to Calliari *et al.* (1985) the most important factors for the evolution of this beach are the prevailing winds, tide and the original shape of the beach, such that beach morphology and the absence of tidal extremes favors beach evolution in Lagoa dos Patos.
According to Dillenburg & Toldo (1990) the action of tides can be considered insignificant at this beach, since scouring is dominated by the circulation of the lake canal. Other factors that reduce the influence of tidal forces are: (a) the length of the estuarine system (65km), (b) the depth of the channel of the Rio Grande (< 15m) and (c) the minimal cross section of the channel (9,000 m^2) which is small compared to the area of the Laguna dos Patos.

MATERIAL AND METHODS

Because a large part of the world's population lives near large bodies of water, the degradation of these environments has been rapid. Thus, our understandings of the phenomena that shape these areas are fundamental for the development of an efficient management strategy, especially in coastal zones.
Sandy beaches are transitional systems, very dynamic and sensitive to perturbation, which are constantly adjusting to the varying local energy levels and are constantly reworked by eolian, biological and hydrological processes to which they are exposed. Beaches may be formed by sediments with varying compositions and granulometries, which, in combination with wave action will determine the beach profile (Hoefel, 1998).
Nomenclature associated with beaches has not been standardized in the scientific literature. Tessler and Mahiques (2000) studied the problem of terminology and concluded that the problems come from the inconsistent classifications systems in English and that were then incorporated in etymological problems due to the adaptation to Portuguese. Here, terminology will follow that found in Angulo (1994), Klein (1996) and Ferreira (1999), as described in **FIGURE 2**.
While the great mobility of beach environments may be considered a restrictive factor in the elaboration of models of beach dynamics, the application of empirical parameters has been shown to be an important tool for the interpretation of the spectrum of variables involved. The study of beach morphodynamics and three-

dimensional variations had its beginning in Japan in the 1960s and the United States in the 1970s with the first sequential models of beach variation. The difficulty in obtaining oceanographic data due to technological limitations at that time resulted in a slow development of the study of beach environments compared to continental environments.

In the beginning of the 1980s the so-called "Australian School of Costal Geomorphology" had its inception. Studies such as Wright (1981), Short & Hesp (1982), Wright & Short (1984) introduced the morphodynamical classification for beaches and used the concept of "mophodynamical stage" to refer to the range of hydrodynamic, depositional, and sediment redistribution processes that are associated with beaches. Six morphodynamical stages were described; **FIGURE 3** illustrates the dissipative and reflective extremes.

It is worth emphasizing that the great majority of the proposed models were developed for open ocean

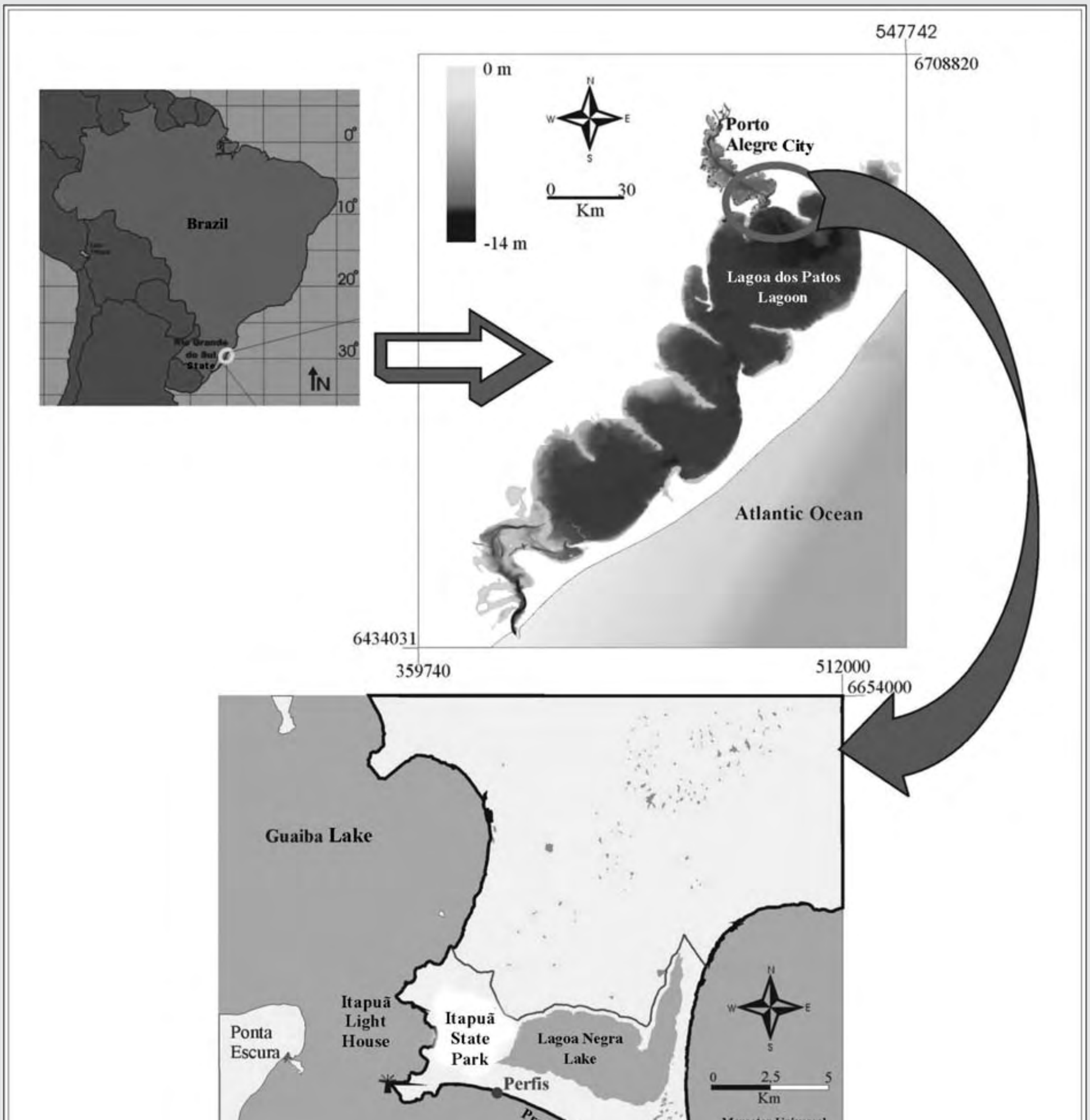

Figure 1. Location of Praia de Fora Beach and the Itapuã State Park together with the Lagoa dos Patos Lagoon

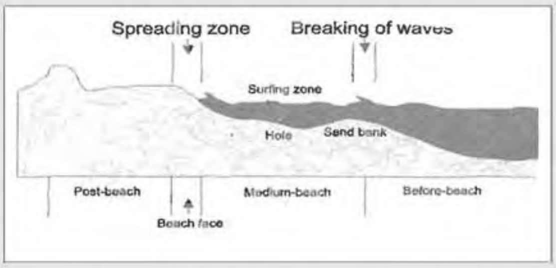

Figure 2. Terminology of beach systems adopted in this study

beaches with the great about of energy involved. The applications of such models to protected beaches with low energy are rare, and the results are not always satisfactory. Discussions about the elaboration of models specific to these systems may be found in Nordstrom (1992) and Hoggs et al. (1996).

In the present case, the beach Praia de Fora, models from the Australian School were tested, since characteristics of Praia de Fora are very similar to open oceanic beaches. This beach extends over approximately 14 km, and is situated in a part of the Laguna dos Patos where the maximum fetch is 53 km and where the waves reach a height that is sufficient to significantly alter the beach profile (Toldo 1994).

The applied methods include the models One Bank and Multiple Banks, from the Australian School, for the application of the following parameters: Nondimensional Omega (Ω), Theoretical Omega (Ω), Bank Parameter (B), Beach Face Declivity (ß Tangent), Surf Scaling Parameter.

Other models included the Equilibrium Profile Model (Dean 1973), the Longitudinal Surf-zone Sediment Transport Model (Shore Protection Manual 1984), External and Internal Depth Limits and Perpendicular Transport model (Sunamura & Takeda, 1984). In addition, a temporal analysis of the variation in the beach line from 1978 to 2001 was carried out.

In this study a collection of data which included wind velocity, direction, frequency and path during a 12 month

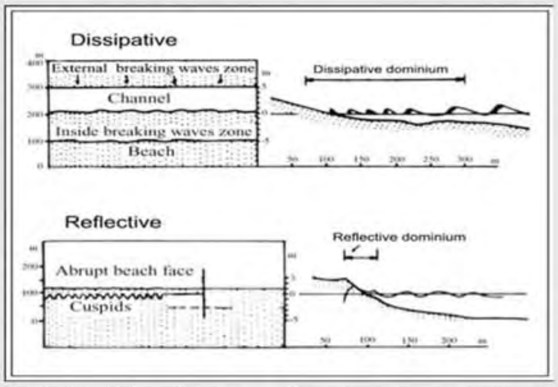

FIGURE 3. Schematic diagram of the two extremes of the morphodynamical stages: dissipative and reflective (Adapted from Short & Wright, 1984)

time series was used (Toldo 1994). Beach profiles were monitored from a fixed reference point, using the water level on 27/05/2000 as the standard (zero) water level. On that day, the tide table from the Hydrographic and Navigation Directorate (DHN) in Rio Grande showed the tide was near its average of 0.22 m.

Profiles were traced following Garcia & Piedade (1978), where a surveyor's level and rule are used to estimate the topography. Additionally, two transverse profiles were measured which extended to the inferior margin of Laguna dos Patos at 6 m depth, using a echo-bathymeter from a boat.

During profile monitoring, sediments were collected along the water line at about 1.1 m depth, subsequently analyzed in the laboratory following Martins et al. (1978) and Ferreira (1999). Textural analysis of these sample followed Folk & Ward (1957) using the program PANCOM (Toldo & Madeiros 1986), which permits that calculation of statistical parameters of the sample granulometric distribuitions.

Monitoring the variations in the beach line at Praia de Fora between 1978 and 2001 was carried out by use of charts fabricated by the Survey Division of the Army (DL) at a scale of 1:25,000 for 1978, and the line from 2001, that was measured by Trimble GPS 4600 with 1 m precision by walking the beach line.

Temporal analysis was carried out with the program IDRISI 3.2, which permits spatial modifications during a fixed time interval.

This type of survey has been widely used by coastal zone researchers, since it allows quantitative and qualitative evaluation in beach line variations. It is worth mentioning that the quality of the data is fundamental for precision in the results. In Rio Grande do Sul, Toldo *et al.* (1999) and Esteves *et al.* (2001) used similar methods and obtained satisfactory results with respect to variations in the beach line. In both cases the information source were charts (Survey Division of the Army) in a scale of 1:50,000. Thus, in this work we gain precision by using the 1:25,000 scale charts.

RESULTS AND DISCUSSION

The results from the parameters studied herein indicate that the environment has great annual energetic variation. Praia de Fora is classified as a beach of low to moderate energy, with characteristics similar to lake beaches yet with occasional high energy conditions, similar to those of open ocean beaches.

Profile overlays monitored in the field permitted beach face estimation, which averaged 16.2 m during the year (**FIGURE 4**). This is important since it shows that Praia de Fora is a sheltered lake environment. Additionally, these profiles show great variability with beach face declivities ranging from 2.8° to 11.3°. Post-beach inundation is frequent in the beaches of Laguna dos Patos because the region is the outlet of a large watershed of approximately 170,000 km², with only one channel connecting it to the sea.

Using the One Bank model in the analysis of profile morphology showed an alternation of beach morphodynamical stages. The Omega parameter (Ω) applied to wave prediction data for 1988 (Toldo 1994) indicated intermediate stages with a frequency of 59%, and a dissipative stage with a frequency of 41%. Using this parameter here, the model indicated the occurrence of all morphodynamical stages proposed by the Australian Model, including reflective stages, which confers the proposition that the Praia de Fora has a great profile mobility. There were discrepancies between the stages predicted by Ω and the observed patterns in the field. These discrepancies were caused by a difference between hydrodynamic conditions acting at the moment of data collection and the stages suggested by the model, which was a consequence of the energetic variation and the morphological alteration of the beach being out of temporal phase with each other. In the Laguna dos Patos these time intervals may be larger, since in this region it is common for several days to pass without conditions necessary to generate waves.

Equilibrium profile concepts were applied to the situation at Praia de Fora by use of two transverse profiles that were measured on the beach line at 6 m depth. These data indicate that Praia de Fora presented, on the day the profiles were measured, a perpendicular sediment transport in an onshore direction, with the beach face being depositional. Statistical parameters of the external and internal limits of the beach defined, with reasonable precision, active longitudinal and transversal sandy transport zones. That is, they defined a zone at the least depth of which significant profile alterations do not occur during the year. These depth values define the limits of the zones in which sediment movement is: (a) very intense, at depths between 0 – 0.9 m; (b) significant, at depths between 0.9 – 5 m; (c) transitional, between 5 – 6 m; and incipient, at depths > 6 m (**FIGURE 5**). These are in agreement with known dynamics of the Laguna dos Patos, where the submerged relief is divided into two large morphological regions: the lake margins, between the beach line and 5 m depth, and characterized by silty and sandy sediments.

The application of the longitudinal sediment transport method, proposed by the Shore Protection Manual, to the predicted tides for the Praia de Fora in 1988, indicated a transport bidirectionality, with approximately 55% going SE and 45% to the NW. These data were compared to those of Toldo (1994), in which the parallel energy flux was calculated, and both were in agreement, as anticipated, with only a 4% difference in the two methods. These results are in agreement with the geomorphological evidence present along the line of the Praia de Fora, such as the existence of erosion or accretion zones at the extremities of this beach system.

Results obtained from application of the method to determine the direction of perpendicular sediment transport indicated that approximately 76% of the time, the sediments were transported in an offshore direction, characterized by beach erosion. In 15%, the sediments are transported in an onshore direction, causing beach accretion. In only 1% of the time, perpendicular transport was null.

All of the parameters used in the mathematical models were elaborated with empirically based studies of oceanic beaches. The application of these parameters to the case study of the Praia de Fora

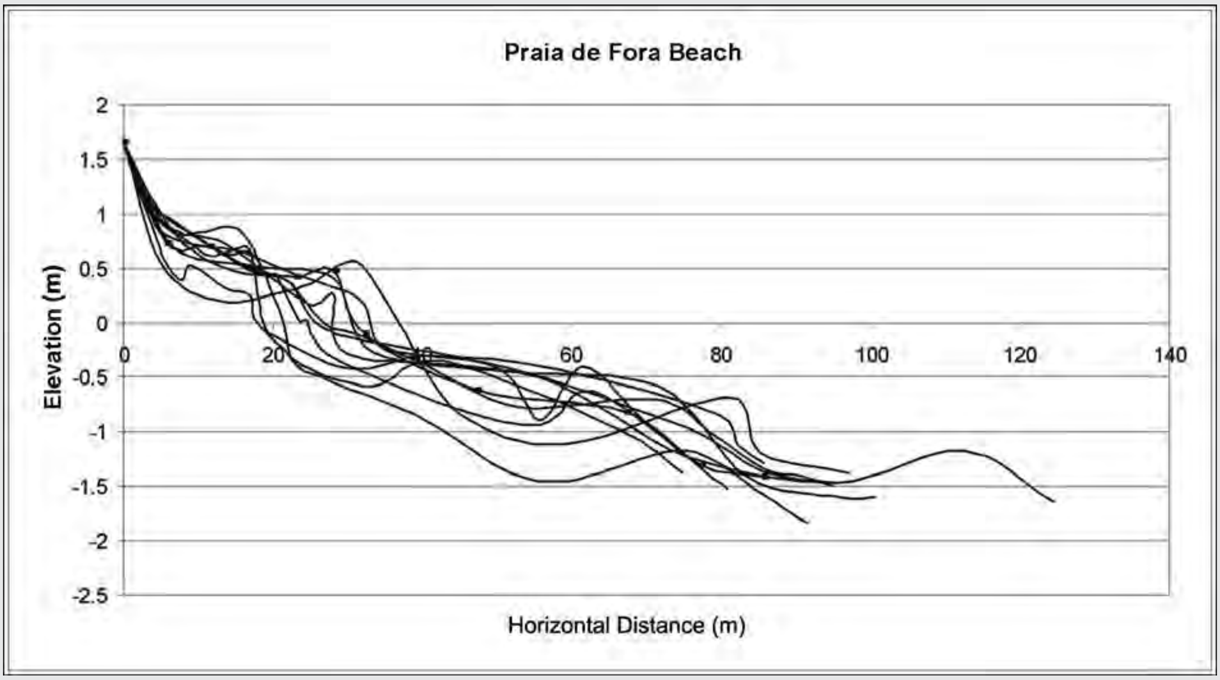

Figure 4. Overlap of the profiles that were monitored in the field. Zero level indicates the water level on 27/05/2000, when the tide table from the Hydrographic and Navigation Directorate (DHN) in Rio Grande showed a water level approximately that of the average, at 0.22m

demonstrated a good concordance between mathematically estimated stages and those observed in the field. This concordance justifies the use of these parameters in lake beaches, as long as the variations fit within the constraints of the models.
The results from the temporal analysis of the beach line between 1978 and 2001 indicated that the beach is receding, stable, or advancing, depending upon which part of the beach is being analyzed. Fifty-eight percent of the Praia de Fora showed signs of erosion, in 14% were signs of accretion, and 28% remained stable. The beach receded up to 80 m in some parts of the eroded areas, and grew up to 40 m in the accretion zones. The rates of beach migration were -3.75 m yr^{-1} in the eroding areas, and 1.75 m yr^{-1} in the accreting areas (**FIGURE 6**). The results obtained herein of the temporal and spatial changes to the beach line of the Praia de Fora, confirm the tendencies predicted by the mathematical models.

CONCLUSIONS: MANAGEMENT STRATEGIES FOR THIS PROTECTED AREA

Graefe et al. (1990) state that park visitors cause direct or indirect impacts on the bodies of water of the parks. These relations depend on the qualitative alterations that occur in these environments as a function of their use. The sources of direct impacts are those that result from activities within the water, while active coast lines and soil use within the watershed indirectly affect aquatic resources.
In agreement with the conclusions on the morphodynamics of the Praia de Fora, it is suggested that management take into consideration the recommendations that follow here.

Risks of Use for Swimmers

While being a lake beach and apparently tranquil, Praia de Fora has a long history of drowning as told by fishermen and old residents of the region. A morphodynamical analysis of the beach indicates an environment with an elevated energy gradient acting in the beach modeling process. These conditions specifically refer to winds, which may occasionally generate waves greater than 0.10 m, which, along with water level, become the hydrodynamic beach-modeling agents. Thus, this energetic, and consequently morphologic, variation represents a risk to swimmers that use the Praia de Fora, especially on days in which the beach is exposed to waves exceeding 0.5 m and the modal stage is dissipative or intermediate, with longitudinal banks and hollows.
Litoral currents follow two patterns that depend on the angle of incidence of the waves to the beach (Muehe, 1995). When waves strike the beach obliquely to the coastline a circular pattern with returning currents develops and results in a series of reentrants on the beach line, separated by beach cuspids. Returning currents, while localized, are also important in the coastal morphodynamics (Wright & Short, 1984), principally in dissipative or intermediate beaches, with important sediment transport activity in the off shore currents of the surf zone. **FIGURE 7** illustrates these dynamics.
Returning currents are considered one of the major courses of drowning in the beaches of Rio Grande do Sul and Santa Catarina. While the Praia de Fora beach dynamics are less intense than oceanic beaches, the potential risk suggests that life guards should be

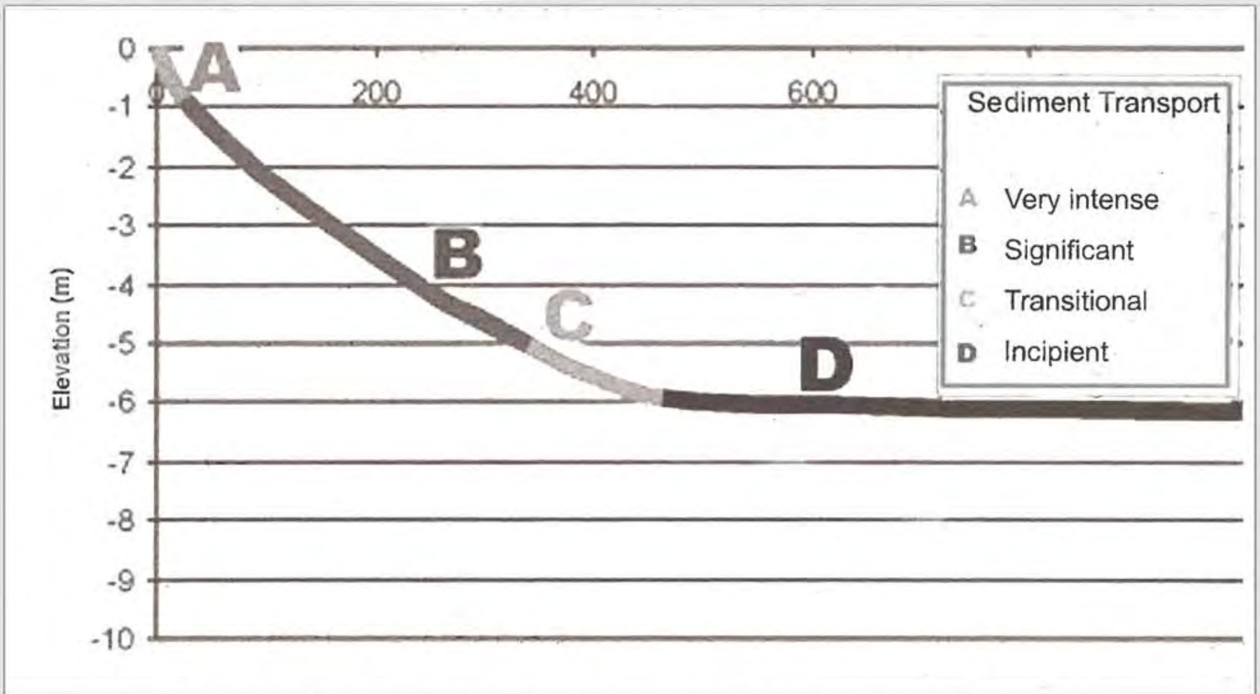

Figure 5. Idealized profile of the Praia de Fora Beach with sectors of the profile being represented where the longitudinal and perpendicular sediment transport is: A – Very Intense; B – Significant; C – Transitional; and D – Incipient

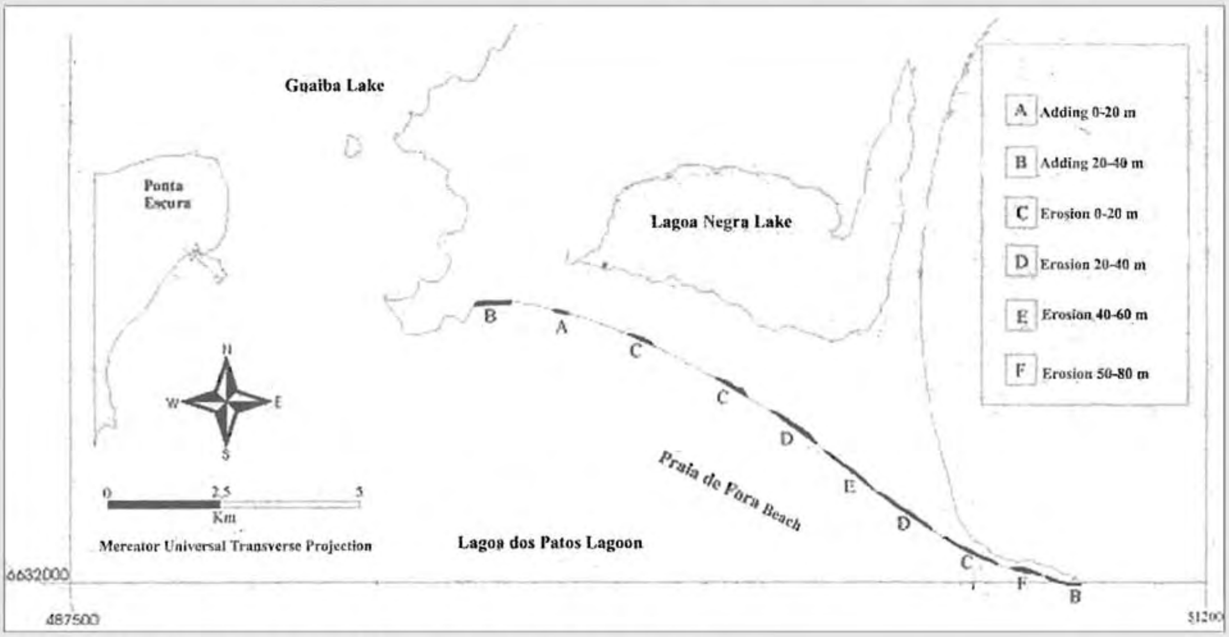

Figure 6. Map showing variations in the beach line between 1978 and 2001

available along the most heavily used parts of the beach. Along with the returning current, we also examined the intense morphological variation of the beach profile to a depth of about 1.3 m, which is considered the preferred area for swimming. As analyzed herein, the beach variations are intense with an active migration of banks and hollows. This, associated with lake water levels, may also be a risk to swimming safety.

Dune Management

Sandy dunes are marked features of a large part of the entire Brazilian coast. The importance of these features as habitat for the local fauna and flora, as well as scenic beauty, has become increasingly appreciated by those that manage these areas (Tabajara et al. 2001).

Dunes come in a wide variety of appearances due to

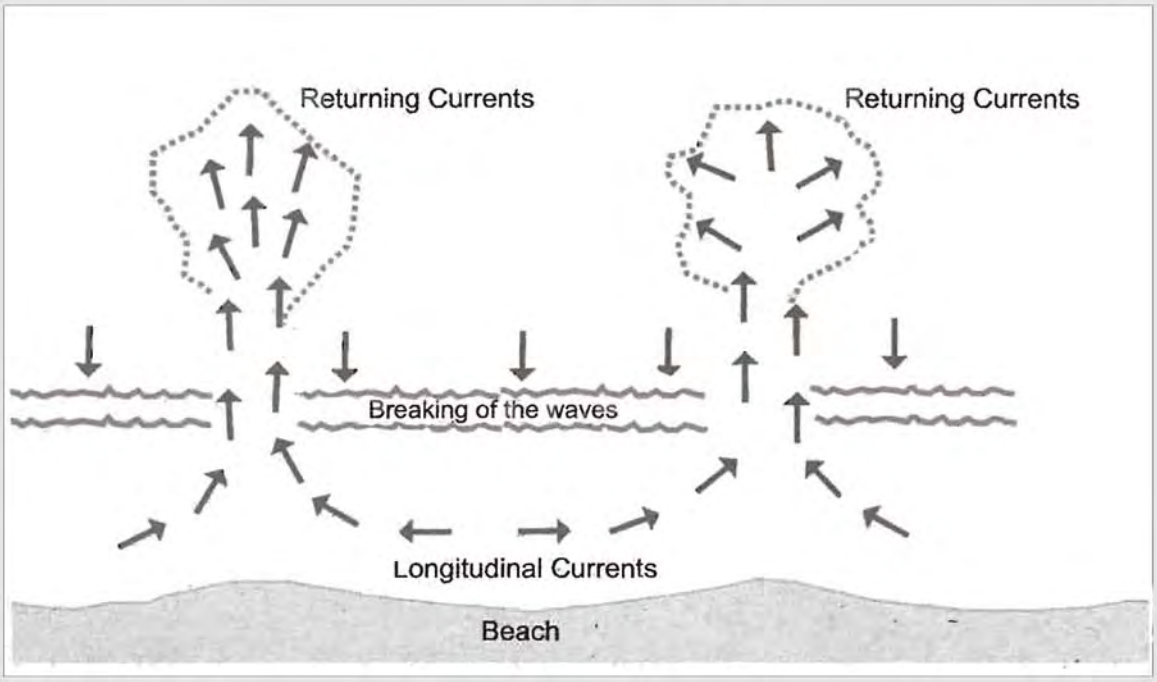

Figure 7. Schematic diagram of the returning currents and currents parallel to the coast in sediment transport (modified from Gruber, 1999)

their dynamic character, resulting from the interactions of various factors, such as sediments, vegetation, wind and anthropogenic activities. The latter of which is responsible for large changes in the geomorphology and ecology of these systems.

In Itapuã Park, dunes provide an environment of great beauty and complexity, with the best represented portion found at Praia de Fora, especially in the northwest part, at Pontal de Itapuã. Before its closing for restoration in 1991, the disorganized use of this area caused several impacts, such as the activation of fixed dunes, in consequence of the deforestation and of sand mining and leveling of the frontal dunes.

It is considered that, along with scenic and environmental importance, the dune field of Praia de Fora, but especially the frontal part, functions as a natural protection against raised water levels of the lagoon. It was observed that the water elevation is fundamental in the dynamics of this environment, making the features of frontal dunes of fundamental importance for beach preservation.

We suggest that studies continue of the dune field of the Praia de Fora along with analysis of their genesis, dynamics and vulnerability of dunes. We also suggest that the Park develop an environmental education action based on the importance of dune preservation for the Praia de Fora.

Sand Mining

Based on the morphological compartmentalization of the lake margin and relationships between morphology, sedimentology and hydrodynamic regime discussed in this study, we consider that the submerged area adjacent to the Praia de Fora, between the beach line and a depth of 6 m, comprises a zone that should not be used for sand exploitation. Due to the absence of a source of sand or external sediment source, this area comprises a sediment reservoir for the entire beach system, making sand mining here unviable.

Anchored to this factor, FIGURE 5 demonstrates that up to the depth of 5 m longitudinal and transversal sediment transport is considerable at Praia de Fora, such that any exploitation here may cause a large disequilibrium of this system, reflected directly in the behavior of the beach line, intensifying erosive or depositional processes, with their associated environmental problems (including park visitation), such as a retro gradation of the entire beach system.

A limit of 6 m in depth as the limit for sediment mining includes all of the lake margin, that reaches to 5 m in depth and including a security zone of 1 m, as a function of changes in lake water levels.

Submersed Boundaries of the Itapuã State Park

While Itapuã State Park has defined above-ground boundaries for several years, no consideration has been given to underwater boundary definition. In the same way that the above ground boundaries impedes real estate exploitation within the ecosystem, we believe that a submerged area adjacent to the park ought to be delimited as a way to help in the management of this protected area.

The creation of submerged boundaries for the Itapuã State Park will bring practical benefits to the parks administration. As an example, we cite Article 212 of chapter XI of the State Environmental Code that determines that mining activities cannot be developed in geographical accidents that have environmental, scenic, historical, cultural, esthetic or tourist values as defined by competent agencies.

Conclusions about the morphodynamics of the region of the Praia de Fora described in this study permit the suggestion of the delimitation of a protection zone at a depth of 6 m, which will protect the environments where dynamics are most intense and consequently susceptible to anthropogenic, damaging, interference (**FIGURE 8**).

We emphasize that the proposed delimitation cannot be extended to the other beaches of the park, because they pertain to another body of water, Lake Guaíba, with its distinct dynamics. Studies with similar objectives are necessary to aid in the determination of submerged boundaries for all of Itapuã State Park, including areas adjacent to the lake's beaches.

In addition to the benefits for conservation and management of the Park, this will generate technical subsidies for the implementation of ecological corridors connecting to Lake Guaíba.

Protection of Barba Negra Island

We also suggest the protection of Barba Negra Island (**FIGURE 8**), formed exclusively by sandy sediments deposited by the lake waters and winds as a result of the dynamics of the outlet of Lake Guaíba into Laguna dos Patos. This is the only island near the park that has these characteristics, such that any alterations of the dynamics of this system may have consequences for the island's structure, causing considerable damage to the system. The island has a little known herbaceous - shrubby vegetation, whose preservation is fundamental in order to better understand this ecosystem (Bueno 1996).

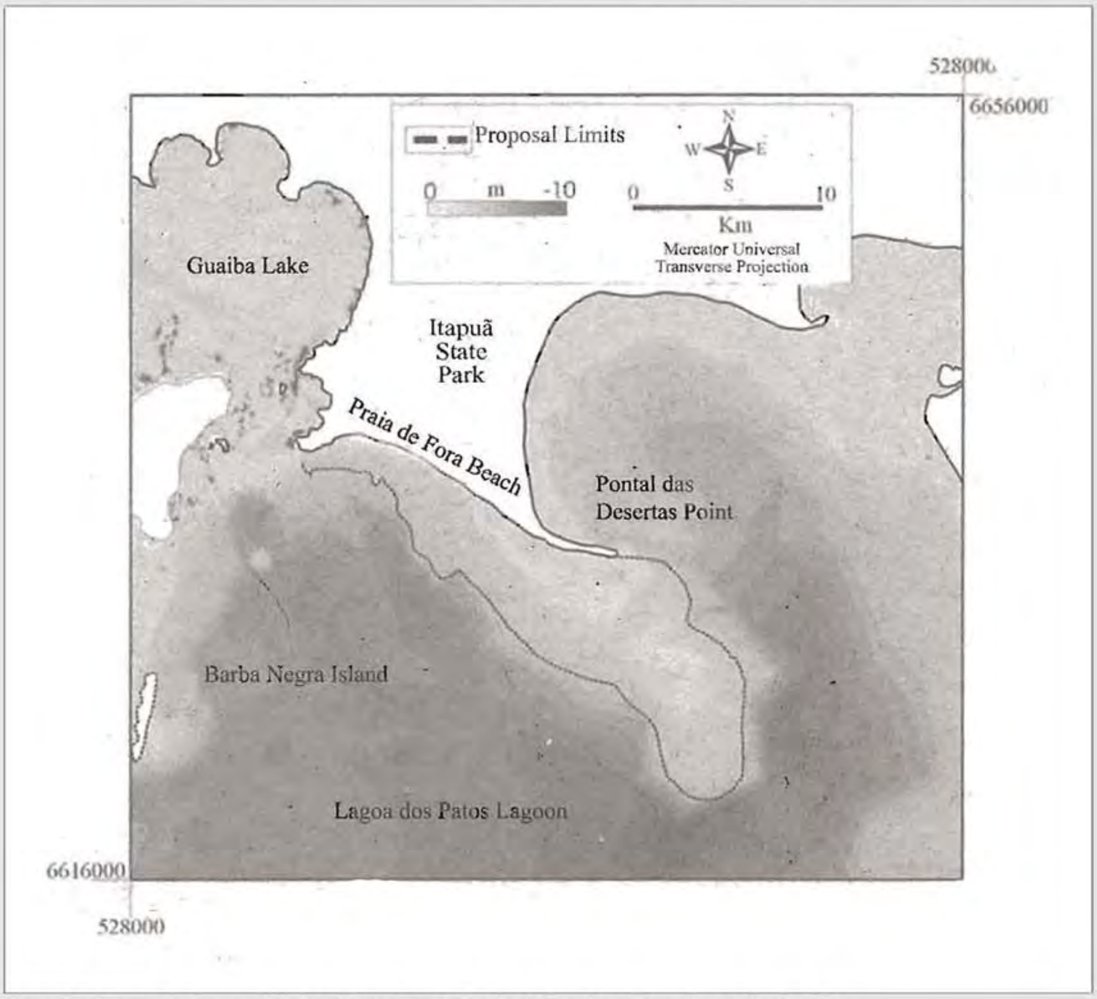

Figure 8. Proposed submerged limits adjacent to the Praia de Fora Beach based on a depth of 6m

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