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QUANTIFYING HARDNESS OF MORPHOSCULPTURAL UNITS TO ASSESS ENVIRONMENTAL FRAGILITY/SENSITIVITY: A CASE STUDY FROM SAO PAULO-STATE COASTAL AREA

ABSTRACT: FIERZ M.S.M. & ROSS J.L.S, *Quantifying hardness of morphosculptural units to assess environmental fragility/sensitivity: a case study from Sao Paulo-State Coastal Area.* (IT ISSN 0391-9838, 2019).

In principle, the coastal plains present the least resistance of materials as well as greater environmental fragilities. The objective of this study is to identify these differences along this plain in São Paulo state, with the use of accessible methodologies and material physical / chemical analysis. The highest points of material resistance are the highest points (SPODOSOL) of high soil organic matter (SOM – 90%), and iron (27%) contents as well as intense hardness, contrary to the hypothesis all coastal plain presents unconsolidated material and high fragility /sensitivity.

KEY WORDS: Morpho-structure; Morpho-sculpture; Geology; Geomorphology; Environmental Fragility / sensitivity.

INTRODUCTION

Brazil has approximately 8500 km of coastline in the South Atlantic. The coastal area is of great importance for the economic development of the country, especially as it presents ports of entry and exit of industrialized products and raw materials and for providing leisure for a large part of the population. However, the environmental fragility / sensitivity is highlighted by its dynamics due to the strong influence of atmospheric terrerstrial, marine and human factors. Geological characteristics, tectonic variations and exogenous processes shaped its current geomorphological setting. The geomorphology of Brazilian coast is quite diverse, presenting sectors with cliffs (sedimentary rocks), sectors with rocky cliffs (rocks of the crystalline complex) and sectors with extensive beaches and coastal plains (with unconsolidated sands) represented here by the coastal systems and processes of the Quaternary period. Coastal sectors of hard rocks appears when Precambrian igneous and metamorphic complexes reach the coastline and are exposed to open sea conditions, as happens in the SE, at the foot of the coastal mountains of Serra do Mar and Serra da Mantiqueira. Such areas, as with many other sectors of the Brazilian coasts, have a complex tectonic history that resulted in a horst and graben structure that configure the indented planform, with numerous islands and bays (Blanco-Chao & *alii*, 2014).

São Paulo state, where the study area is located, presents coastal morphologies corresponding to different rock formations, especially in Serra do Mar, a hill that separates the Continent from the coast. The coastal area is approximately 600 km long, presents part of the coast with inlets or small coves embedded in promontories of crystalline rocks. The northern and southern part of displays thick coast plains, so that the plateau is more distant from the coast. In this context, the study area called Peruíbe Cove is inserted, as shown in fig 1.

Theory of Dynamic Equilibrium (Hack, 1965), according to which differences of material composition as well as the processes directly affecting the geomorphological systems can define its resistance and the destructuring of its dynamic equilibrium, directly related to the Environmental Fragility sensitivity. In this way, the main objective of this study is to show the importance of relief compartmentalization to studying the differences of environmental Fragility/ sensitivity along Peruíbe coastal plain in São Paulo, through specific methodologies, physical and chemical analysis of the materials that compound the geomorphological compartments (geomorphological systems and subsystems).

According to (Brunsden & Thornes, 1979), the sensitivity of the landscape to changes is expressed with the similarity that is given by the transformations in the controls of the sys-

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The contents of this paper have been presented in the framework of the session S16 Coastal Geomorphology and Management (chairs: Prof. G. Mastronuzzi , Department of Earth and Geoenvironmental Sciences, Aldo Moro University, Bari, Italy and Prof. N. Chandrasekar, Manonmaniam Sundaranar University, India) at the 9th International Conference on Geomorphology that was held from 6th to 11th November 2017 at Vigyan Bhawan, New Delhi, India, in agreement with IAG - International Association of Geomorphologists and EGU - European Geosciences Union.

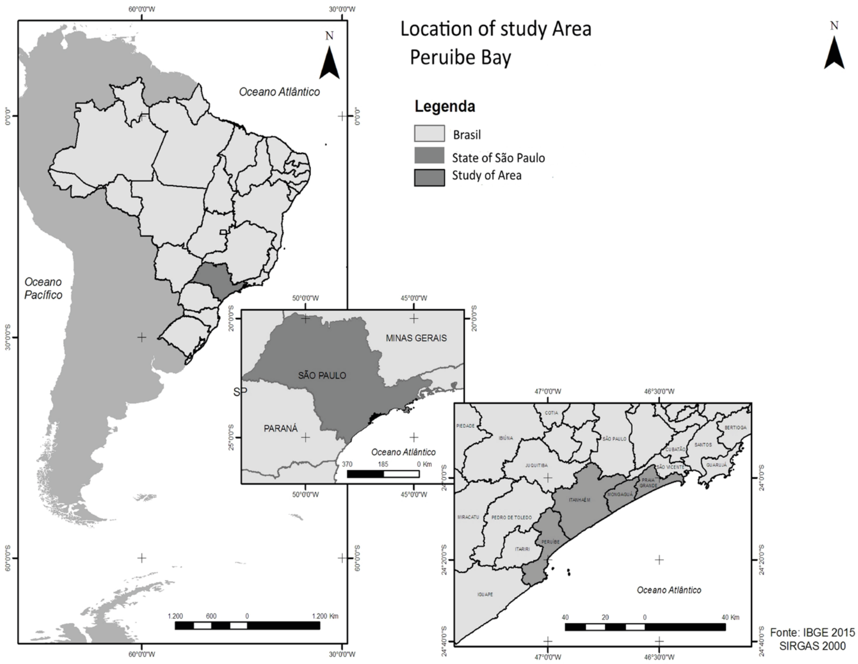

FIG. 1 - Location of Peruibe Bay.

tems that will produce a sensitive, recognizable and persistent response. The answer involves two aspects: i) the propensity for change, and ii) the system ability to absorb change.

Fragility/sensitivity is understood as the tendency of the relief to be altered from its dynamic equilibrium state easily, either naturally or due to artificial factors such as the anthropic ones. Environmental fragility/sensitivity represents the threshold between dynamic equilibrium and non-equilibrium (Thorn & Welford, 1994) in non-anthropogenic environments.

MATERIALS AND METHODS

For the subdivision of the geomorphological systems, we followed the (Ab'Saber, 1969) proposal for Quaternary research, which follows the sequence:

1) topographic compartmentalization in large geomorphological compartments;

2) surface structure of the landscape, chronology, and propositions interpretative in sequence of the paleo-climatic quaternary and morpho-climatic processes;

3) landscape physiology for morpho-climatic understanding and pedogenetic processes, in total action.

The second proposal was used by (Brunsden & Thornes, 1979), which is related to the delimitation of geomorphological subsystems in coastal areas, to elaborate the model in which coastal relief can be divided into two factors of propensity for change:

a) Fragility sensitivity subsystem of intense fragility/sensitivity – are highly sensitive to change impulses with rapid transition to other stages, filter the sudden changes and energy inputs by the variation of climate and sea level, among which are the fluvial channels as well as the river plains, intertidal plains, beaches; ephemeral processes and define subsystems of unstable dynamic equilibrium.

b) Resistant or non-intensive fragility/sensitivity subsystems – due to the higher distance from the direct attack areas of the energy inputs – are more resistant to sudden variations, undergo less intense changes and exhibit stable dynamic equilibrium.

The third used proposal was from (Ross, 1992) to relief compartmentalization called morpho-structures as resulting from endogenous processes and forms defined by lithology. Morpho-sculptures are the result of more recent processes of relief sculpture based on the (Penck, 1924) definitions for the elaboration of relief taxonomy and based too in (Tricrt, 1977) proposal for the elaboration of environmental fragility/sensitivity study, later adapted by (Fierz, 2008) research on the coastal plains. By understanding environmental fragility/sensitivity as the propensity to dismantle a system in a dynamic equilibrium, it is believed the "fragility/sensitivity of natural environments in face of human interventions is greater or lesser due to their genetic characteristics" (Ross, 1994).

According to (Kennedy & Chorley, 1971) and earlier systems classification defining aspects that characterize systems, the following points are important for the research focus: morphological systems representing forms; the process-response systems proving the degree of dependence between the systems relations between the process and the forms resulting from it, characterizing the system globalization; and the controlled systems constituting man's performance over the process-response systems. Its functionality depends on the magnitude and frequency of the inputs and outputs of internal changes of the systems that occur because of their self-regulation or negative feedback to create a state of equilibrium among various components of these process-response systems.

According to (Fierz, 2008), in this context, the study of the environmental fragility/sensitivity started from the focus on the importance of the dynamics in the nature and the interactions inherent in its response processes among system component elements. Any intervention in this dynamic results in integration changes of the elements or in the landscape constituent elements and consequently in its dynamic equilibrium.

The term "environmental fragility/sensitivity" can be conceived from the concepts related to the precepts of the general theory of systems, in which the elements of nature are considered as of mutual interaction, in which the meaning of "the whole is more than the sum of the parts" is identifying the systemic character. In this sense, the environmental fragility/sensitivity would be explained by the possible breaks in the interaction between the elements of the natural system.

Because of the understand environmental fragility/ sensitivity as the propensity to dismantle a system in a dynamic equilibrium, the "fragility/sensitivity of natural environments in face of human interventions is greater or lesser due to their genetic characteristics" (Ross, 1992). Based on the morpho-structure and morpho-sculpture concepts by Mecerjakov & Guerasimov, he elaborated a model of relief compartmentalization represented by 6 taxon, in which the scale variation and information detail allow the relief compartmentalization. Also starting from the precepts of Ecodynamics by (Tricart, 1977), elaborated an analysis model of environmental fragility/sensitivity, whose declivity variation and the changes made by humanity define the propensity transformations.

The idea of interaction of systemic analysis, wherewith systems acquire functionality and process-response effect, which depend on the input magnitude and frequency and the system internal changes, occurs because of their self-regulation or negative feedback (Kennedy & Chorley, 1971) define different equilibrium classes enabling the evolution of process-response system.

- Static balance: there are no changes in time.
- Constant equilibrium state: occurs in the variation over an average condition of constancy.
- Dynamic equilibrium: variation over average change conditions.
- Equilibrium in change: static equilibrium, separated by episode of changes.

In this way, each system presents its own dynamics characteristics, as well as different levels of fragility/sensitivity, which can be evaluated according to their balance and propensity to change over time or in the presence of external disturbances.

A method used to verify the propensity for changes along the coastal plain was Stolf penetrometer, an instrument that allows the analysis of soil compaction up to 1 meter deep. This instrument is used to measure soil compaction along the plains and inlets of marine deposits. It has dynamic penetration characteristics and is commonly called dynamic penetrometers: the rod penetrates the soil through the impact of a weight falling from a constant height, in free fall. The number of impacts required to penetrate the thickness of a given layer is counted (Stolf, 1991).

The model used was the planalsucar (Stolf, 1991). Following the specifications of the American Society of Agriculture Engineers, it features the following characteristics:

Table 1 - Specifications of the American Society of Agriculture Engineers

weight that causes the impact - 4kg;
free fall course - 70 cm;
cone base area - 1.29 cm2.
Unit used in scientific articles, MPa, for g = 10 m / s2:
R (MPa) = 0.56 + 0.689 × N (impacts / dm),
that is, R (MPa) = 0.1 R (kgf / cm 2).
Exemplifying: with two impacts, the depth ranged from 11 to 15 cm.
N (Impacts / dm) = 10 × 2 / (15-11) = 5, i.e. resistance = 5 impacts / dm;
R (kgf / cm 2) = 5.6 + 6.89 × 5 = 40.1, i.e. strength = 40.1 kgf / cm 2;
R (MPa) = 0.1 × 40.1 = 4.01, i.e., strength = 4.01 MPa.

Another method is the Grounded Penetrating Radar (GPR). This system consists of acquiring information from the subsurface of the Earth with a radar sensor that could track the underground. This range depends on the type of antenna coupled to the equipment to obtain a higher or lesser depth, as well as resolution in the differentiation of the deposition layers of sedimentary material. This type of radar does not reach high depths, it reaches up to 50 meters. In this study two types of antennas were used, one of 70 MHz, which reaches a greater depth, but the sharpness of the produced image is smaller and another of 200 MHz reaching lower depth and higher resolution.

Field Work. Field stretches in which the resistance tests of sedimentary cover with the penetrometer were carried out contemplated information along the whole plain. Significant samplings were carried out throughout the plains area to establish degrees of resistance, and subsequently environmental fragility / sensitivity. In fig. 2, it is possible to observe the stretches of field traveled, and later the graphs elaborated with the resistance data of the soils in them as well as their descriptions.

RESULTS

The studied area can generically be represented by relief compartmentalization presented by (Ponçano & *alii*, 1981), in which the authors classify three compartments of coastal region, high hill, hills, and coastal. In this study it was chose to call them coastal morpho-structures (macrocompartments). With greater detail, it is considered the morpho-structure, denominated coastal plain can be subdivided into morpho-sculptures (smaller geomorphological compartments) commonly denominated as: beach, fluvial plain, fluvial terrace, intertidal plain, marine terrace, fluvial-marine plain, marine terrace covered by sand dunes and cords, hills, and coastal hills. Thus, in this study, it was elaborated the representation of these characteristics of geomorphological compartments or subsystems occurring in the coastal region of São Paulo state are represented in the geomorphological map.

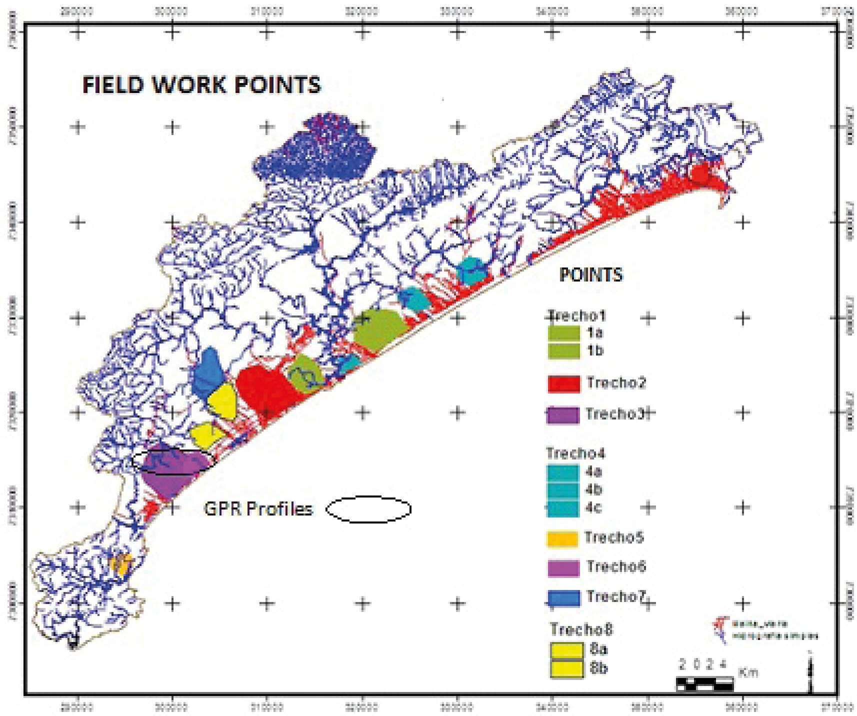

FIG. 2 - Localization of sampling points in Field.

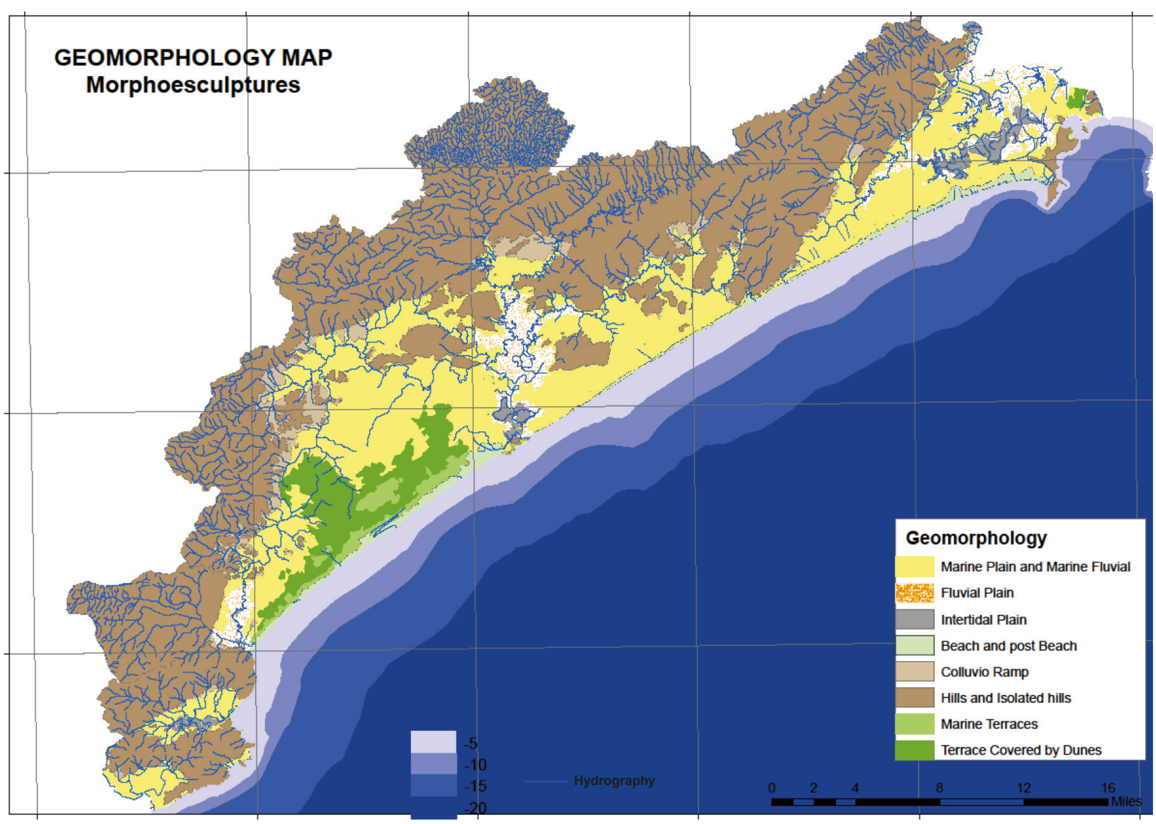

FIG. 3 - Geomorphology of Periube Bay.

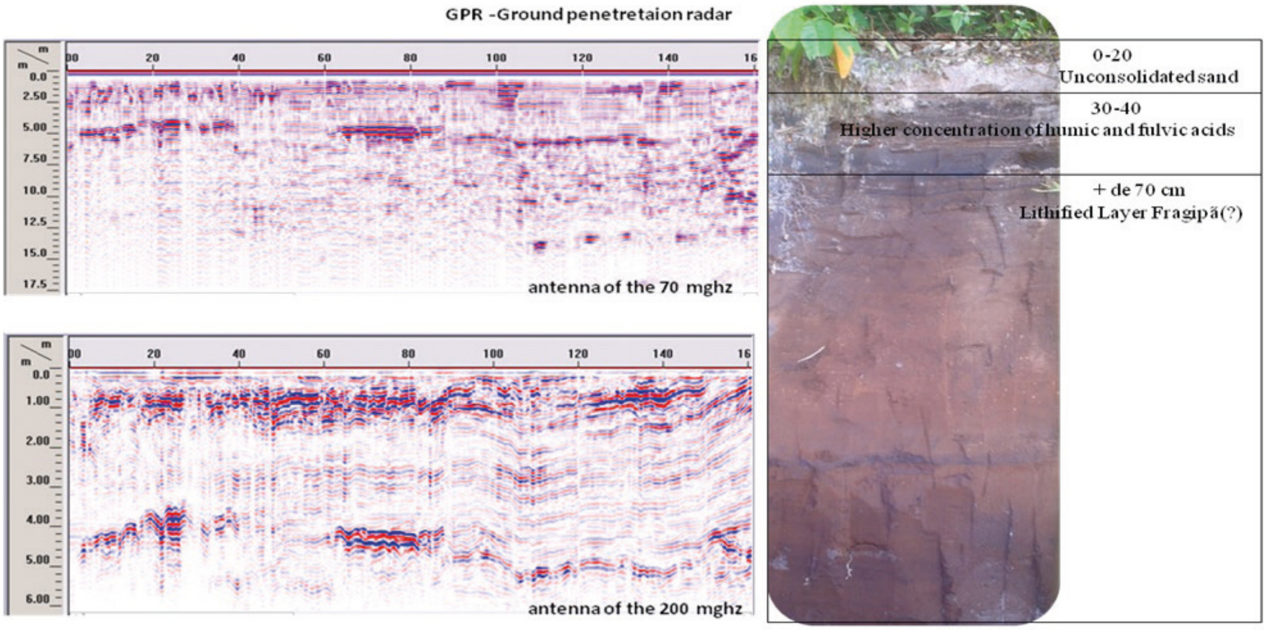

FIG. 4 - GPR Images and Soil Profile.

Regarding the composition of each compartment materials, it has the following composition: the beach consists of fine to very fine sand in the beaches that present dissipative characteristics and low slope. On these sands, the quartzarênic neosol is developed. On beaches with reflective characteristics of higher slope, the sands are thick to very thick.

The marine and fluvial marine plains are covered by low beach ridges and by partially flooded intercordion depressions. The cordless coastal plains are associated with Santos's Transgression, are restricted in distribution and are very difficult to identify.

The highest points of the coastal plain, classified as marine terraces correspond to ferrocordic spodosol hydromorphic or non-hydromorphic sandy texture, and quartzarênic neosols, which develop on Santos's Transgression sediments under similar conditions.

The composition of the material of geomorphological compartments or systems also helps to define its environmental fragility / sensitivity. Thus, at first all coastal plain is extremely fragile, however, this initial idea was overcome, because there is a compartment in the coastal plain that besides being higher topographically, presents very resistant material. In this way, a more in-depth investigation was required, an evaluation of this formation along the plain.

In addition to the analysis of the physic-chemical composition of the material that supports these forms, GPR method was used to try to define the depth and the variation along the profile. For GPR method, two data capture antennas were used. One of them with 70 MHz, which provides higher depth in the electromagnetic pulses, but with the information on the more generic layers no expressing the details. The other antenna, with 200 MHz, provided detailed information regarding the layers along the profiles. However, its electromagnetic pulses reach lower depths.

Five profiles were made along the coastal plain, concentrated on the area. With an extension of 840 m, the first profile was established in the continent-ocean direction, the others were perpendicular to the first. The second profile was of smaller extension, reaching about 500 m. The third profile, 280 m, the fourth profile, 60 m, and the fifth profile, established opposite the previous ones, about 340 m.

The importance of the realization of these profiles in the study area in Peruíbe consisted in verifying the cause of the presence of this thick layer and dark gray brown color of hardened character and sandy composition, and organic matter, being the fine sand very thin, with thickness approximately of 2 m or more and varied in length, considering this type of process occurs from Brazilian northeast. However, in some stretches of studied area, it does not exist, or when it exists it presents as a thin layer, varying from 4 to 20 cm in the smaller stretches, among the lighter sand layers.

The data obtained with GPR in the field were treated, as established by (Porsani & *alii*, 2004), and the reflection profiles were processed using the software Gradix (Interpex). The basic processing used consisted of the following steps: a) dc filter application (*wow* correction, which is a low frequency noise); b) correction of time zero; c) application of time gains (filter of the type SEC – spherical exponential compensation, linear, constant and programmed); d) bandpass filtering, and e) application of moving average space filter (three dashes). One of the profiles is shown here as an example (fig. 4).

In the field, samples were also collected from the soils and later analyzed in the laboratory. The analyzes consisted of granulometric and chemical evaluation of all samples from all field points, with emphasis on the area that presented the greatest resistance, as shown in figs 5 and 6.

The chemical composition is represented in the graph above. By establishing an analysis of the components, relative to the components determining the amount of nutrient in a soil, the amount of Ca, Mg and K is very small compared to the amount Al and H (33 and 179.5 m mol/dm^3, respectively) indicating if this layer were a soil, it would be very poor in nutrients and high acidity and would have a dystrophic soil classification.

Based on the work of (Prado & *alii*, 2007), which guided this generalized analysis of soil components, when the pH in H_2O is higher than the pH in KCl, the delta pH is negative, indicating predominance of negative charges, and in such cases, the soil retains more cations (such as calcium) than anions. The amount of organic matter of 79 g/dm^3 corresponds to the high amount of composition between the different elements that constitute the analyzed material.

If the cation exchange capacity (CTC) is low, the soil stores a small amount of calcium, magnesium, potassium, sodium, hydrogen, and aluminum. If the cation exchange capacity (CTC) is high, the soil stores large amounts of calcium, magnesium, potassium, sodium, hydrogen and aluminum.

When the base saturation of the soil (V) is high, that is, greater than or equal to 50%, the soil is eutrophic (rich in nutrients, especially calcium). It happens because more than half of the soil-reservoir (CTC) stores these nutrients represented by the sum of bases (SB). When the aluminum saturation of the soil (m) is high, that is, greater than or equal to 50%, the soil is alkaline (low in calcium but at the same time high in aluminum toxic to the roots).

In fig. 6 it is possible to observe in the graph the high amount of iron in the sample of the point of greatest resistance, justifying the recent pedogenetic character. Large amount of iron indicates recent formation feature.

The graph of fig. 6 shows the amount of iron in highest compartment samples, while the high composition of organic matter is represented by the composition of humic and fulvic acids. These are so-called spodosols with predominance of spodic B horizon, with accumulation of or-

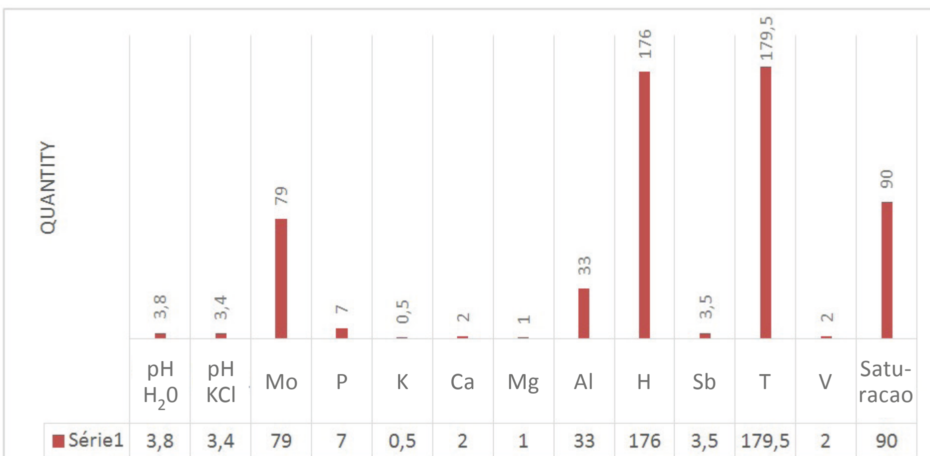

Fig. 5 - Graph of chemical composition of soil sample.

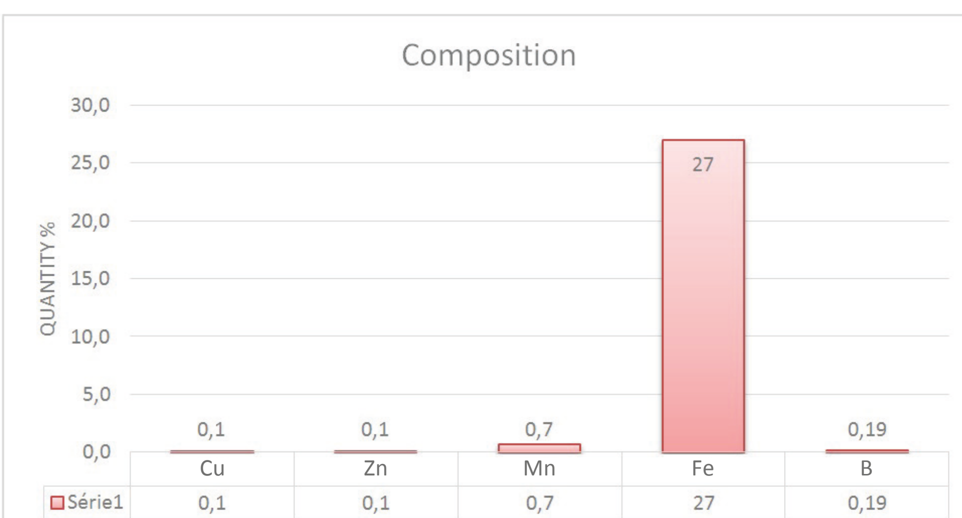

Fig. 6 - Graph of chemical composition of soil sample.

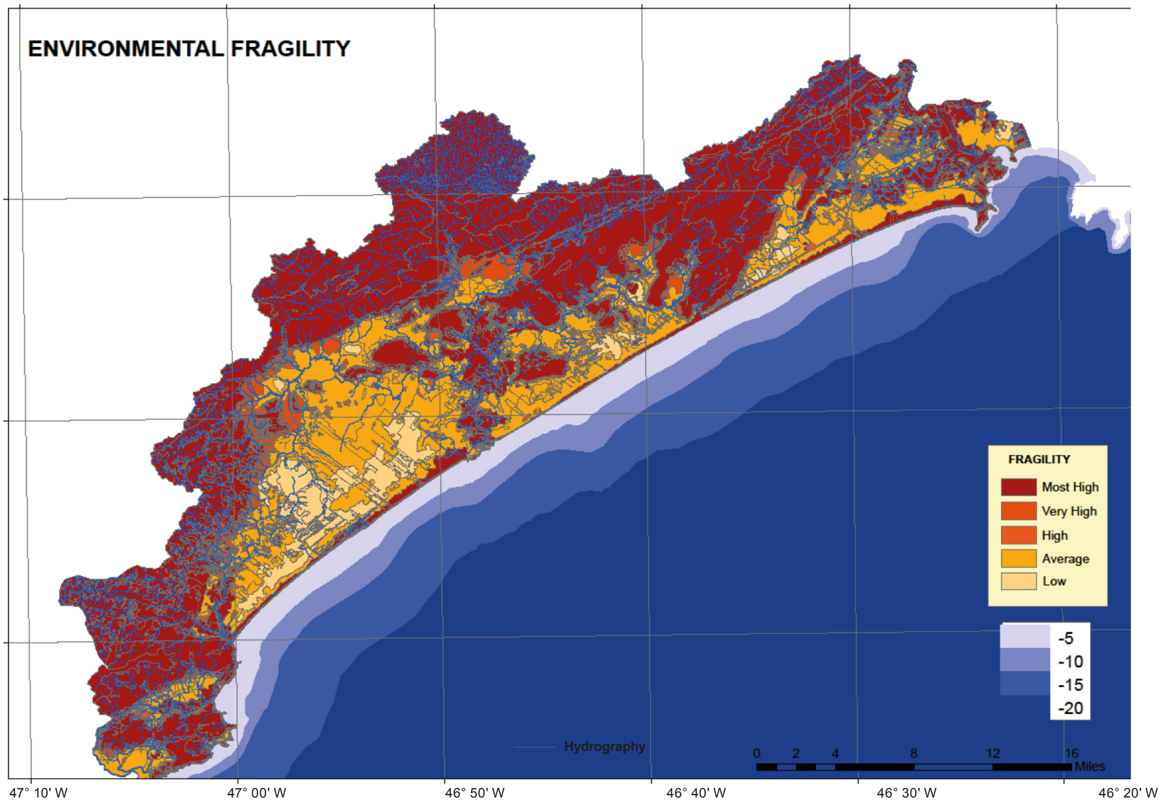

FIG. 7 - Map of environmental fragility / sensitivity of geomorphological systems.

ganic matter and iron and dark coloration, inherited from the humic acids. The spodosol, soil typical of the region, is directly associated to the formation of spodic B horizon, a horizon with podzolization that shows a certain variation in its coloration along the vertical profile, alternating the humic and fulvic acids.

Those soils may be associated with the formations of marine terraces and the old Pleistocene lagoons. These occurrences are in a slightly higher terrain and are interpreted as resulting from paleo lagoons.

The environmental fragility/sensitivity map (fig. 7) follows the boundaries of the unit defined by the geomorphological features correlated with the other characteristics of the physical environment, especially the material resistance data, to define the degree of fragility/sensitivity of each geomorphological compartment.

The environmental fragility/sensitivity in the Peruíbe cove also followed a subdivision pattern of the subsystems where the fluvial and intertidal plains, as well as the beaches were classified as subsystems of very high environmental fragility/ sensitivity, because they are made of materials more susceptible to environmental changes.

Other compartments also followed the same classification pattern of fragility/ sensitivity, except the marine terrace where the most resistant layer of depth of more than two meters. This compartment or subsystem is the highest marine training in the area. It is a subsystem of intrinsic resistance differing from the environment. This subsystem was classified as having low environmental fragility/sensitivity.

The other subsystems, such as fluvial-marine plain, post-beach, dune-covered marine terrace, colluvium ramps, were classified as high, medium, medium, medium and low fragility / sensitivity, respectively.

The classification of extremely high fragility/sensitivity was attributed to the intertidal, fluvial and beach plains, the lowest compartments and composed of materials that are not very resistant to extreme climatic changes and therefore are the first compartments to be reached with these changes, to receive the energy inputs of magnitude and frequency reaching their resistance threshold. Its state of dynamic equilibrium is of a temporal order less than the more resistant subsystems.

Meanwhile, other subsystems are unaffected, not suffering any change in their energy and matter exchanges, remaining in their state of dynamic equilibrium. These subsystems are those located at higher altimetric levels and, in general, have materials more resistant or less susceptible to energy inputs. The highest relief subsystems are the marine terraces, river terraces, hills, marine plains, colluvium ramps, mountain ranges. However, somehow these subsystems are always evolving and losing material for the maintenance of the subsystems located system downstream, but they receive materials from the upstream ones. When these exchanges do not occur, if there is only the loss of material, then there is erosion or an intrinsic lowering by the transformation of the chemical elements that compose them.

Regarding the environmental fragility/sensitivity in the study areas, it is important to highlight the peculiar characteristics regarding the resistance and composition of the materials of each morphosculptural subsystem were primordial factors to define the level of Fragility/sensitivity of each subsystem.

DISCUSSIONS AND CONCLUSIONS

To understand geomorphological variations on the coast, a geomorphological taxonomy of the coastal area was established to facilitate and subsidize the analysis of environmental fragility/sensitivity on São Paulo state coast, focusing on geomorphological characteristics of the plain coastal areas. In this aspect geomorphological character of this study summed up in which the forms, materials and processes analyzed show the importance of the study of relief in the research directed to nature aspects.

The representation of the relation between dynamic equilibrium inspired by the Hack model and environmental fragility/sensitivity explains the sequence of the description of the relief in equilibrium and dynamic non-equilibrium from the forms (morphosculptures or subsystems), following to altimetric levels for the resistance of the materials, compaction and finally the determination of the higher or lesser environmental fragility/sensitivity.

The dynamic equilibrium, according to (Hack, 1965), for whom the resistance of the materials composing the shapes, supported in the determination of environmental fragility/sensitivity, because it is the intensity of the resistance of these materials as a threshold that defines the degree of magnitude and frequency of the energy input forces promoting the evolution of these forms of relief.

The material resistance data acquired with the use of the impact penetrometer demonstrated the resistance to penetration of the equipment varies along the plain directly related to the material and, consequently, to the variations of compartmentalization relief forms. If the form altitude is intrinsically linked to the materials, consequently these morpho-sculpture variations will directly interfere in their resistance.

Each theoretical-methodological basis provided concepts and parameters for diverse landscape analysis, as well as to classify the fragility/sensitivity through the integrated analysis of the components to analyze material resistance. These materials have different forms in nature and are gradually conditioned to the morphogenetic and pedogenetic processes of coastal areas. These materials also suffer the interference of the exogenous processes, characterized by differences in temperature, moisture, pressure, and effects caused by climatic variations influencing the genetic formations due to differences in erosive and depositional processes by cause of mechanical erosion, sediment, or chemical material probably caused by the reaction between water and constituent elements of various types of relief and the materials that constitute the landscape. The anthropic activities are also included as enhancers of the exogenous processes that act as modelers of coastal landscape.

After these findings, some questions were raised. The lower, the more fragile the subsystem, because is the resistance less? What makes the material more compact in São Paulo state coast? Fine materials, moisture, traffic, urbanization, resistance, neotectonics in nature? Considering the idea of the relation altimetry *versus* resistance *versus* age *versus* fragility/sensitivity, there are still some questions:

The correlation between altimetric levels and soil resistance can be the answer to the questions about material resistance, relief and fragility / sensitivity in the coastal plains. The higher the formation (the morphosculture or subsystem), the more compacted and resistant is it? Thus, there is the idea that the higher reliefs consist of more resistant formations and remain elevated in the landscape because they present some resistance to the active erosive dynamic processes. Does this apply to a coastal plain? How much lower is less tough? Can this be associated with the greater or lesser amount of available water, the lower presence of colloids and finer materials that constitute the permanence of local moisture for longer? Can it be associated with the initial process of diagenesis by the physic-chemical transformation process that has occurred in this cementation of humic acid with its crystallization in the sediments? Some of these questions will be answered in this synthesis, others can only be clarified with more intensive and in-depth studies.

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