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Coastal Erosion Risk Assessment, Shoreline Retreat Rates and Causes of Coastal Erosion Along the State of São Paulo Coast, Brazil

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Abstract - Monitoring on coastal erosion problems along the São Paulo shoreline have been carrying out by the author since mid the 80's, including almost 87% of the whole 430 km length of sandy beaches. Eleven types of indicators of coastal erosional processes have been recognized, which have been attributed to seventeen causes, among them ten correspond to natural mechanisms and seven are due to anthropogenic interference. In this paper is presented rates of shoreline retreat based on the Bruun Rule application for six of the most threatened beaches, for a period as long as 56 years. Risk assessment is also estimated for these six beaches, based on two criteria: (*i*) the total number (sum) of types of coastal erosion indicators found along the shoreline (frequency among the 11 types); and (*ii*) general spatial distribution (percentage of surface area) of coastal erosion indicators along the shoreline. Causes and effects of the coastal erosional processes are discussed for these six beaches. Results reveal high rates of shoreline retreat, even in non-urbanized areas, as well demonstrate that the six beaches are at very-high risk. Moreover, they indicate that natural mechanisms are very important as cause of coastal erosional processes in São Paulo, sometimes most them the human-induced causes. These studies have widely been supporting the State Plan for Coastal Zone Management, in order to create special rules for occupation and some activities along the shoreline, including engineering works, building and sand beach exploitation. Besides, results are being recorded in a geoenvironmental information system for the Coastal Zone of the State of São Paulo (Project SIIGAL), which is in phases of implantation.

Keywords - coastal erosion risk, shoreline retreat, natural and anthropogenic causes.

INTRODUCTION

The majority of worldwide coasts is experiencing a wide range of anthropogenic and natural pressures. Anthropogenic pressures are consequence of rapid urbanisation, population growth, tourism activities, port and harbor development, industrialization, natural resources exploitation, waste assimilation and environmental pollution. The most important natural pressures include sea-level rise and climate change. In the last century, the worldwide relative sea-level rise has shown average values between 10 and 15 cm (Gornitz, 1995). Forecasts suggest that sea level will rise between 0.30 to 1.10 m until the year 2,100 (Gornitz, 1995), but the current best estimate for coastal planning purposes is a 0.66 m rise (Warrick & Oerlemans, 1990 *apud* Peck & Williams, 1992; Healy, 1991).

Impacts of sea-level rise have been well documented by many authors (Healy, 1991). The most significant impacts are identified as: increased coastal erosion and shoreline (duneface) retreat; increased frequency of storms of tropical origin; increased storm structural damage and coastal flooding; salt contamination of coastal groundwater landwards; damage to engineering works such as drainage and effluent disposal systems.

Coastal erosion is a worldwide phenomena. About 20% of the world's coasts are sandy and 70% of these are undergoing erosion (Shepard & Wanless, 1971 *apud* Aubié & Tastet, 2000; Morton, 1979; Bird, 1985, 1986). Many worldwide shorelines have been included as vulnerable to coastal erosion and inundation due to projected rising of relative sea level (Emery & Aubrey, 1991 *apud* Peck & Williams, 1992), among them the southern-southeastern Brazilian coastline. Reasons for modern prevalence of widespread erosion on world shorelines may be classified into two categories (Morton, 1979; Bird, 1985, 1986; Short & Hesp, 1982; Bruun & Schwartz, 1985; Titus, 1986; NRC, 1990; Komar, 1995; Mimura & Nunn, 1998; among others): (*i*) natural causes related to sea-level rise (long and short-terms), change in wave regime (increased storminess), reduction in sediment supply (losses of sediments offshore, onshore, alongshore and by attrition), coastal circulation dynamics (changes and stable effects), susceptibility to erosion of the coastal elements (beach, dunes and cliffs), beach and surf zone morphodynamics, coastal subsidence and compaction,

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tectonic; (*ii*) anthropogenic causes, which may be direct - construction of sea defenses, sand extraction, coastline urbanisation, dredging, river damming, reclamation of wetlands, or indirect - resulting from/ in climatic changes. The majority of the authors does agree that sea-level rise is the principal cause for the prevailing coastal erosion worldwide. Bruun & Schwartz (1985) calculated that sea-level rise would contribute with 10 to 100% for beach erosion around the world.

Coastal erosion is also a widespread problem along the whole Brazilian coastline. However, studies concerning coastal erosional processes and their causes are relatively recent here. Researches have been attributing these processes to either natural mechanisms (Soares *et al.*, 1995; Calliari *et al.*, 1996, 1998; Dominguez & Bittencourt, 1996; Mendes & Faria Jr., 1996; Dillenburg & Kuchle, 1999; Dominguez *et al.*, 1999; Tomazelli *et al.*, 1999), or anthropogenic factors (Angulo, 1995; Dantas *et al.*, 1996), or both of them (Valentini & Neves, 1989; Costa, 1994, *apud* Bastos & Silva, 1996; Souza & Suguio, 1996, in press; Abreu de Castilhos & Gré, 1996; Bastos & Silva, 1996; Manso *et al.*, 1996; Souza, 1997; Klein *et al.*, 1999).

There are a few studies concerning either rates of shoreline retrogradation or characterization of predominant processes along the shoreline in Brazil. Besides, papers about risk assessment are also rare. Toldo Jr. *et al.* (1999) have concluded that between 1975 and 1997, among 630 km length of open beaches of the State of Rio Grande do Sul, 528 km have been under erosion, 50 km under progradational processes and 52 km have shown no significant variation. Through studies concerning coastal erosion risk assessment for the State of São Paulo, Souza & Suguio (in press) have concluded that among the 430 km length of sand beaches, 22% are at very-high risk, 19% are at high risk, 31% are at moderate risk, 18% are at low risk and 5% are at very-low risk.

SÃO PAULO COAST REGIONAL SETTING

The São Paulo coastal zone presents physiographic characteristics differentiated between the northern and the southern areas, mainly related to the distance from the Serra do Mar mountain ridge and the shoreline. The largest coastal plains are placed in Southern Littoral (Fig. 1), where widespread outcrops of Pleistocene marine terraces are predominant in relation to the Holocene deposits. Northwards, Holocene deposits become wider than the Pleistocene ones.

Sandy beaches include almost 430 km length. Their characteristics also change along the littoral, defining seven different morphodynamic compartments (Souza & Suguio, 1996; Souza, 1997) (Fig. 1). Compartments I and III present high-energy dissipative beaches (exposed beaches). In Compartments II, IV and V, beaches are mainly intermediate, although low-energy dissipative (protected beaches) and high-energy reflective (exposed beaches) beaches are present. Beaches located inner the São Sebastião Channel (Compartment VI) have singular morphodynamic behaviour, presenting backshore/foreshore zones with low-energy reflective characteristics and shoreface zone with low-energy dissipative characteristics. In Compartment VII, beaches present mixed characteristics along the same beach arch, varying from intermediate towards low-energy dissipative state, or they are low-energy reflective (protected beaches). Sands are predominantly fine to very-fine and very well sorted along the Compartments I, II, III IV and V; medium and coarse sands percentages increase towards Compartments VI and VII, while sediments become moderately sorted (Souza, 1997).

The occupation of the São Paulo coastal zone goes back to the time of the first arrival of the Portuguese in 1500. Four centuries later, human occupancy has followed different patterns between the Southern Littoral, the Santos Metropolitan Region (*Baixada Santista*) and the Northern Littoral (Fig. 1). Presently, about 5.5% of the State of São Paulo population live on coastal zone, which is translated into 2,057,000 inhabitants (FIBGE, 2001). The most intense occupancy is at *Baixada Santista* region, due to its proximity to the São Paulo Metropolitan Region, the economical development fostered by the Santos Port and the Cubatão Industrial-Petrochemical Pole, as well as by tourism activities associated to summerhouses. In the Southern and Northern littoral, economic activities geared to fishing and tourism have always prevailed. Among them, the Northern Littoral has been under the most intense urbanisation, at least after the 1980's. Social-economical pressures built up in those regions and the accelerated urbanisation have been established environmental degradation. Despite of this, considerably large areas of the São

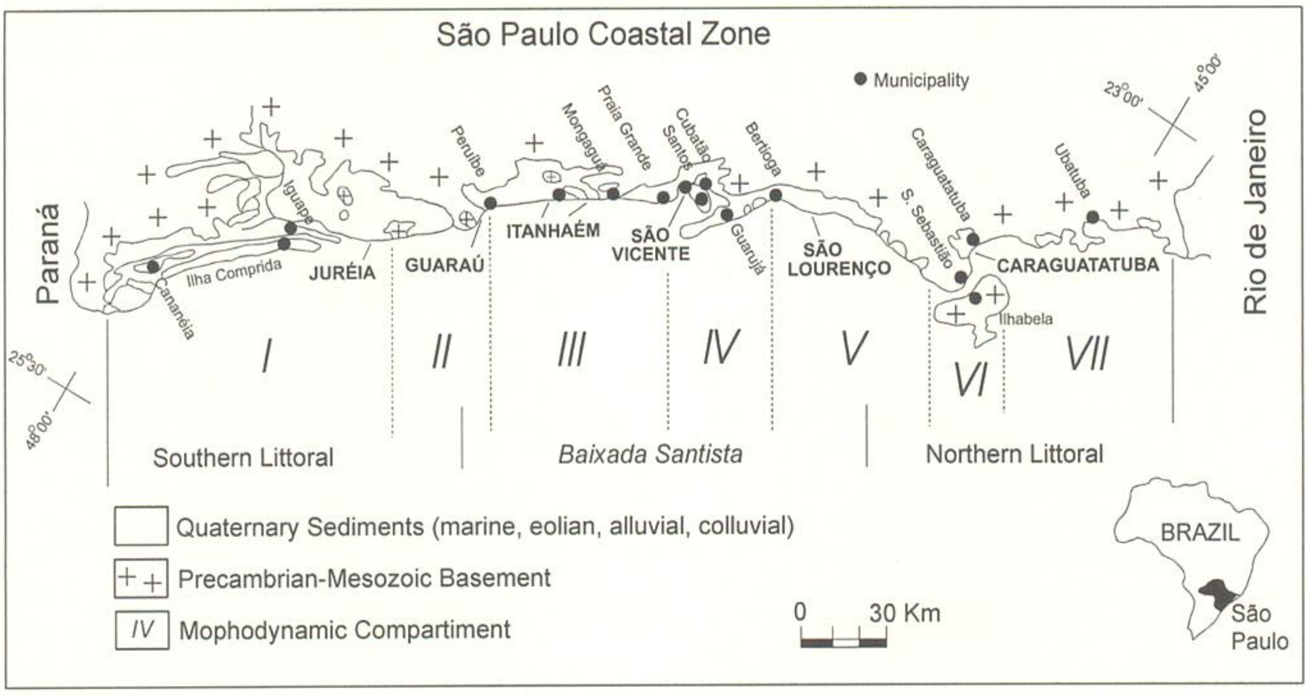

Figure 1 - Morphodynamic compartments and location of studied beaches (indicated in capital letter on the map)

Paulo coastal zone still conserve well-preserved ecosystems, such as large tracts of slope forest, "*Restinga*" vegetation (type of vegetation that recovers almost the whole coastal plains) and mangroves.

Impacts generated by those pressures on the São Paulo coastal zone are rather evident and translated into geological hazards such as coastal erosion, flooding and landslides; public health problems including soil and underground water contamination, air and surface water pollution due to inadequate disposal of domestic, hospital and industrial waste residues; and degradation of wide areas caused by disorganized urbanisation and industrial, port and mining activities (Souza, 2000).

Sea level data obtained from three tidal gauges placed at Ubatuba, Santos and Cananéia cities show an average sea-level rise about 30 cm for the last 100 years (Mesquita, 1994). Even without any forecasts on the future sea level variations in Brazil, some specialists believe that worldwide tendencies would be followed.

In order to exemplify the principal mechanisms associated to ongoing coastal erosional processes at the São Paulo shoreline, six beaches have been chosen (Fig. 1), among the most threatened beaches of each morphodynamic compartment, to be presented here as for their coastal erosion risk assessment, shoreline retreat rates and main causes of severe erosion.

COASTAL EROSION INDICATORS ALONG THE SÃO PAULO SHORELINE

Coastal erosion has become a constant threat that has been responsible for social and economic losses along the São Paulo coast (Souza & Suguio, 1995, 1996, in press; Souza, 1997, 1999; Souza & Alfredine, 2000). Monitoring studies on coastal erosion along the São Paulo shoreline have been carrying out by the author since mid the 80's, including almost 87% of the whole 430 km length of sandy beaches. Those studies has reveled that coastal erosion is the prevailing process on the majority of the beaches (Souza & Suguio, 1996, in press; Souza, 1997, 1999).

Quantitative data relevant for calculating beach sedimentary budget at São Paulo, such as sediment loads brought by rivers, wave climate and longshore drift rates, are not available yet. In order to circumvent these deficiencies, the approach used by Souza (1997) was to identify indicators of coastal erosion, as well their distribution along the shoreline and their prevalence in certain sites of the beach. Moreover, these studies have been driven towards the identification of the causes of the ongoing coastal erosion, within an integrated coastal management approach.

Eleven types of indicators of coastal erosional processes have been recognized along the whole São Paulo shoreline (Souza & Suguio, 1995, 1996, in press; Souza, 1997, 1999), as shown in Table 1. It is important to point out that these indicators are being identified in areas far from sites under complex dynamic processes, such as fluvial mouths and lagoonal outlets or entrances. These indicators result from many integrated and complex processes ongoing along beach and shoreline, which involve both natural and anthropogenic causes, of short and long-term scales of duration. Location where the ongoing coastal erosional processes are along the São Paulo shoreline can be found in Souza & Suguio (1996) and Souza (1997).

COASTAL EROSION RISK ASSESSMENT

Varnes (1984) defined Risk as the expected number of lives lost, persons injured, damage to property or disruption to economic activity due to a particular natural hazard.

The process of determining risk to the environment from natural mechanisms and anthropogenic stresses involves a great multiplicity of effects or endpoints, complexities and often many uncertainties.

. Coastal erosion is a natural hazard to any shoreline, in especial if sea level is rising. In other words, any element such as the own beach (environmental and aesthetic sense), people (not in loss of lives, but in tourist and leisure activities), properties,

Table 1 - Indicators of coastal erosional processes along the São Paulo shoreline (Souza, 1997)

	Indicators of Coastal Erosional Processes
(I)	Very narrow or no backshore zone due to the fact that higher waters of ordinary spring tides are reaching up to the uppermost portion of the beach
(II)	General and progressive landward shoreline displacement (retrogradation) trend, during the last four decades, with a clear decrease of whole beach width or more intensified on certain sites of beaches (urbanized or non-urbanized beaches)
(III)	Progressive erosion of eolian and Holocene marine deposits situated along the coastline, this does not resulting in erosional scarps or cliffs
(IV)	Severe erosion of Holocene eolian and/or marine deposits situated along the coastline forming cliff-bordering terraces or erosional scarps
(V)	Destruction and burial of mangrove and *Restinga* vegetation frontal strips adjacent to the beach, due to erosional retrogradation followed by landward shoreline displacement (in general for non-urbanized sites)
(VI)	Subaerial exposure of peat bog from ancient lagoonal or mangrove deposits on foreshore and upper shoreface surfaces
(VII)	Development of "artificial terraces" at the rough walls, along urban beaches, exposing successive beach sands layers alternated with embankment layers (only for urbanized beaches)
(VIII)	Persistent destruction of engineering works (parallel or non-parallel to the shoreline structures, houses, cemeteries and other buildings) built up over Holocene marine and/or eolian deposits, or on backshore, foreshore and surf zones
(IX)	Reactivation of ancient uplifted wave-cut terraces (2-6 m high above the present sea level) formed on crystalline basement rocks; or development of new wave-cut terraces on Holocene/Pleistocene marine deposits adjacent to the beach
(X)	Heavy minerals concentrations on foreshore zone, in general associated with other evidences of beach erosion
(XI)	Development of beach embayment formed by concentrated rip currents associated to stable presence of an updrift zone or a divergence center of longshore drift cells (two updrift zones side by side) placed at fixed sites on the beach

goods and economic activities will be prone to the coastal erosion, as well all of those elements will be highly vulnerable to this process. Although this process is able to occur all the time on a beach, its prevailing at the most part of the time will be a result of specific conditions, as mentioned above.

In order to establish a fast and practical coastal erosion risk assessment for the São Paulo coastline, Souza & Suguio (in press) have proposed a risk zoning based on two principal criteria: (*i*) *the total number (sum) of types of coastal erosion indicators found along the shoreline* (frequency among the 11 types described in Table 1); and (*ii*) *general spatial distribution (percentage of surface area) of coastal erosion indicators along the shoreline*, may be either one evidence or a group of them. Table 2 shows the arrangement between these criteria in order to obtain the risk classification matrix.

The risk assessment obtained for all beaches of São Paulo was presented by Souza & Suguio (in press). Results revealed that morphodynamic compartments I and II are at Very-High risk, morphodynamic compartments III and VI are at High risk, morphodynamic compartments IV and V are at Moderate risk and morphodynamic compartment VII is at Moderate-to-Low risk. Moreover, according to these results, about 42% of the São Paulo sandy beaches are at Very-High and High risk, including together about 60% of the sandy shoreline of São Paulo, among them almost 50% are non-urbanized areas.

The risk classification obtained for the six beaches studied here is presented in Table 3. It demonstrates that all of them are at very-high risk.

SÃO PAULO SHORELINE RETREAT RATES

The erosion effect of sea-level rise was expounded by Bruun (1962) and has since been widely promoted in the literature and a number of studies have purported to verify the theory (Healy, 1991). The essential concepts in the Bruun Rule are: (*i*) a nearshore-beach-dune system is assumed to be in dynamic equilibrium in 2-dimensional shore-normal profile; (*ii*) as sea level rises the equilibrium profile[1] is displaced landwards as the beach and dunes erode; (*iii*) sediment eroded from dunes and beach is transferred seawards and deposited on nearshore bottom, equal in volume to the material eroded; (*iv*) the sea floor is supposedly built up in direct proportion to the elevation increase in sea level in order to attempt to regain the same shape as the original equilibrium profile, thus maintaining a constant water depth along the profile; (*v*) the sediment is transferred offshore to a limiting depth and distance depending on wave environment and sediment grain size. To the above essential points, Hands (1983 *apud* Healy, 1991) adds two conceptually important ideas: (*vi*) not all the sediment undergoing erosion may be redeposited within the shore-normal profile as some may be lost to the active zone; (*vii*) material being redeposited on a beach and shore-normal profile may need to be "overfilled" in the beach renourishment sense. Despite of some authors have found some problems and conceptual difficulties in Bruun Rule, in general it has been well accepted and applied in many places. The advantage of this rule is that it provides a mechanism for obtaining quantitative estimates for erosion induced by past, present and future sea-level rise.

In order to find out further evidences of the long-term sea-level rise effects along the São Paulo coast, Souza (1997) carried out some studies on marine charts, that were published between 1938-1939 and 1993-1994. Results have shown morphological changes, which are indicated by two main tendencies: (*i*) a generalized displacement seawards of the isobath lines, and (*ii*) a generalized decreasing on nearshore-inner continental shelf slope. These geomorphic changes appear to mirror the Bruun Rule concepts.

Table 2 - Coastal erosion risk classification matrix (Souza & Suguio, in press).

Total Number of Coastal Erosion Indicators	Spatial Distribution on the Beach				
	> 60%	41 – 60%	21 – 40%	≤ 20%	
10 – 11	*Very-High Risk*	*Very-High Risk*	*High Risk*	*High Risk*	
7 – 9	*Very-High Risk*	*High Risk*	*Medium Risk*	*Medium Risk*	***RISK***
4 – 6	*High Risk*	*Medium Risk*	*Medium Risk*	*Low Risk*	
1 – 3	*Medium Risk*	*Medium Risk*	*Low Risk*	*Low Risk*	***CLASSES***

Table 3 - Risk classification obtained for some of the studied beaches at São Paulo (see Table 1 for description of coastal erosion indicators)

BEACH	Coastal Erosion Indicators											Distribution on the beach	RISK CLASSI-FICATION
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI		
Juréia	x	x	x	x	x			x		x	x	80%	*Very-High*
Guaraú	x	x	x		x			x	x	x	x	95%	*Very-High*
Itanhaém	x	x	x	x	x		x	x	x	x	x	90%	*Very-High*
São Vicente	x	x	x				x	x	x	x	x	100%	*Very-High*
São Lourenço	x	x	x	x	x		x	x		x	x	90%	*Very-High*
Caraguatatuba	x	x	x	x	x	x	x	x		x	x	90%	*Very-High*

Bruun (1983, 1988) reviewed conditions for use of his rule, and presented a predictive model whereby the shoreward recession distance "S" (meters retreat per 100 years), of the equilibrium profile following a rise in sea level of elevation "a" (given in meters of rise per 100 years) is related to "h", the maximum depth of exchange of material between nearshore and offshore inner shelf (m), and "l", the offshore distance limit of exchange (m), such that:

$$S = a \,.\, l/h \,.$$

For the practical application of Bruun Rule, determination of the appropriate limit of exchange depth and its offshore extent is one of the most perplexing problems. Healy (1991) presents a wide discussion about these problems and also other concepts that have been introduced by other authors concerning the Bruun Rule. Bruun (1962, 1988) suggested that a typical depth for the limiting depth for active transport of the eroded material offshore by wave action would be between 13-18 m. Bruun[1] (1988) further suggests that it usually be possible to evaluate the outer limit of exchange by results of sedimentological investigation, maintaining that bottom material normally decreases in size oceanward. Many authors have found beach sands move offshore still in the zone of wave influence at about 20-40 m depth (Healy, 1991).

Many authors have tested the Bruun Rule through both laboratory and field experiments and they have conclude the rule is valid (Schwartz, 1967; Rosen, 1978; Dubois, 1975; Bird, 1986; among others). Rosen (1978) demonstrated that the erosion rate predicted by the Bruun Rule fits the long-term measured rate with a 3% error.

Estimates of shoreline retreat based on the Bruun Rule are calculated for six cross-shore transects along the São Paulo coastline (Table 4). They are the most representative profiles in each morphodynamic compartment, once they have exhibited the largest seaward displacement of the isobaths, and because they are related to the six beaches studied here - Juréia, Guaraú, Itanhaém, São Vicente, São Lourenço and Caraguatatuba (Fig. 1) – which correspond to the most threatened beach in each compartment. In Table 4 are presented two different values for "l", which have been obtained from marine charts edited in 1938/1939 and 1993/1994. Values of "a" and "h" were considered constant for both periods. Based on sedimentological data it is assumed here 20 m depth as a reasonable value for "h". Shoreline recession or retreat rates ("S") were converted on meters per year. "Sm" is the arithmetic average between the both values of "S", and it corresponds to the average erosion rate obtained for a period as long as 56 years. The term "DS" results of the difference between the two values obtained for "S", and it corresponds to the erosion rate trend for the analyzed period. Positive sign of "DS" means that the rate is rising up.

Sea-level rise rate in Santos area is 0.11 m/century (Harari & Camargo, 1995). It is clearly lower than the rates obtained for the other sites of the São Paulo coast. As discussed by Souza (1997), sea-level rise in Santos area would be higher than the values obtained by Harari & Camargo (1995). Tidal gauge is placed in an island inside the estuary, thus its records would be affected by any change in water level inner channels. Disturbances could be caused by many natural or human interference, such as subsidence (estuaries are places under permanent subsidence),

[1] Bruun (1988) defined an equilibrium beach as a "statistical average profile which maintains its forms apart small fluctuations including seasonal fluctuations".

Table 4 - Estimates of shoreline retreat for São Paulo coast calculated through Bruun Rule: S = a . I/h (S = shoreline recession; a = sea-level rise per 100 years; h = maximum exchange depth of material between nearshore and inner shelf; I = distance offshore to h). Location of beaches-transects is in figure 1.

Morpho-dynamic Compartment	Profile	a (m/century)	I (x 10^3 m)		h (m)	S (m/year)		Sm (m/year)	ΔS (m/year)
			1938-9	1993-4		1938-9	1993-4	1938-94	1938-94
I	J	0.4*	8.7	15.7	20	1.74	3.14	2.44	+ 1.4
II	Gr	0.4*	9.0	14.5	20	1.80	2.90	2.55	+ 1.1
III	IT	0.3**	10.1	11.2	20	1.52	1.68	1.60	+ 0.16
IV	SV	0.3**	13.0	13.7	20	0.72	0.75	2.00	+ 0.03
V	SL	0.3**	4.3	15.8	20	0.24	0.87	1.51	+ 0.63
VII	CG	0.3*	20.3	22.6	20	3.05	3.39	3.22	+ 0.34

Where:
J – Juréia; Gr – Guaraú; IT – Itanhaém; SV – São Vicente; SL – São Lourenço; CG – Caraguatatuba.
(*) Data from tidal gauges placed at Cananéia (Compartments I and II) and Ubatuba (Compartment VII) obtained by Mesquita *et al.* (1995).
(**) Average rate of sea-level rise calculated for the State of São Paulo (Mesquita, 1994).

silting processes, and effects of dredging and mining of sediments from rivers and tidal channels. On basis of this, it was assumed a sea-level rate of 0.3 m/century for the calculations of shoreline retreat in Compartments III, IV and V, once it is the average rate for the whole São Paulo coast (Mesquita, 1994).

Despite of likely errors, the results demonstrate that along the whole São Paulo shoreline erosional processes enhanced between 1938 and 1994. Values of "Sm" indicate high average rates of shoreline recession of 1.51 m/year (Compartment V) up to 3.22 m/year (Compartment VII).

Paskoff (1979 *apud* May & Schwartz, 1981) has classified as "rapid erosion" values higher than 0.10 m/year of shoreline retreat for Tunisian coast. May & Stapor (1996) have obtained high shoreline retreat rates of 5-7 m/year (over the period 1920-1971) for the South Carolina coastline. High rates of landward shoreline displacement, up to 3.0 m/year, have also been recorded by Robichaud & Begin (1997), along the eastern coast of Canada, where, as at the São Paulo coast, tidal regime is microtidal and ongoing sea-level rise is between 20 and 40 cm/century.

Comparing S(1938-1939) and S(1993-1994) and "DS" values, it is clear that shoreline recession rates have been relatively stable at the morphodynamic compartments III, IV and VII, although they have been rising a little. The highest rate is found at the morphodynamic compartment VII (3.39 m/year) in 1993, while the lowest one is at the morphodynamic compartment V in 1939 (0.24 m/year). Values of "DS" indicate that the highest rising rate of shoreline recession is at morphodynamic compartments I (+1.4 m/year) and II (+1.1 m/year). Therefore, important changes appear to have occurred in morphodynamic compartments I and II. At first, it could be attributed to anthropogenic interference, as it is assumed for the Guaraú Beach (Fig. 2), which occupation has increasing since the 1980's. Nevertheless, it is unreal for the other two beaches of this compartment and the whole compartment I. Both of them have undergone local and soft urbanisation, once they include wide areas requiring environmental preservation and conservation, such as the Environmental Protection Area of Ilha Comprida and the World Natural Heritage of LAGAMAR that includes the whole Estuarine-Lagoonal Complex of Cananéia-Iguape (compartment I), and the Ecological Station of Juréia-Itatins (Juréia Beach and the whole compartment II, except the Guaraú Beach). It is important to notice that ongoing severe erosion is occurring even on non-urbanized sites of these compartments.

Recent studies carried out at the Juréia Beach indicate that between 1973 (1973-topographic chart) and 2001 (field measures with GPS–Global Positioning System), the shoreline underwent a landward retrogradation of about 400 m. Figure 3 shows the lower foreshore at Juréia Beach, where an ancient *Restinga* forest was destroyed and buried by beach sands. In this place, a 300 m width-strip of Holocene

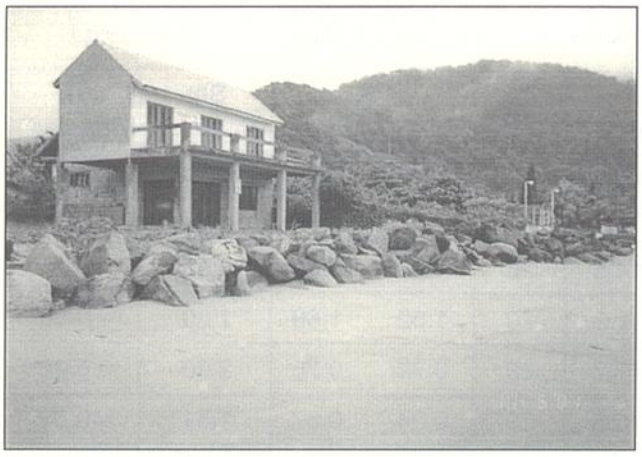

Figure 2 - Severe coastal erosion on Guaraú Beach (central sector). This site is northward from the stone-groin placed at Guaraú River mouth.

Figure 3 - Severe coastal erosion on Juréia Beach. This place is at the central sector of the beach, where Holocene beach ridges and dunes used to outcrop some years ago. *Restinga* trees are being buried by foreshore sands due to rapid shoreline retreat, that is about 400 m for the last 28 years in this site.

marine terrace and dunes has been eroded. This result means a rate of 11.4 m/year, which is about 4.7 times higher than the average rate obtained by using the Bruun Rule. However, it must not to be considered as a pattern for the whole São Paulo shoreline.

Morphodynamic compartments III, IV, V and the southern part of the compartment VII have undergone intense urbanisation during these 56 years. Therefore, it appear that human interference has not been played an important role on the shoreline retreat during the analyzed period, once the values of shoreline retreat rates have kept similar.

CAUSES OF COASTAL EROSION ALONG THE SÃO PAULO SHORELINE

The causes of coastal erosion along the São Paulo shoreline are attributable to natural processes enhanced by anthropogenic activities, or *vice-versa* (Souza & Suguio, 1995, 1996, in press; Souza, 1997, 1999). Tables 5a and 5b encompass respectively a set of probable natural and anthropogenic causes for coastal erosion at the São Paulo shoreline, their effects and associated processes. Table 6 shows the set of causes that are assumed for the six studied beaches, which main mechanisms are discussed as follows.

a) Juréia Beach

As commented above, this high-energy dissipative beach belongs to the environmentally most well-preserved sector of the São Paulo littoral. Sedimentary sources appear to be the most important of the whole coast, due to some reasons: coastal plain is the largest of the State; Ribeira de Iguape River is the biggest one of the state coast; human occupation is rare and confined to small places; frontal dunes (inactive) and marine terraces are very well-preserved; sedimentary interchanges occur between Ilha Comprida and Juréia beaches, the former being an important source for the last one (Souza, 1997). Even so, as Juréia Beach as Ilha Comprida Beach are undergoing severe erosion even in areas far from the occupied sites (Fig. 3). This phenomenon demonstrates that natural processes are very important and they can lead up to 100% of the coastal erosion on this beach (Table 6).

The most important causes of beach erosion at Juréia Beach appear to be: sea-level rise and its effects, coastal circulation dynamics associated to the "stable focus effect", and "hydraulic mole – bypassing" effects played by the Ribeira de Iguape River.

b) Guaraú Beach

This low-energy dissipative to intermediate beach started to be occupied in mid the 1960's. First of all there was a large strip of sands sharing a few houses from the beach. Nowadays, however, some houses are on the foreshore (Fig. 2) and they are being threatened by wave attack.

Guaraú River mouth used to migrate sometimes northwards, sometimes southwards, threatening the inhabitants and their properties. So, in mid the 1970's a big stone-groin was built on the left margin of the river, in order to stabilize the mouth at the southern ending of the beach. This inadequate structure has

Table 5a - Natural causes of coastal erosion, their most important effects, and associated processes (Souza & Suguio, in press)

Factors and Causes	Effects and Associated Processes
(1) Coastal circulation dynamics: presence of divergence centers of longshore drift cells in certain places of the beach ("stable focus effect" associated to wave refraction).	At updrift zones of longshore drift cells predominate erosional processes. When two updrift zones occur side by side (divergence center), rip currents are formed, causing accentuated erosion and embayments on the beach.
(2) Beach morphodynamics: mobility, susceptibility and natural vulnerability to beach erosion.	Transitional beaches present greater mobility, being more susceptible to erosion than the others; dissipative beaches are more susceptible to erosion than reflective beaches (the latter represents the most erosional stage of the former); low energy beaches are less susceptible than the others states.
(3) Long-term sea-level rise is an ongoing process on rates of 30-cm rise in the last 100 years.	Accelerated coastal erosion could be in part a consequence of long-term sea level rise, resulting in shoreline retrogradation and beach width decreasing.
(4) Effects of long-term sea-level rise (Bruun Rule): beach erosion and deposition of sediments on adjacent nearshore and continental shelf.	Part of the sand eroded from the beach is transported seaward, and a large amount of them are deposited and retained there. These processes occur as beach response towards the maintenance of its equilibrium profile.
(5) Holocene evolution of the coastal plains: negative sedimentary budget, dynamics of coastal current circulation.	The evolution of the coastal zone throughout mainly the Holocene could interfere in the present sedimentation dynamics due to amount of available sediments trapped within the coastal system.
(6) Naturally inefficient sediment supply coming from the continent, beaches and nearshore zone; or losses of sediments towards them.	The permanent supply of sediments is very important in order to maintain the beach sedimentary budget in equilibrium, mainly under sea-level rise conditions. If sedimentary supply is insufficient, erosion will ensue.
(7) Short-term sea-level rise caused by combined effects of: storm surges (meteorological tides) and spring tides; esteric effect, due to the occurrence of a greater volume of warmer sea water of the Brazil Current (in April/May) and cold fronts passage.	These combined effects can rise sea level higher than 2.0 m, flooding beaches and shifting the surf zone landward, causing severe erosion along beaches and destroying man-made structures along the shoreline.
(8) "Sand Bypassing effect", "Cape effect" and "Hydraulic Mole effect", all of them caused by headlands/promontories or tidal/rivers mouths or entrances, which presence interrupts and deflects shore drift seawards.	Where headlands or promontories, large river mouths or tidal inlets/entrances are present, longshore drift is interrupted and sediments are diverted seaward by rip currents and/or they are trapped updrift the interrupted site. Consequently, erosion occurs downdrift of the interrupted shoreline, also resulting in an insufficient sediment supply.
(9) "Trapping effect" due to the presence of wide bays, tidal inlets/entrances and river mouths.	Some wide bays are natural sediment traps, mainly whether they are downdrift of coastal currents. Because an amount of sediments are trapped inside them, it cause erosion on surrounding beaches. Where tidal or river flows are stronger than longshore currents ("hydraulic mole effect"), sands are trapped on updrift-side, causing downdrift starvation and erosion.
(10) Contemporaneous negative sedimentary budget originated by natural processes	The sedimentary deficit on a beach can be cause and effect of coastal erosional processes. All natural factors mentioned above also induce the negative sedimentary budget on the beaches

Table 5b - Anthropogenic causes of coastal erosion, their most important effects, and associated processes (Souza & Suguio, in press).

Factors and Causes	Effects and Associated Processes
(11) Intense urbanisation of the coastline with: destruction of dunes and/or eolian deposits and Holocene marine terraces, with eventual occupation of the backshore zone.	These interventions cause erosional processes due to the elimination of some the most important sand sources. Besides, in general, walls are built in order to share urban area from the beach. They may interfere on coastal currents and sedimentary processes patterns, especially during storms and spring tides. Besides, these areas are prone to flooding.
(12) Construction of hard or soft sea/land interface structures, placed parallel and non-parallel to the shoreline, on the upper zone of the beach or throughout the beach and surf or breaker zones.	Groins, jetties, drainage channels (non-parallel), seawalls, revetments, bulkheads, embankments (parallel), breakwaters and other structures interfere on coastal currents circulation pattern, thus modifying the wave approach angle, and changing the sedimentary budget. In general, they enhance shoreline erosional processes.
(13) "Trapping effect" associated to artificially structures.	Non-parallel to the shoreline man-made structures (groins, jetties etc.) are effective sand traps, because they interrupt longshore currents and hold sediments on updrift-side, causing lee-side starvation and erosion.
(14) Sand exploitation of the beach through: illegal mining, beach cleaning, and dredging of streams.	These activities cause erosion on the own beach and on neighboring beaches, since they alter beach sedimentary budget.
(15) Mining of fluvial sands (channels and mouths), dredging in tidal channels, and on continental shelves.	They disturb regional sedimentary budget and produce erosional processes on fluvial, estuarine, and lagoonal systems. Consequently they cause beach erosion.
(16) Conversion of lagoons, estuaries, marshes, swamps, mangrove swamps, fluvial plains and tidal flats into building sites (reclaimed areas); changes in drainage pattern.	This affects the regional sedimentary budget, because sediment sources decrease, increasing erosional processes inner the coastal system and, consequently, on the beach. Besides, many of these reclaimed areas are prone to flooding.
(17) Contemporaneous negative sedimentary budget due to anthropogenic interventions	Sedimentary deficit on a beach can be cause and effect of erosional processes. All anthropogenic factors mentioned above also induce negative sedimentary budget in the beaches.

interrupted the southward longshore currents, it leading to the total filling of the beach on updrift side of the groin. Consequently, severe erosion started on downdrift beach. In addition to this, as much sediment has kept retained updrift, severe erosion has also been migrating northwards. At present, the groin is almost totally collapsed and buried by sand beaches. Other natural processes are also important there, such as sea-level rise and "bypassing – cape" effects (northwards coastal currents travelling from the Compartment I are diverted seawards on this sector of the shoreline).

c) Itanhaém Beach

This high-energy dissipative beach is also prone to the combined effect of many natural processes and human interference (Fig. 4). Itanhaém Beach has been playing a role of bypassing zone ("bypassing effect") of sediments between Peruíbe and Praia Grande

Table 6 - Causes of the ongoing coastal erosion at the studied beaches (see tables 5a and 5b for descriptions of the causes)

BEACH	Causes of Coastal Erosion																
	NATURAL										ANTHROPOGENIC						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Juréia	x	x	x	x		x	x	x	x	x							
Guaraú	x		x	x	x		x	x		x	x	x	x				x
Itanhaém	x	x	x	x	x	x	x	x		x	x	x		x			x
São Vicente	x		x	x			x		x	x	x	x	x	x	x	x	x
São Lourenço	x	x	x	x		x	x	x	x	x	x	x	x			x	
Caraguatatuba	x	x	x	x		x	x	x	x	x		x	x	x	x	x	

beaches, since the Pleistocene time until nowadays, with longshore currents driving predominantly northwards (Giannini, 1987; Souza, 1997). It may be verified by the quite different spatial arrangement of Quaternary deposits between Peruíbe, Itanhaém and Praia Grande coastal plains. Pleistocene terraces almost outcrop at the present shoreline at Peruíbe coastal plain, once Holocene beach ridges occur in a narrow frontal strip. This figure changes gradually towards up to Praia Grande coastal plain, where Holocene beach ridges outcrop on a wide area, which certainly has been downdrift zone during all the Holocene time. At present, Itanhaém Beach is still an important sedimentary source for Praia Grande Beach, as concluded by Souza (1997). In addition to this, the rocky-promontory located between Peruíbe and Itanhaém beaches plays a role of "cape effect", it blocking sediment transportation and diverting sands seawards.

Human interference along this beach has caused the destruction of frontal Holocene marine deposits and dunes. However, backshore zone was not originally occupied. Nowadays, many sites are severely threatened by erosion forming cliffs on Holocene deposits (Fig. 4). Sand mining from this beach is also an important cause of the ongoing negative beach sedimentary budget. As a consequence of severe erosion, engineering works have been made, as stone-revetments and concrete-walls.

d) São Vicente Beach

Until mid the 1960's, São Vicente and Santos beaches used to have free interchanging of sediments, sands transported from Santos towards São Vicente Beach by westward longshore currents. In this time, this connection was interrupted because the Porchat Island was artificially connected to the continent. After that, São Vicente Beach had started undergoing a progressive erosion, because its main sand source used to be the Santos Beach. Erosional process had been enhancing due to many other human interventions, such as: heavy urbanisation of the shoreline, including over backshore zone; emplacement of five stone-groins along the São Vicente Beach, in order to reduce the erosion; and implantation of a long stone-groin, in 1973, at the western ending of the Santos Beach, in order to guide a sewage pipeline (Souza, 1997, 1999; Souza & Alfredine, 2000). After those, westward longshore currents along the Santos Beach had started returning towards inner bay and depositing there. Although all of these interventions have resulted in negative impacts for the São Vicente Beach, they are responsible for the highly positive sedimentary budget at Santos Beach.

São Vicente Beach used to be low-energy dissipative, but nowadays its extremely eroded profile on updrift side exhibits low-energy reflective

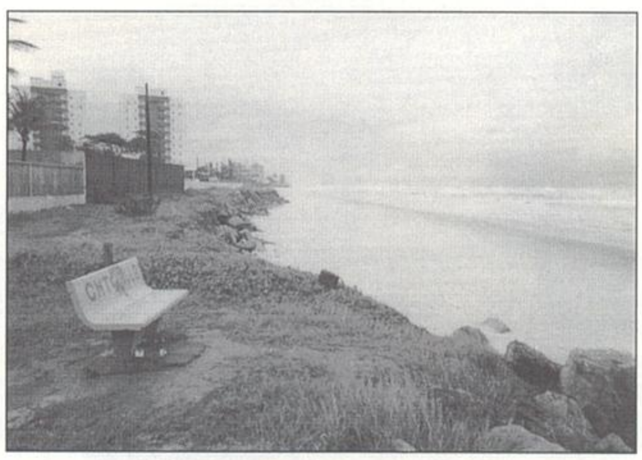

Figure 4 - Severe erosion on Itanhaém Beach (central sector). Note that the embankment and the stone-revetment placed there in order to protect the beach against erosion are being destroyed.

characteristics (Fig. 5). Man-made structures (groins, stone-revetments and concrete walls) have been accelerating erosional processes along the whole beach.

e) São Lourenço Beach

This intermediate to dissipative beach is threatened by natural erosional processes as the other are. However, it has also undergone some human interventions. The urbanisation of this area is relatively recent, since the 1980's.

Apparently, the most important natural causes are: sea-level rise and its effects; local and regional coastal dynamics processes; the "trapping effect" has played by Santos Bay (coastal currents traveling northwards from the southern coast enter right inside the Santos Bay, which transported sediments are "captured" and deposited there) that is summed to the "cape effect" has played by the Santo Amaro (Guarujá) Island. Thus, beaches at the southern part of the morphodynamic compartment V are updrift section of those interrupted coastal currents driving northwards. In addition to this, São Lourenço Beach does not have rivers as sedimentary source, but only a few streams flowing to the beach. Occupation of the shoreline and destruction of frontal Holocene marine deposits and small dunes are the most important anthropogenic causes of erosion (Fig. 6). There is only one undone man-made structure (stone-groin) placed at its southern endpoint, where would be implanted a marine.

f) Caraguatatuba Beach

Caraguatatuba Beach is threatened by natural processes and anthropogenic interference, each one contributing with an important role. This beach presents mixed morphodynamics, typical of a headland-bay beach, with low-energy dissipative characteristics at its ending sections, and intermediate state along the remainder beach. An extensive sandy tidal flat lies at its southern ending, from the Juqueriquerê River mouth southwards. Net longshore drift is southward along the beach, though there are small longshore cells driving

Figure 5 - Severe erosion on São Vicente Beach (central sector). Stone-groins and -revetment and concrete-wall are not able to protect the beach against erosion. Porchat Island, that was artificially connected to the continent, is at the upper-right side of the photo.

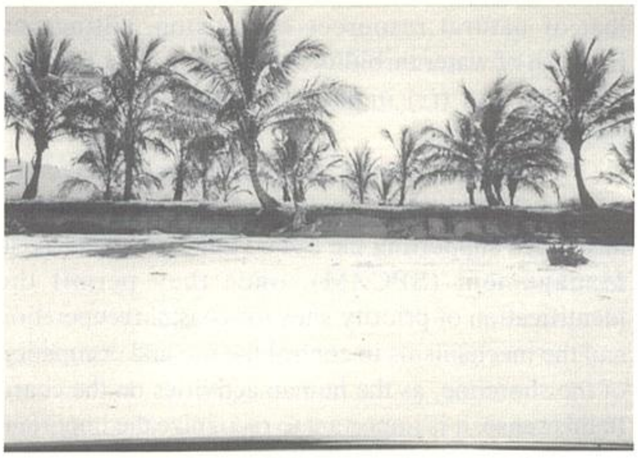

Figure 6 - Coastal erosion on São Lourenço Beach (central-northern sector). Small cliffs are cutting Holocene marine deposits and embankment layers.

in opposed direction (Souza, 1990, 1997). Urbanisation has been keeping far from the shoreline. At present, accelerated coastal erosion is in progress in many places of the beach. These processes may be explained by the overlap of anthropogenic causes on presently occurring natural ones (Souza, 1990, 1997, 1999).

Caraguatatuba became known in 1967, when occurred a catastrophic event of landslides and close to 2 millions tons of materials buried the urban center and reached the coastline (Souza, 1990). Right later the catastrophe, there was an intense silting process in the northern sector of the beach, causing beach widening and growing southwards sandy spits. However, the replacement southward of all those materials occurred rapidly, so that in 1975 stone-groins and stone-jetties were implanted there, in order to detain beach erosion. With the placement of all of these cross-shore structures, southward longshore currents have started being sectioned into smaller cells. Consequently, sands had been trapping on the updrift side of each structure, and intense erosional processes had taken place on the downdrift side. The large volume of sediments transported southwards were deposited on the sandy tidal flat. Until the late 1970's,

Figure 7 - Severe erosion on sandy tidal flat of Caraguatatuba Beach (southern sector). Ancient mangrove deposits are outcropping on upper tidal flat and mangrove trees are being buried by sands due to rapid shoreline retrogradation.

tidal flat was bordered by a 40 m width sandy beach, which by the 1980's had become a 12 m width beach of coarse to very coarse sands (Souza & Furtado, 1987). Presently, the beach of fine sands is not wider than 2 m. The Juqueriquerê River, that is the largest one in this region and also the most important source of sediments to the local beaches, has never undergone human-induced changes that could alter the beach sedimentary regime. "Stable focus" effect, played by a divergent center of two longshore currents located between the Juqueriquerê River mouth and the southern beach endpoint (Souza & Alfredine, 2000), appears to be the most important natural cause of ongoing severe erosion along all the beach bordering sandy tidal flat (Fig. 7). Theoretically, erosion could not occur on this place, because it is downdrift zone of net longshore drift and Juqueriquerê River is quite near.

CONCLUSIONS

Shoreline recession rates for six of the most threatened beaches of São Paulo, calculated on basis on the Bruun Rule, reveal concerning values for two of them, higher than 1.0 m/year, both beaches lying on non-urbanized areas. Results obtained from coastal erosion monitoring suggest that natural mechanisms would be leading coastal erosional processes within an important role, although human-induced changes certainly are accelerating them or introducing new effects or impacts on beaches. Natural mechanisms include: sea-level rise and its effects on nearshore sedimentation; present and Holocene coastal circulation dynamics; particular effects associated to the coastal geomorphology ("cape", "hydraulic" and "trapping" effects); coastal currents circulation ("stable focus" effect); and other effects of global warming and climate change (storms). Anthropogenic causes are mainly associated to the shorefront urbanisation, placement of man-made hard structures and beach sand mining.

Effects of the real ongoing shoreline recession along the State of São Paulo shoreline are felt through the presence of eleven types of indicators of coastal erosion. Moreover, many impacts due to beach erosion may be identified, such as: (*i*) chronic loss of lands and ecosystems; (*ii*) reduced supply of sandy sediments; (*iii*) destruction of human properties; (*iv*) increase of flooding by storm surge with associated wave attack damages; (*v*) lands and facilities impacted by storm-induced erosion; (*vi*) need of expensive engineering works and recuperation measures; (*vii*) lost of natural resources by erosion, silting and increase of water turbidity; (*viii*) scenic beach beauty collapse; and (*ix*) impacts in tourist activities and economic losses.

Comparative risk assessment carried out for the whole São Paulo shoreline, as well as the other studies, have been supporting the State Plan for Coastal Zone Management (SPCZM), once they permit the identification of priority sites for coastal recuperation and the mechanisms to control the use and occupation of the shoreline, as the human activities on the coast. In this sense, it is important to recognize the important role played by natural mechanisms, in order to avoid future coastal problems and to prepare for the uncertainties of the future. Besides, results of the risk assessment are inputs of a geoenvironmental information system for the Coastal Zone of the State of São Paulo (Project SIIGAL), which is in phases of implantation (Souza, 2000). This system will be integrated to the SPCZM and could help the municipalities to establish better rules and laws for the use and occupation of the shoreline.

Finally, it is important to emphasizes that superimposed on the long-term trends of shoreline behavior, there are likely local erosional phenomena acting on time scales of decades, which can cause severe retreat of the shoreline even in areas otherwise characterized by long-term trends for progradation.

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