# Landslide susceptibility mapping in the coastal region in the State of São Paulo, Brazil


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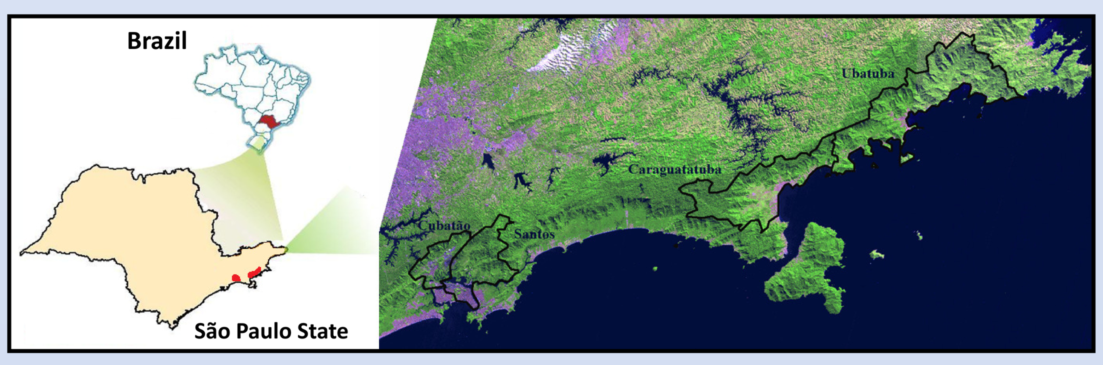
## Objectives

The objective of this study was to present a methodology by using free Geographic Information System and free database aiming the landslides susceptibility mapping, so that it can provide a usefull and reliable tool for natural disasters management. Additionally, the information of human occupation was integrated to landslide susceptible areas to indicate possible risk areas on the landscape, which was validate by comparing the results with risk areas previously mapped.

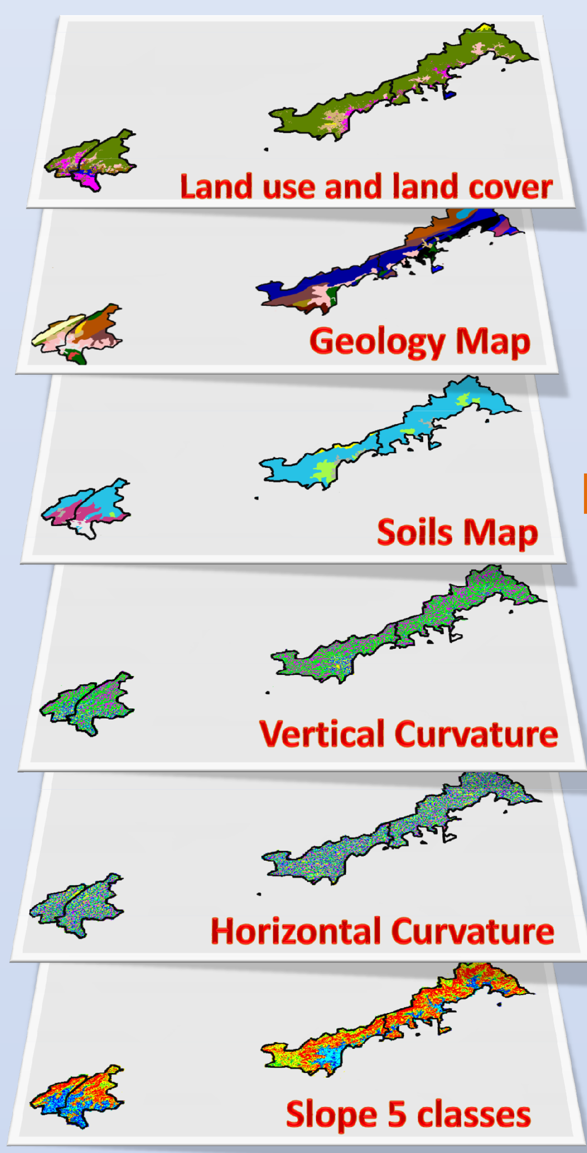
## Study Area




The study area corresponds to four Brazilian municipalities located on the coast of São Paulo: Ubatuba, Caraguatatuba, Santos and Cubatão. These four municipalities were chosen for the preliminary analysis by having a natural disaster historical involving landslides and, also, by having great economic importance, mainly due to its port facilities, industry pole and local tourism. More than 720.000 people lives on these four cities and during the summer season this number can get over than one million. The total area is about 1600km2, located largely in the slopes of the Serra do Mar, in highly rugged terrains. In these cities, urban sprawl happened quickly under the smooth plains, near the coast, where presented viable conditions for constructions. Especially during the second half of the last century, the regular areas that relied on the local infrastructure were practically exhausted due to the great population growth and property speculation. These cities has some legal restrictions about the verticalization process , which has led the urban sprawl migrated toward areas close to the slopes and hills. This feature, linked to property speculation favors the illegal occupation in conservation areas and/or in risk areas. Thus, in the past we have examples of natural disasters involving landslides that caused deaths in Ubatuba, in February 1988, with 6 dead, and the great disaster occurred in Caraguatatuba, in 1967, where the estimates indicate that more than 400 deaths, among others.

## Methodology

Before producing the susceptibility maps, the thematic maps related to landslide susceptibility must be weighted. The weights vary from 0 to 1, where 0 indicates classes with no relationship to landslide occurrence and 1 indicates classes with a high relationship to landslides. This weighting transforms the thematic maps onto a numerical grid, in which each class of map receives a weight (from 0 to 1) All this steps was done by using the software SPRING. The following Table displays the susceptibility values for all classes present in the different themes addressed in this study.




| Theme | | Weight | Theme | | Weight |
|---|---|---|---|---|---|
| ***Geology*** | *Type of rocks* | | ***Soil Class*** | *Acronym* | |
| | *Igneous* | | Haplic Cambisols | CX | 0.8 |
| Rhyolite, granite, dacite | | 0.37 | Melanic Gleisol | GM | 1.0 |
| Granodiorite, quartz, diorite | | 0.40 | Yellow Latosol | LA | 0.4 |
| Migmatite, gneiss | | 0.43 | Red Latosol | LV | 0.4 |
| Phonolite, syenite | | 0.47 | Red-yellow Latosol | LVA | 0.4 |
| | *Metamorphics* | | Red Nitosol | NV | 0.7 |
| Mylonites, quartz, muscovite, biotite | | 0.57 | Mesic Organosol | OU | 1.0 |
| Staurolite schist, schists garnetiferous | | 0.67 | Red-yellow Argisol | PVA | 0.7 |
| Phyllite, metasiltstone | | 0.70 | Lithic Neosol | RL | 1.0 |
| Marble | | 0.77 | Quartzarenic Neosol | RQ | 1.0 |
| Quartz sandstone | | 0.80 | Spodosols | EKg | 0,75 |
| Conglomerate | | 0.83 | Distrofic Fulvic Neosols | RUbd | 0,35 |
| Siltstones, mudstones | | 0.90 | Mangrove | SM | 0,10 |
| Shales | | 0.93 | Urban | URB | 1.0 |
| Limestone, dolomite | | 0.97 | ***Slope*** | *Class* | |
| | *Sedimentary* | | Higher than 45° | Mountainous | 1.0 |
| Sediments Unconsolidated: alluvium, colluvium | | 1.0 | 20 to 45° | Heavy undulation | 0.8 |
| | | | 8 to 20° | Undulation | 0.5 |
| ***Landuse*** | | | 3 to 8° | Smooth undulation | 0.3 |
| Agriculture | | 0.8 | 0 to 3° | Plane | 0.2 |
| Urban Area | | 1.0 | **Vertical Curvature /** | **Horizontal Curvature** | |
| Adult *Eucalyptus* | | 0.5 | Very Convex / | Very Divergent | 0,2 |
| Young *Eucalyptus* | | 0.7 | Convex / | Divergent | 0,3 |
| New *Eucalyptus* /soil exposed | | 1.0 | Retilineous / | Flat | 0,5 |
| Forest | | 0.4 | Concave / | Convergent | 0,8 |
| Pasture | | 0.7 | Very Concave / | Very Convergent | 1,0 |

For the geological data, the relationships of different types of rock with landslides was considered as the basis for the weighting. Igneous rocks had the lowest landslide probabilities, and intermediate metamorphic and sedimentary rocks had a lower resistance to weathering, *i.e.*, a greater landslide probability.

For the different soil types, the weights were based on the premise that soils with a higher amount of sand tend to be more susceptible than soils with more clay.

The topography was addressed through horizontal and vertical curvatures and the slope. The horizontal curvature refers to the divergent/convergent character of flows of matter on the ground when analyzed on a horizontal projection. This curvature is related to the processes of migration and accumulation of water, minerals and organic matter in soil caused by gravity, and plays an important role in the resulting water balance and pedogenesis.

Concave areas are more susceptible to landslides than convex areas, receiving the highest weights in the susceptibility table. Terrain with convergent profiles presents a higher risk of sliding incidents than divergent profiles, thus receiving higher susceptibility weights. The slope map was divided into 5 classes in accordance with those suggested by many authors in literature, with weights attributed to each slope class.

The volume of material removed and transported by rainwater is related to the density of vegetation cover and the slope declivity, and with vegetation removal, these processes become more intense, especially in areas with steep slopes. The weights assigned to each land use class depend on the type of vegetation coverage.

**Weights for <u>Fuzzy Gamma Technique</u>**

**Susceptibility Map** + **Risk Areas Map** = **Final Analisys**

The six themes of geology, land use and land cover, soils, slope, vertical and horizontal curvatures, were combined to generate a final susceptibility map using the fuzzy gamma operator. The fuzzy operator was introduced by Zadeh (1965) and allows a more realistic treatment of imprecise and subjective data that are part of analyses of physical environments. Fuzzy logic is able to model real problems where uncertainties and inaccuracies are present. Inaccuracy limits, called fuzzy sets, admit partial pertinence and are mathematically defined, as if Z denoted an object space; however, the set A in Z is the set of ordered pairs (Equation (1)):

$$A = (z,\ MF_A^F(z)) \text{ for all } z \in Z \quad (1)$$

The pertinence function $MF_A^F(z)$ is known as "the degree of membership of Z in A". The fuzzy membership value must lie in the range from 0 to 1 and reflects the degree of certainty of membership. The fuzzy theory employs the idea of member functions and expresses the degree of membership with respect to some attribute, in this case landslide susceptibility.

The fuzzy gamma operator consists of the product of the fuzzy algebraic sum and the fuzzy product. Equation (2) represents this operator.

$$\mu_{combination} = \left(1 - \prod_{i=1}^{n} \mu_i (1-\mu_i)\right)^{\gamma} \cdot \left(\prod_{i=1}^{n} \mu_i\right)^{1-\gamma} \quad (2)$$

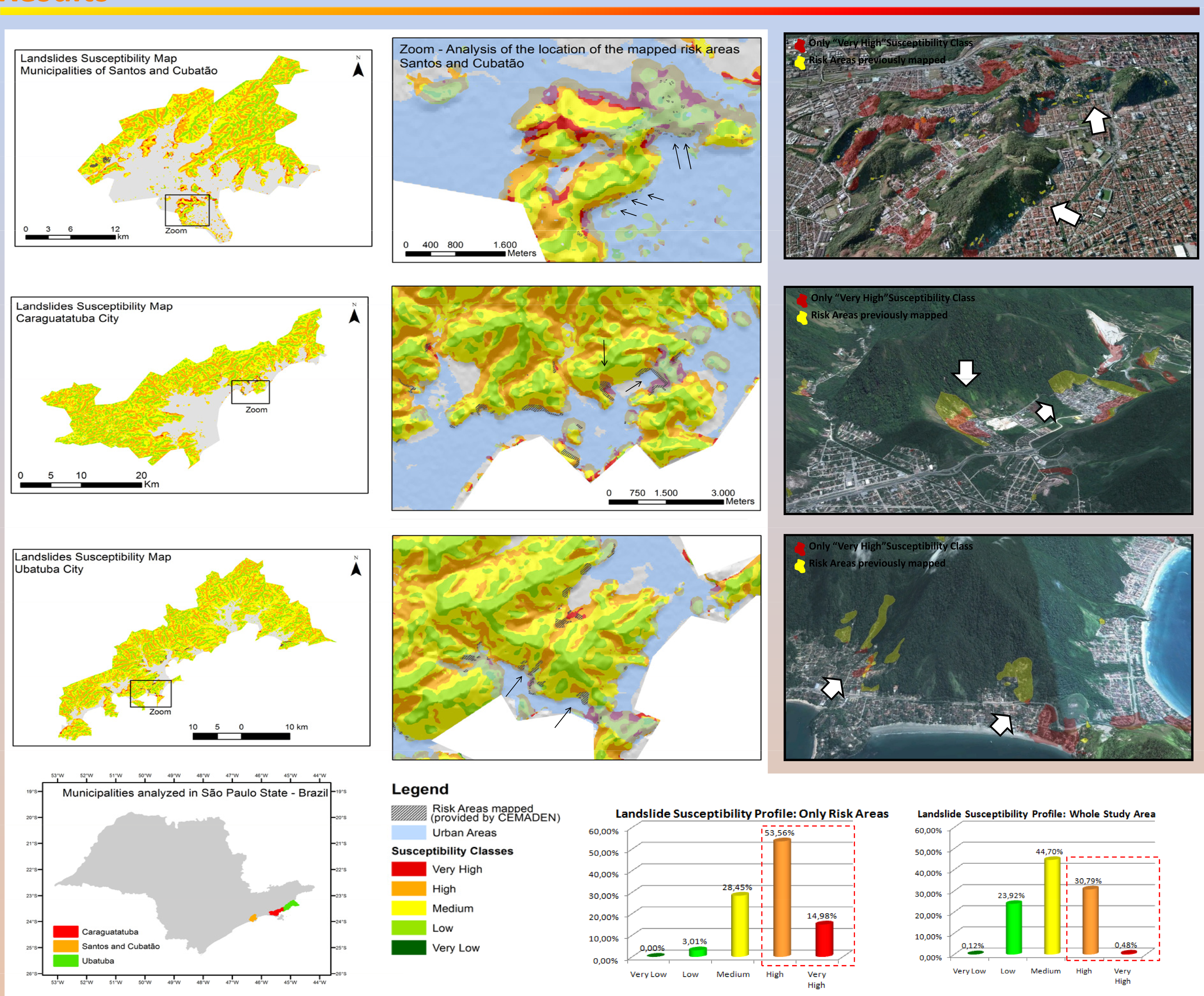
where ***γ*** *(gamma)* is a parameter within the range (0,1). The first term of the equation is named the fuzzy sum and the second term is the fuzzy product. When $\gamma = 0$, the fuzzy combination is equal to the product and when $\gamma = 1$, it is equal to the sum.

For Bonham-Carter (1994)the values in the range from 0 to 0.35 show a "diminutive" character, *i.e.*, they are always less than or equal to the smallest input fuzzy member; the values in the range from 0.8 to 1.0 have an "increasing" character, in which the output value will be equal to or greater than the value of the largest fuzzy member input values, and the range from 0.35 to 0.8 does not have an "increasing" or "diminutive" character.

Susceptibility maps were generated with values of gamma equal to 0.8. These input value do not have a diminutive or increasing character and were used in several studies. After the generation of susceptibility maps, they were divided into five susceptibility classes equidistant, varying from 0 to 1, with a gap equals 0,20.

Finally, aiming at a better visualization of the results, a "mask" was created to filter the mapping areas with slopes less than 10%. This step is based on the regional historical data and consulted literature, that indicate there is no occurrences of landslides for these cases.

## Results




## Discussion

The final maps generated are shown in figures in the left side. For each municipality analyzed (Ubatuba, Caraguatatuba,Santos and Cubatão) are presented detailed maps (zoom) with the inclusion of risk areas previously mapped, provided by CEMADEN (crosshatched in the maps). In most of the risk areas, the calculated susceptibility corresponds on classes "high" and "very high" (approximately 70% of the areas - the details are presented on the two graphs at the bottom right). However, there were also cases of risk areas located in classes with susceptibility "medium" and "low". These cases were not expected, but can be explained by several factors. The main one would be the methodology used to map areas of risk that, in many cases, are not necessarily overlapped with the locations prone to landslides. As can be seen in the images from Google Earth® (at right), some risk areas (highlighted in yellow) correspond to urbanized places that are just below the steep slopes. I.e., the mapping of risk areas not delineated the locations susceptible to the phenomena, but where there is a risk of mass movement could achieve the urbanized area. On the other hand, in some places the mapping of risk areas correspond to the definition of specific residences that are located on sites with very high susceptibility to landslides (highlighted in red). These disparities between the mappings of risk areas can come from different work teams, who may have used different methodologies and standpoints.

## Conclusions

In general, the mapping of landslides susceptibility by using Fuzzy Gamma methodology presented satisfactory results in this study. However, it was observed that the validation of the results using the risk areas previously mapped is not the best alternative to evaluate the accuracy of the methodology, mainly due to the difference between the factors that define the existence of imminent risk and the probability of landslides occurrences (susceptibility). Even so, approximately 70% of the risk areas mapped are located exactly in regions with <u>high</u> and <u>very high</u> susceptibility, which indicates the good quality of the results. When crossing the satellite images (by Google Earth®) it was observed that the location of areas with "very high" susceptibility also corresponds to vulnerable urban areas. All these factors can characterize the methodology applied as a good tool to guide future interventions and also emergency actions for natural disasters that involves landslides.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