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Extreme Events Assessment Methodology Coupling Rainfall and Tidal Levels in the Coastal Flood Plain of the São Paulo North Coast (Brazil) for Engineering Projects Purposes

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Abstract

The North Coastal Region of the State of São Paulo, which comprises the Municipalities of Caraguatatuba, São Sebastião, Ilhabela and Ubatuba, is one of the most prone to flooding Brazilian areas, owing to hydrological extreme rainfall events usually coupled with extreme tidal levels. This risk is also high due to human lives and material assets, with increasing population rates and the settling of large Companies such as the Oil industry, with reduced defense measures and works.

The catastrophic scenario of the city of Caraguatatuba, in March of 1967, resulted from one of the most serious natural disasters in Brazil, fosters discussions about probabilities of rainfall events and rise in the sea level in coastal areas. Hence, this research is a consequence of this reality. The research presented is founded on an innovative methodology based on the analysis of past data of rainfall stations and tidal stations in the region of the North coastal zone of the State of São Paulo (Brazil). The analysis developed approached the meteorological, hydraulic and statistical knowledge areas. Practical results were used for designing macro-drainage, fluvial and maritime projects, that associate the probability of occurrence of certain types of rainfall coupled with their corresponding increase in tidal levels.

Keywords: Meteorology; Hydrology; Maritime hydraulics; Rainfall; Tidal levels; Extreme events; Natural disasters; Geomorphology; Debris-flow

Introduction

This research is inserted into an area of Civil Engineering, in the interface between Maritime Hydraulics (tidal levels) and Hydrology (rainfall). Our main objective was to evaluate rainfall events combined with tidal levels, and to obtain practical results applicable to fluvial and maritime projects in the Santo Antonio River Basin (Figure 1), located in the city of Caraguatatuba, on the North Coast of São Paulo /Brazil. Coastal areas are subject to severe sea action and precipitation. The north coastal region of São Paulo is known for its orographic rainfall, caused by moisture fronts from the Atlantic Ocean; when they collide with the mountain range of Serra do Mar, there is precipitation on the coastal towns. There is a great demand for studies on the subject, mainly with historical occurrences of disasters in the last century. According to Brigatti and Sant'AnnaNeto [1], the Northern Coast of São Paulo, for its own natural characteristics and the recent economic dynamics, is characterized as an area in which studies aimed at better understanding the natural and anthropogenic factors are developed, and are extremely important.

For illustrating the magnitude of the 1967 disaster, images of Caraguatatuba were collected right after the debris flow (Figure 2a, 2b and 2c). Figure 2d shows the city of Caraguatatuba in 2012 (Santo Antonio River basin), with a population of approximately 100,000 inhabitants. It is notorious that a similar event to that of 1967 would cause significant damages. Some consequences of this particular event were:

- 2 million ton of mobilized material;
- 436 registered casualties, 400 buildings destroyed, 3,000 displaced people among 15,000 inhabitants;
- 4m to 5m high block deposits were formed along the Santo Antonio River. The largest boulders weighed between 30t and 100t;
- Widening of the Santo Antonio River: from 10m to 20m to 60m to 80m in some areas.

As well known, in the coastal area, the combined effect of rainfall and high tides can generate the classical phenomenon called "tidal flooding" [2]. This effect, associated with the landscape and debris-flow generated by a continuous rainfall in the fragile territory, produces a combined risk of natural hazards because the coastal cities are particularly vulnerable to flood under multivariate conditions (i.e. heavy precipitation, high sea level, storms, etc).

It follows that the combined effect of multiple sources and the joint probability of extremes should be considered to assess and to better manage the flood risk in the coastal zone.

It is worth noting that the study of the joint effect between the tide and the rainfall flooding effect has been one of the most important areas of knowledge developed in the research community in the new century [2-5]. However, most of this analysis was conducted using numerical modeling and neglecting a detailed statistical analysis between rainfall and tide data recorded [5].

In this study, we developed a multivariate probability model to study the join risk probability and focused on the area of the Sao Paulo North Coast where we currently find a lack of study and analysis. This

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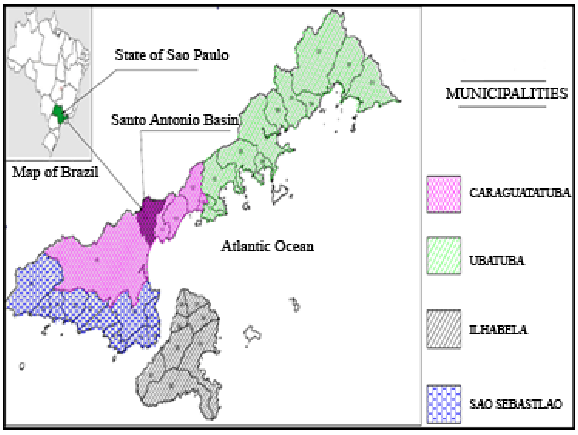

Figure 1: Municipalities of the North Coastal Region of the State of São Paulo (Brazil)

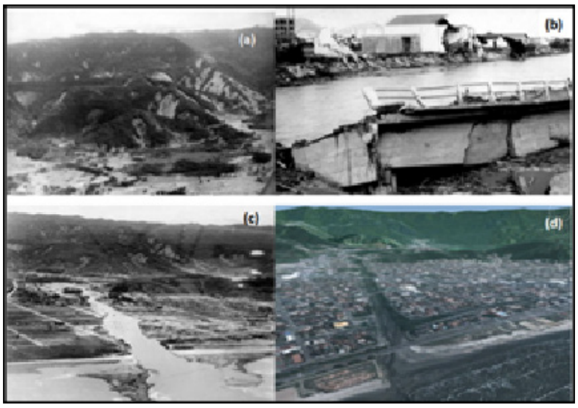

Figure 2: Aerial photographs of the Santo Antonio river at different times.

a) scars on mountains after the 1967 rainstorm ;

b) bridge over the Santo Antonio river destroyed by the debris-flow in 1967;

c) Santo Antonio river mouth after the 1967 rainstorm (five times heavier than normal);

d) Santo Antonio river mouth in 2012.

study fits this regional context, and our purpose is to provide consistent analyses of historical data of tidal levels and rainfall.

Methods

Given the evident extreme rainfall events and random sea level behavior, the discussion on whether there is an interdependence of two variables and, especially, how they have been developing faced with climate change was fostered. The methodology described in this item was adapted from HIDROCONSULT [6], which conducted a similar study for Cubatão city, Central Coast of São Paulo State. The methodology adopted was founded on four steps as follows:

- collection, processing and data validation of tidal levels for the North Coast region of the State of São Paulo;
- collection and processing of rainfall data for the region of the North Coast of the State of São Paulo;
- understanding, development and application of statistical methodology, combined with the occurrence of rain-tide for Caraguatatuba region;
- obtaining graphs and tables of probabilities of the occurrence of certain phenomena involving rainfall and tides;

Step 1: Getting the database

The database was composed of two groups: tidal levels and rainfall values. The characteristics of these values are explained below.

Tidal data: The tidal level data come from different sources of different institutions, as described:

- IGC tidal station (CartographicandGeographic Institute) inUbatuba;
- IOUSP tidal station (Institute of Oceanography, USP-University of São Paulo) inUbatuba;
- CTH tidal station of Hydraulic Technological Center in Martinde SáBeach/Caraguatatuba;
- São Sebastião Harbour tidal station;
- Buoyof CEBIMar (Marine Biology Center, University of São Paulo) in São Sebastião.

The compilation of information from tidal stations generated a large database from 1954 to 2005, with some intermediate gaps. This database comprises over 225,000 hourly values of tidal levels.

Rainfall data: The composition of the rainfall database in the city of Caraguatatuba started with searches of data viability in Agência Nacional de Aguas [7]. TheE2-046 rainfall station (Caraguatatuba) contains data from 1943 to 2010, totaling 24,603 daily values of rainfall heights, and was thus considered in this research.

Step 2: Data compilation

From the database of tides and rainfall heights, the second procedure for applying the methodology was performed: data compilation.

The tides and rainfall values were organized so as to allow direct relationships between the daily rainfall in the Santo Antonio River Basin, and its levels in the tidal stations of the Northern Coast of São Paulo State. Table 1 illustrates how the data for the month of January 1954 were compiled. At the end of step 2, 9,361 days with the relationship between rainfall and tides (High tide; Low tide and Mean sea level) were recorded.

Step 3: Division of database into rainfall groups

The third step of the methodology divides the database into groups, based on the accumulated daily rainfall: $P \geq 0$ mm/day, $P \geq 25$ mm/day, $P \geq 50$ mm/day, $P \geq 75$ mm/day, $P \geq 100$ mm/day. The division of the database into groups is an important step in the process, because each rainfall track represents a probabilistic curve of occurrence of rain-tide phenomenon, as demonstrated ahead.

Step 4: Reorganization of database, parameterized by tidal levels

The data were reorganized, after the separation into rainfall groups (see Step 3), following the guidance below:

- for each precipitation interval (it is convenient to separate them into different worksheets), the table was rearranged in decreasing order, using tidal levels (higher tides at the top of the table) as a parameter. This methodology also has to be applied

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Date	Data of tidal Station (IBGE Reference)			Rainfall (mm/day)
	Low Tide (cm)	MeanSeaLevel (cm)	High Tide (cm)	
01/01/1954	-74.83	-26.96	15.17	0
02/01/1954	-78.83	-34.92	4.17	0
03/01/1954	-62.83	-13.13	20.17	16.7
04/01/1954	-54.83	12.50	60.17	14.5
05/01/1954	-85.83	-8.54	45.17	7.9
06/01/1954	-97.83	-19.50	25.17	3.2
07/01/1954	-75.83	-16.92	25.17	4.2
08/01/1954	-56.83	4.87	45.17	0
09/01/1954	-57.83	-3.83	29.17	0
10/01/1954	-67.83	-20.21	8.17	0
11/01/1954	-64.83	-19.54	4.17	0
12/01/1954	-44.83	-19.79	3.17	0
13/01/1954	-34.83	-11.83	27.17	0
14/01/1954	-31.83	-1.21	30.17	0
15/01/1954	-59.83	-11.08	35.17	0
16/01/1954	-64.83	-14.17	28.17	0
17/01/1954	-71.83	-15.29	28.17	0
18/01/1954	-64.83	0.00	44.17	0
19/01/1954	-77.83	-6.67	38.17	1.2
20/01/1954	-79.83	-12.67	36.17	0
21/01/1954	-62.83	-8.13	41.17	3.3
22/01/1954	-61.83	-7.00	37.17	2.5
23/01/1954	-61.83	-9.92	36.17	0
24/01/1954	-42.83	-6.00	30.17	0
25/01/1954	-39.83	-14.67	13.17	0
26/01/1954	-38.83	-11.25	13.17	0
27/01/1954	-26.83	-7.08	11.17	0
28/01/1954	-40.83	-18.46	-1.83	0
29/01/1954	-51.83	-21.83	2.17	0
30/01/1954	-48.83	-15.46	16.17	0
31/01/1954	-57.83	-6.38	36.17	0

Table 1: Example of compilation of daily tidal levels and daily rainfall heights, for the Santo Antônio Basin, in January 1954

separately to daily Low tides, daily Mean Sea Level and daily High tides;

- note that the rainfall values should always be kept with the equivalences of daily tides (as in Step 2);
- for each precipitation interval, the major annual events of tide (for Low tides, smaller annual events should be chosen) should be selected, because the Return Period (TR) will be calculated in years.

As a result of this step, there are several tables (one for each precipitation interval), sorted from highest to lowest tides (Minimum daily Low tides, Highest daily Means Sea Levels and Highest daily High Tides) with annual extreme values. It is worth observing that the event (days) must be repeated at different intervals, for instance, the same day with rains over 100 mm (P>100 mm/day) rains over 75 mm (P> 75 mm/day).

Step 5: Calculation of probability of combined events (rainfall-tidal level)

At this stage, probabilities of occurrence of certain sea level are calculated, associated with a rainfall range using a Gumbel mixed-model as suggested by Yue et al. [8]. Table 2 illustrates this step. For each precipitation interval described in step 3, a different table was generated.

Results and Discussion

Based on the methodology described in the previous section, more relevant results were obtained. Figure 3 shows the graphical result from the statistical analysis of the previous item. From the graph, Table 3 summarizes the main values useful for both for maritime and fluvial hydraulic projects in the region. For a macro drainage project, for example, a 50-year Return Period is considered. By assuming this hypothesis, it is necessary to adopt a Mean Sea level of 50.69 cm for any daily rainfall (P>0 mm/day). Note that for the same Return Period (50 years) simultaneously with more rainy days (P> 100 mm/day) a lower Mean Sea Level (40.59 cm) may be assumed; hence,

Mean Sea Level (maximum Annual) IBGE Reference (cm)	*Day*	*Rainfall (mm)*	*Probabilities of occurrence P (%)*	*Order Number*
52.00	30/05/1988	26.2	2.86%	1
49.79	07/07/1989	0	5.71%	2
49.28	22/06/1990	0	8.57%	3
48.93	31/07/1980	4.1	11.43%	4
47.79	15/08/1999	0	14.29%	5
45.33	10/05/1956	3.5	17.14%	6
45.11	13/05/1959	1.6	20.00%	7
44.44	20/02/1995	63.5	22.86%	8
44.42	10/02/1966	0	25.71%	9
43.96	23/11/1970	0	28.57%	10
42.56	11/03/1987	17.8	31.43%	11
42.52	11/06/1993	19.4	34.29%	12
41.13	17/07/2000	3.7	37.14%	13
40.66	17/06/1971	6	40.00%	14
40.59	19/12/1994	15.2	42.86%	15
40.20	07/01/1996	21.8	45.71%	16
39.87	12/02/1998	22.3	48.57%	17
39.43	05/07/1991	0	51.43%	18
37.85	16/07/1992	2.1	54.29%	19
37.52	05/05/1963	0	57.14%	20
36.75	22/05/1978	5.3	60.00%	21
36.57	07/04/1979	13.5	62.86%	22
35.69	10/06/1983	3.2	65.71%	23
35.48	09/12/1982	2.3	68.57%	24
34.93	30/09/1981	1.8	71.43%	25
34.28	26/05/1958	8.8	74.29%	26
33.35	29/07/1955	0	77.14%	27
33.04	15/04/1986	0.5	80.00%	28
32.24	13/12/1972	16.5	82.86%	29
31.37	04/07/1965	0.8	85.71%	30
30.32	26/03/1997	1.1	88.57%	31
30.22	30/03/1964	20.6	91.43%	32
29.62	11/05/1954	1	94.29%	33
12.76	22/12/1977	35.9	97.14%	34

Table 2: Calculation of probability of combined events (P≥0 mm/day andMean Sea Level), for the Santo Antonio Basin

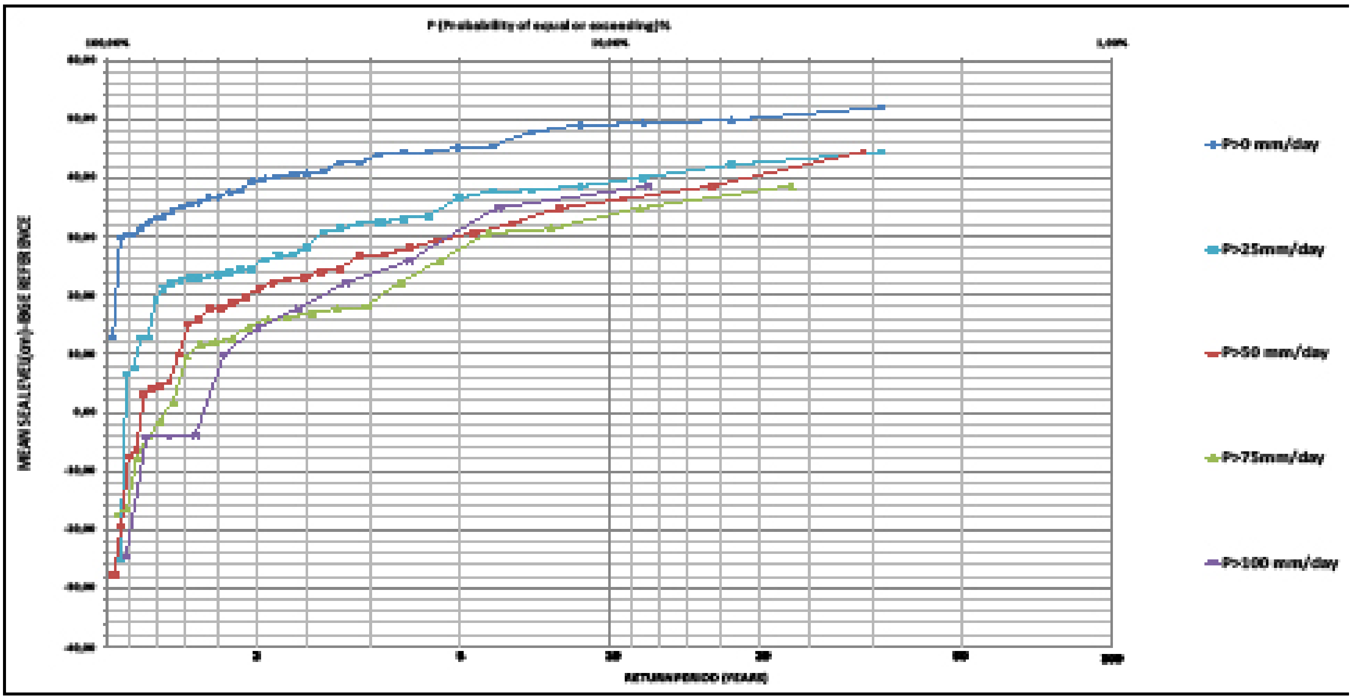

Figure 3: Graph of probabilities (rainfall x mean sea level)

Rainfall (mm/day)	*ReturnPeriod (TR)-Years*							*Mean Sea Level (cm)-IBGE Reference*
	2	*5*	*10*	*20*	*50*	*75*	*100*	
>0	38.56	46.11	49.18	50.28	50.69	50.75	50.77	
>25	25.74	37.86	43.82	45.75	46.27	46.30	46.31	
>50	20.69	30.33	36.77	40.81	43.49	44.11	44.42	
>75	14.89	25.62	33.54	39.13	43.13	44.08	44.57	
>100	11.95	31.64	37.71	39.81	40.59	40.71	40.76	

Table 3: Results applicable to Engineering projects (Rainfall x Mean Sea Level)

an elevated sea level along with heavy rain is less likely to occur. Another important concept is, for example, days with the same rainfall characteristics (i.e.: P> 0 mm/day), as larger Return Periods (less likely to occur) are selected, simultaneous higher sea levels must be adopted.

This statistical analysis can be completed with a hydrodynamic analysis as shown by Sakai et al. [9]. The Authors show that the tide level and the rainfall analysis can be used as boundary conditions for an analysis made with a hydro dynamical model (FLO-2D). The results, simulation of the catastrophic event of the 18th March 1967, demonstrate how, in the coastal area, the risk is generated by an association of different situations: rainfall, debris flow and tide flooding. The area affected by the flooding was plotted on the map (see Figure 4) in order to facilitate understanding the results.

By composing both the results presented in Figure 4 and in Table 3, the real catastrophic scenario of an event of this size is fully characterized. According to Brigatti and Sant'Anna Neto [1], regarding the occurrence of floods and flooding, the north coast has unique characteristics, mainly provided by its physical aspects and land use. The occupation on the banks of rivers and their mouths, together with a peculiar atmospheric dynamics and tidal fluctuations, commonly cause serious socio-environmental damages. The interrelationship ocean-atmosphere-continent is extremely complex and leads to an uncertainty region. In the specific case of the episodes related to floods and flooding, many aspects must be considered, namely:

- the meteorological factors (mainly related to the cold fronts going through the region and the variations of their elements, especially wind, rainfall and atmospheric pressure);
- the coastal dynamics (its relations with meteorological events, currents and depositional processes that directly influence the rates of discharge of rivers, besides the tidal dynamics, notably related to spring tides episodes;
- the land use and anthropogenic influences (change in surface flow and absorption along the coast);

The North Coast region of the State of São Paulo is located in an area with important atmospheric activities. The mountains of Serra do Mar act as a barrier to the atmospheric flow from the ocean and its presence gives the region a complex configuration in relation to rainfall, as noted by Conti [10], and the orographic effect greatly participates in this dynamic [11].

From the climatic point of view, the element that most stands out is the rain, with areas that have the highest total rainfall in Brazil (with an annual average of over 4000mm/year, 6000mm/year reached in extreme

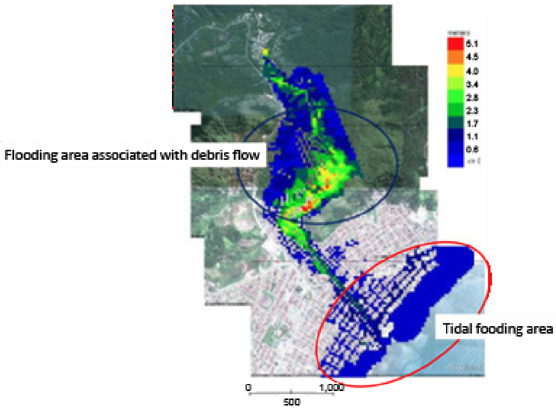

Figure 4: Flood depth and areas affected in the event of 18th March 1967 simulated with the FLO-2D model [9]

years). There is also the presence of "rain shadow islands" provided mainly by the massive island of São Sebastião, which is located in the north of the São Sebastião channel and over the Caraguatatuba bay region. In these areas, total rainfalls are lower (around 1800mm/year). From the point of view of the performance of atmospheric systems, the region is dominated by tropical masses, but due to their transitional climate position, it presents constant frontal systems (cold fronts), which, together with the morphological and the Serra do Marrange, accounts for the most extreme rainfall events [12].

These climatic characteristics, coupled with a strong slope of the relief, the small extension of the coastal plain, the shapes of the basins of major rivers and the ocean dynamics, characterizes a fragility region, aggravated by irrational occupation and the construction of numerous roads, with the presence of irregularly occupied areas and projects poorly carried out in areas susceptible to extreme episodes [13].

Conclusions

The coastal regions of Brazil constantly suffer with extreme events due to both heavy rainfall and sea forces (waves, tides, currents). The study of natural phenomena must begin with a continuous collection of data. It is understood as essential that any analysis is based on collection, storage and processing of data of natural variables (tidal levels, rainfall heights, waves, currents, etc.), to allow treating the phenomena statistically, linking them to the probabilities of occurrence. This research is inserted in this initial process. From statistical studies, the results can be applied to Engineering practice. The coastal projects should consider the lessons learned from past events, both with the direct application of statistical analyses, and by using mathematical models, such as input data for simulations of natural events. In recent decades, from databases and mathematical models, an Engineering advanced section is committed to discussing, whether the projects already built will suffer from climate change, such as the increase of the Mean sea level, more frequent heavy rainfall and debris-flow events that destroy cities on the coastal floodplain. Therefore, repair works will become increasingly more frequent in these regions.

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References

1. Brigatti N, Sant´Anna Neto J (2008) Dinâmica climática e variações do nível do mar na geração de enchentes, inundações e ressacas no litoral norte paulista. *Revista Formação-Especial 20 anos, 2*: 25-36
2. White LW (2010) Tidal and Rainfall Flooding Evaluation for Cape Henry, Cape Story by the Sea and Lynnhaven Colony. Ed Parsons & Brinckerhoff, Vrigina, USA.
3. Jones DA (1998) Joint probability Fluvial-Tidal Analyses: Structure Functions and Historical Emulation. Institute of Hydrology-Wallingford & Ministry of Agriculture, Fisheries and Food and the Natural Environment, Project FD04017
4. McInnes KL, Macadam I, Hubbert GD, Abbs DJ, Bathols J (2005) The effect of the climate change on storm surges. In Climate Change in Eastern Victoria-Stage 2, Ed CSIRO, Australia
5. Lian JJ, Xu K, Ma C (2013) Joint impact of rainfall and tidal level on flood risk in a costal city with a complex river network: a case study of Fuzhou City, China. Hydrol Earth Syst Sci 17: 679-689
6. Hidroconsult (1979) *Análise Probabilística de Ocorrência Conjugada de Eventos Máximos Chuva-Maré*. Estudo realizado para SOMA Secretaria de Obras e do Meio Ambiente, DAEE- Departamento Estadual de Águas e Energia, São Paulo
7. ANA-Agência Nacional de Aguas (2005).
8. Yue S, Ouarda T, Bobée B, Legendre P, Bruneau P (1999) The Gumble mixed model for flood frequency analysis. J Hydrol 226: 88-100.
9. Sakai de Olivera R, Cartacho DL, Arasaki E, Alfredini P, Pezzoli A et al. (2013) Extreme events assessment methodology coupling debris flow, flooding and tidal levels in the coastal floodplain of the Sao Paolo North Coast (Brazil). International Journal of Geosciences, in review.
10. Conti JB (1975) Circulação secundária e efeito orográfico na gênese das chuvas na região lesnordeste paulista. IGEOG/USP, São Paulo 79-82.
11. Cruz Olga (1974) A Serra do Mar e o Litoral na Área de Caraguatatuba-SP-Contribuição à Geomorfologia Litorânea Tropical.
12. Tavares R, Sant´Anna Neto JL, Santoro J (2002) Chuvas e escorregamentos no Litoral Norte Paulista entre 1988 e 2001.
13. Souza C (1998) Flooding in the São Sebastião region, northern coast of São Paulo state, Brazil. Anais da Academia Brasileira de Ciências, São Paulo.
14. ITA (2009) Mudanças Climáticas Globais e impactos na zona costeira: modelos, indicadores, obras civis e fatores de mitigação/adaptação. São José dos Campos.

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