Extreme events assessment methodology as a tool for engineering adaptation measures – case study of North Coast of Sao Paulo State (SP)

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3 Extreme Events Assessment Methodology as a Tool for Engineering Adaptation Measures – Case Study of North Coast of São Paulo State (SP), Brazil

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 Brazilian areas most prone to flooding and debris flow deposition, owing to hydrological extreme rainfall events, usually coupled with extreme tidal levels.

The catastrophic scene of the city of Caraguatatuba March 18, 1967, resulting from one of the most serious natural disasters in Brazil, fosters discussions about probabilities of heavy rainfall-caused events and subsequent rise in the sea level in coastal areas. The research is founded on an innovative methodology based on the analysis of past rainfall and tidal station data, complemented with debris flow measurements and coupled with FLO-2D hydrodinamical model. The analysis involved meteorological, hydraulic, geotechnical and statistical knowledge areas applied to the region of the North coastal zone of the State of São Paulo (Brazil).

The obtained results are a good predictor of the probability of occurrence of certain types of heavy rainfall-caused events such as flooding or debris flow, coupled with a corresponding increase in tidal levels.

These practical results are intended to be used for urban planning, designs of macro-drainage, fluvial, maritime projects and debris flow retention structures.

Keywords: Meteorology, Hydrology, Maritime Hydraulics, Rainfall, Tidal Levels, Extreme Events, Natural Disasters, Geomorphology, Debris-Flow, Flooding

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3.1 Introduction

It is well established that the Brazilian Coastal Zone (BCZ) is important to the development of the country, given that most of total internal production is exported by harbors and waterways. To illustrate the relevance of BCZ, Figure 3.1 demonstrates the production of the municipalities, in excess of R$ 1 billion. It is note-worthy that the most important economic regions are situated around the São Paulo State. In spite of the fact that these coastal areas are economically developed, they are exposed to natural forces, such as orographic rainfall, tidal levels, debris flows and flooding. Understanding the relationship with the environment is of critical importance; as a consequence, this research was undertaken in the area of Civil Engineering, involving the interface between Maritime Hydraulics (tidal levels and hyper-concentrated flows), Hydrology (rainfall) and Geotechnics (percolation and landslides) specifically, and applied on the Northern Coast of São Paulo State (Figure 3.2).

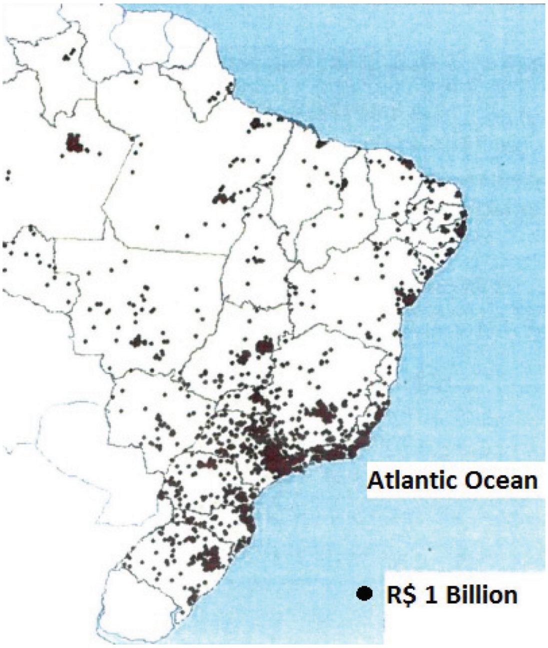

Figure 3.1: Production of Brazilian municipalities greater than one billion Reais.

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.

From the climatic point of view, the most impactful element is rainfall, with areas that have the highest total rainfall in Brazil (with an annual average of over

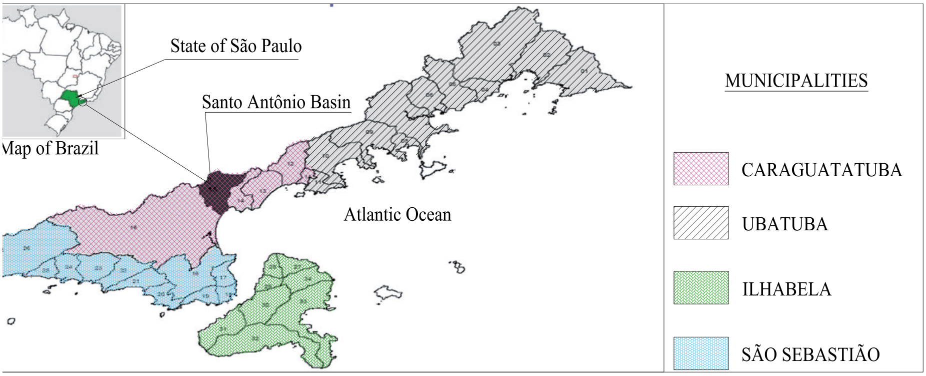

Figure 3.2: Municipalities of the North Coastal Region of São Paulo State (Brazil).

4000 mm/year, 6000 mm/year reached in extreme years) (CPTEC 2009). There is also the presence of “rain shadow islands” provided mainly by the massive island of São Sebastião (Ilhabela), affecting the areas north of the São Sebastião channel and the Caraguatatuba bay region. In these areas, total rainfall is lower (around 1800 mm/year). Due to its climate-influenced position, the region is dominated by tropical masses and presents constant frontal systems (cold fronts), which, together with the morphological structure and the Serra do Mar mountains, account for the events caused by the extreme rainfall (Conti 1975).

There has been a great demand for studies on the subject, mainly due to historical occurrences of disasters in the last century. According to Brigatti and Sant’Anna Neto (2008), the Northern Coast of São Paulo, because of its own natural characteristics and the recent economic dynamics, is regarded as an area where studies are currently aimed at better understanding the increasing effects of natural and anthropogenic factors.

In order to illustrate the magnitude of the 1967 disaster, images of Caraguatatuba were collected immediately after the debris flow (Figure 3.3(a)). Figure 3.3 shows the city of Caraguatatuba in 2012 (Santo Antônio River basin), with a population of approximately 100,000 inhabitants. It is of great concern that another event similar to that of 1967 could cause significant damage.

Some consequences of the 1967 event were:

- 7.56 million tons of mobilized material;
- 436 casualties registered, 400 buildings destroyed, 3,000 displaced people out of 15,000 inhabitants;
- Four to five meters high block deposits were formed along the Santo Antônio River. The largest boulders weighed between 30 t and 100 t;
- widening of the Santo Antônio River: from ten meters up to 20 m and from 60 m to 80 m in some areas.

Well known, the study of the combined effects of the tide, rainfall flooding and debris flow has been one of the most significant areas of study in the new century (Jones

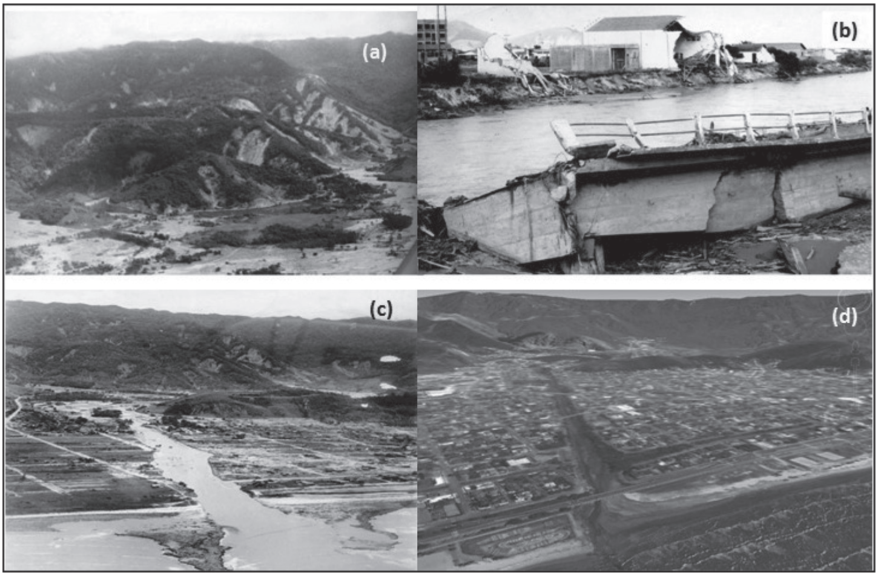

Figure 3.3: Aerial photographs of the Santo Antônio river at different times. (a) scars on mountains after the 1967 rainstorm; (b) bridge over the Santo Antônio river destroyed by the debris-flow in 1967; (c) Santo Antônio river mouth after the 1967 rainstorm (five times greater than usual); (d) Santo Antônio river mouth in 2012.

1998; McInnes et al. 2005; White 2010; Lian et al. 2013). In recent years, a great deal of attention has been given to showing the separate impact of the events; nevertheless, only the combined effects have been successfully studied.

Recently Lian *et al.* (2013) studied the combined effect of rainfall and tidal level of the receiving water body on flood probability and severity in Fuzhou City, which has a complex river network.

The main purpose of this research was to evaluate the events caused by heavy rainfall combined with tidal levels. The obtained study results were applicable to urban planning fluvial and maritime projects and debris flow retention structures in the Santo Antônio River Basin (Figure 3.2) located in the city of Caraguatatuba on the North Coast of São Paulo / Brazil.

In this study, a multivariate probability methodology was developed to study the joint risk probabilities of rainfall and tide, and focused on the area of the São Paulo North Coast where studies and analyses are currently lacking. Furthermore, it provided a combined analysis of historical data of tidal levels and rainfall. Then, basing on the data recorded in the debris-flow catastrophe of 18th March 1967, a simulation with the hydrodynamic model FLO-2D was run to analyze the effects of flooding and debris flow.

Finally, comparing the results obtained by the statistical analysis and the deterministic model, policies for effective land use and management are suggested.

3.2 Methods

Given the evident extreme rainfall events such as flooding and debris flows and random sea – level behavior (applied for meteorological tide), the focus of the discussion will be on whether there is interdependence between these variables and, especially, how the variables are related to climate changes.

The first stage of the study was based on realistic data applied in a statistical methodology of concomitant rainfall and tidal level, producing results that represent the probabilistic scenarios of occurrence which is extremely important to determine drainage system policies. Similarly, these results are applied in deterministic methodologies (mathematical models) as input data, used in the second stage of this study.

The methodology described in the first stage (statistical stage) was based on Hidroconsult (1979), which carried out a similar study for Cubatão city, located on the central coast of the State of São Paulo; moreover, it represents a similar condition of rainfall and topography.

The statistical methodology adopted was founded on the following:

- 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 applied to a combined occurrence of rain-tide for the Caraguatatuba region;
- obtaining graphs and tables of probabilities of the occurrence of certain phenomena involving rainfall and tides.

The debris flow and flooding studies, which represent the second stage of the research (deterministic step), related to the extreme rainfall events were performed according to this relationship between both variables (rainfall and tide level).

In this case, the methodology was organized as follows:

- collection, processing and data validation of topographic, geotechnical, rainfall and urban occupation information;
- data input in a digital model (capable of simulating debris flow and flooding);
- calibration and validation of the information input based on the real event which happened in March 1967;
- verification of the results in the area affected by debris flow and flooding, and also their physical parameters such as flow speed and deposition depth in order to aid future urban planning and defense effort. This analysis will also be performed considering the tide level associated with the rainfall event which may trigger these phenomena.

3.2.1 Getting the Database

The database was divided into the following groups: tidal levels, rainfall values and geographic data. Data characteristics and capture are explained below.

3.2.1.1 Tidal Data

The tidal level data come from different sources and institutions, namely:

- IGC tidal station (Cartographic and Geographic Institute) in Ubatuba;
- IOUSP tidal station (Institute of Oceanography, USP – University of São Paulo) in Ubatuba;
- CTH tidal station (Hydraulic Technological Center) on Martin de Sá Beach / Caraguatatuba;
- São Sebastião Harbour tidal station;
- Buoy of CEBIMar (Marine Biology Center, University of São Paulo) in São Sebastião.
- The compilation of information from tidal stations enabled us to generate a large database from 1954 to 2005, with some intermediate gaps. This database comprises over 225,000 hourly values of tidal levels.

3.2.1.2 Rainfall Data

The composition of the rainfall database in the city of Caraguatatuba started with investigation of data available from ANA (Agência Nacional de Águas), which represents a Federal Agency of management of water (ANA 2005).

The E2-046 rainfall station (Caraguatatuba) contains data from 1943 to 2010, totaling 24,603 accumulated daily rainfall values and thus it was taken into consideration in this study.

For the debris flow and flooding simulations, which are events that require greater data resolution (minimum hourly rate), the daily values provided by ANA are not optimal. Hence, a statistical analysis was necessary in order to achieve a reliable conversion between both resolutions, as demonstrated in the paragraph 3.2.3.2.

3.2.1.3 Geographic Data

Geographic data comprises topographic, urban occupation and geotechnical data.

Topographical plans from the Cartographic and Geographic Institute of the State of São Paulo (IGC-SP) at a 1:2000 scale were used to define the topography of the lower region of the Santo Antônio River basin, associated with smaller scale maps obtained from Cruz (1974) for its greater areas (Figure 3.4).

The inhabited areas of the municipality were also mapped in order to better highlight the association of the flow and flooding-affected areas with the risks that the populations face (Figure 3.5).

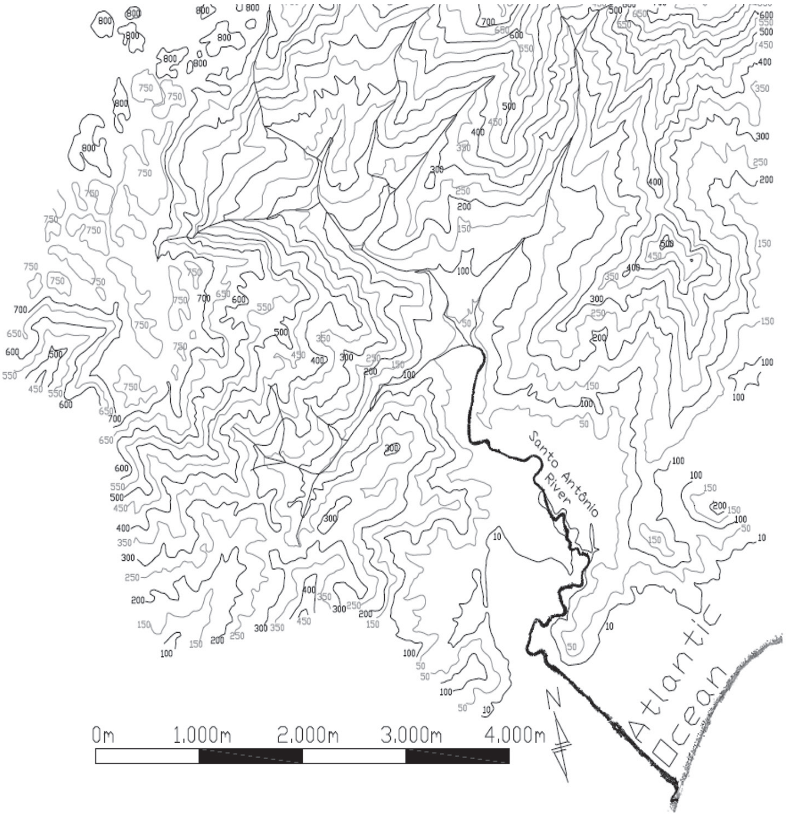

Figure 3.4: Topographical plan for Santo Antônio River Basin (contour lines each 50m).

3.2.2 Analysis of Rainfall and Tidal Data

3.2.2.1 Data Compilation

Referring to the methodology as described in the previous paragraph, the compilation of a tide and rainfall database was performed as initial step.

Tide and rainfall values were organized so as to highlight direct relationships between the daily rainfall in the Santo Antônio River Basin and levels in the tidal stations of the Northern Coast of the State of São Paulo.

Table 3.1 illustrates, as an example, how the data were compiled for the month of January 1954.

At the end of this step, 9.361 days have both rainfall and tides measurements (High tide; Low tide and Mean Sea Level). According to Figure 3.6, tidal behavior of São Paulo North Coast is characterized as semi-diurnal, meaning that in a period of 12.42 hours a complete tide wave occurs (one peak of both High and Low tide); consequently, in a period of approximately 24 hours, two High and two Low Tide levels are recorded.

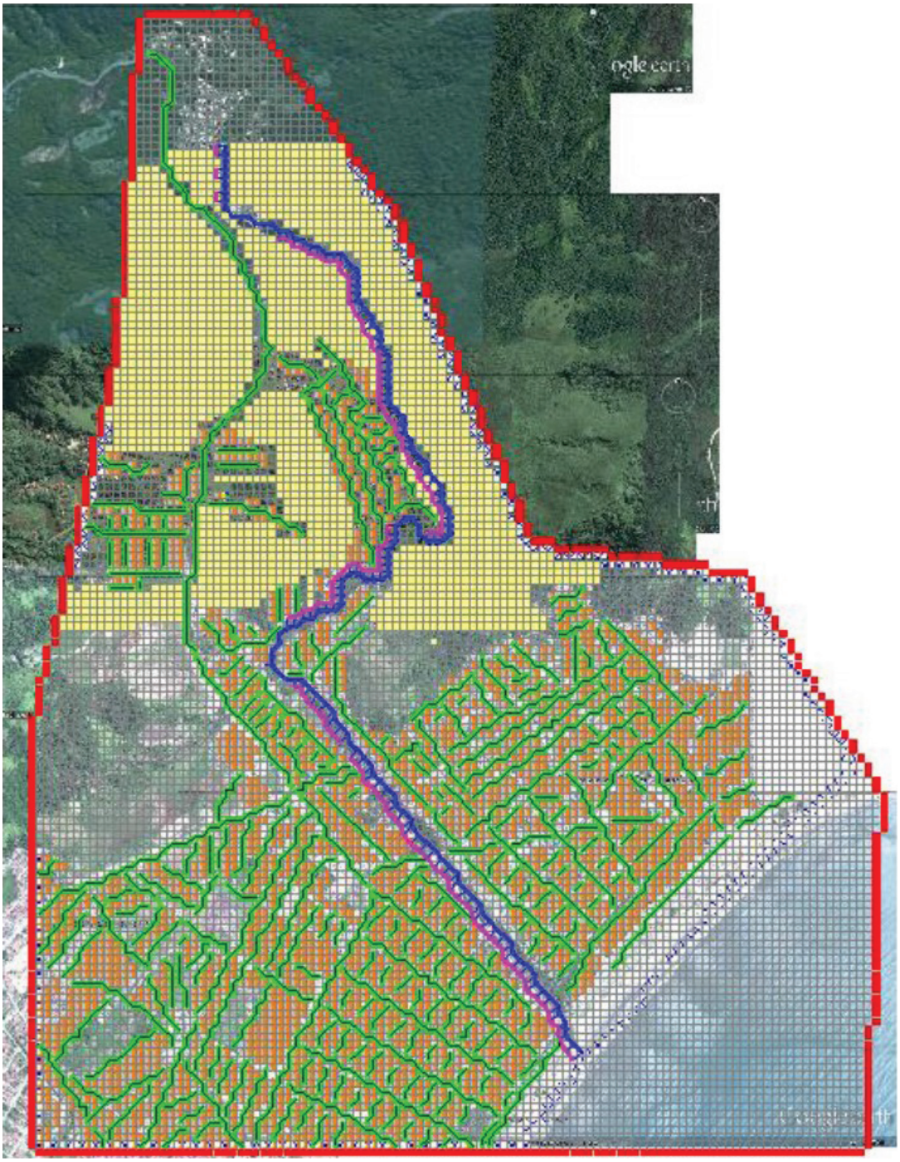

Figure 3.5: Inhabited areas of Santo Antônio River Basin (red – model boundaries, blue – Santo Antônio River’s left bank, magenta – Santo Antônio River’s right bank, green – roads and streets, orange – buildings, yellow – areas with high resistance to superficial flow).

Based on the methodology proposed by Hidroconsult (1979), only the highest and the lowest peaks in each day are selected for the analysis; therefore, the daily Mean Sea Level (MSL) is the result of arithmetic average of all measurements in a period of 24 hours.

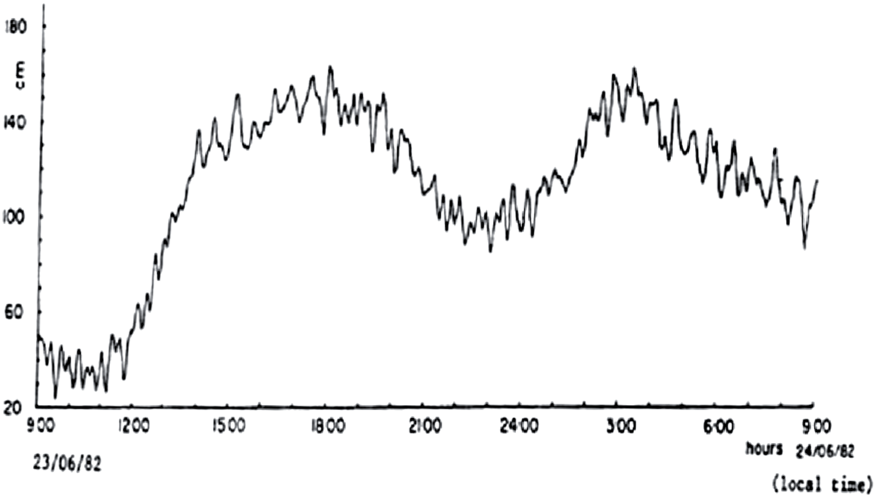

Figure 3.6: Semi-diurnal behavior tide on 23/06/1982 and 24/06/1982.

3.2.2.2 Division of Database Into Rainfall Groups

The next step in the methodology is to divide the database into groups, based on the accumulated daily rainfall: P ≥ 0 mm/day, P ≥ 25 mm/day, P ≥ 50 mm/day, P ≥ 75 mm/day, P ≥ 100 mm/day. The division of accumulated daily rainfall into these groups followed the concept that the range of measurements is between 0 mm/day and 190 mm/day; thus, in order to obtain 5 groups of accumulated daily rainfall, the intervals of each group is 25 mm/day. The application of this methodology in another region, where the rainfall range is larger, can generate large interval as, for example, each 50 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 the occurrence of rain-tide phenomena, as demonstrated below; as a consequence, small rainfall ranges implies more probabilistic curves.

The altimetry levels followed the IBGE reference, which represents the Brazilian standardization of surface levels (Brazilian altimeter Datum), according to the Imbituba tidal station located in Santa Catarina State. It is absolutely important to equalize all measurements of tidal levels to the same altimeter reference.

3.2.2.3 Reorganization of the Database Parameterized by Tidal Levels

The data were reorganized, after the separation into rainfall groups, following the guidelines below:

- for each precipitation interval (it was convenient to separate them into different worksheets), the table was rearranged in a decreasing order, using tidal levels

Table 3.1: Example of compilation of daily tidal levels and daily rainfall, for the Santo Antônio Basin, in January 1954.

Date	Data of tidal station (IBGE Reference)			Rainfall (mm/day)
	Lowest Low Tide (cm)	Mean Sea Level (cm)	Highest 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

as a parameter (highest tides at the top of the table). This methodology can be applied separately to daily Low tides, daily Mean Sea Level and daily High tides, according to specific applications. As an example, for drainage it is appropriate to use the Mean Sea Level values, for navigation the extreme measurements are appropriate, whereas for flooding analysis, the Highest tidal levels are suitable;

- note that the rainfall values should always refer to the corresponding daily tide values;
- for each precipitation interval, the largest annual tide occurrence (in the case of Low tides, the smallest annual occurrence) should be selected because the Return Period (TR) will be calculated in years. This explains the reason for the use of the maximum annual values in Table 3.2.

As a result of this step, there are several tables (one for each precipitation interval) sorted from the highest to the lowest tides with annual extreme values. It is worth noting that the event (day) must be repeated at different rain's intervals. For instance, it is possible to have the same day with rain over 100 mm (P > 100 mm/day) and rain over 75 mm (P > 75 mm/day).

3.2.2.4 Calculation of Probability of Combined Events (Rainfall Tidal Level)

At this stage, probabilities of occurrence of certain sea levels are calculated, associated with a rainfall range using a Gumbel mixed-model as suggested by Yue *et al.* (1999). Table 3.2 illustrates this step for the precipitation interval P ≥ 0 mm/day and mean sea level. For each precipitation interval, a different table was created. The highest sea levels represent lower probabilities of occurrence, compared with lower tides; consequently, the table shows the statistical probability of occurrence of each event (sea level) to be equaled or exceeded by year concomitantly with P>0 mm/day. In other words, the application of following values (P>0 mm/day and MSL 12.76 cm) represents a probability of 97.14 % of occurrence of this daily event during the year, independently of the other past years. This concept explains the relationship of Return Period in years related with daily event.

3.2.3 Debris Flow and Flooding Analysis

3.2.3.1 Topographic Data Treatment

A data transformation was made from the scanning of paper-formatted documents into the AutoCAD program, and later by tracing the contours of the images. For each of them, the elevation was defined, and the data were then exported into the FLO-2D for subsequent simulation of the event as suggested by Grimaldi *et al.* (2013).

Table 3.2: Calculation of probability of occurrence of combined events (P ≥ 0 mm/day and Mean Sea Level), for the Santo Antônio Basin.

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

continued **Table 3.2:** Calculation of probability of occurrence of combined events (P ≥ 0 mm/day and Mean Sea Level), for the Santo Antônio Basin.

Mean Sea Level (maximum annual) IBGE Reference (cm)	Day	Rainfall (mm)	Probabilities of occurrence P (%)	Order Number
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 3.3: Daily rainfall observed from three different points of the Santo Antônio river basin in the week preceding the disaster of March 18th, 1967.

Station	Coordinates	Days of March 1967 – Daily Rainfall (mm)						
		12	13	14	15	16	17	18
Rio do Ouro	S 23°38’ W 45°26’	0.8	6.5	10.7	0.3	6.5	50.4	195.5
Caputera	S 23°37’ W 45°26’	7.4	0.1	2.7	63.1	7.2	9.2	240.8
Fazenda São Sebastião	S ? W ?	10	0	50	0	20	115	420
Daily Average						13.425	72.4	319.075

3.2.3.2 Rainfall Data Treatment

Unlike the previous detailed data treatment (paragraph 3.2.2), the rainfall event simulated here is not based on a random whole series of days, but only on those days of the week which predicted and culminated in the huge debris flow catastrophe of 18th March 1967. The daily rainfall values used are shown in the Table 3.3.

The processing of turning these daily-based values into hourly-based data was carried out by a statistical method that was developed by CETESB and DAEE (government sanitary / electrical energy companies) (DAEE/CETESB 1980). This method is based on transformation coefficients, presented in Table 3.4, which have been defined though statistical analysis of pluviographic rainfall data in relation with total daily rainfall values.

For example, in order to transform a daily rainfall value into an hourly value, it should be multiplied by the factor 24 h/1d, so as to comprehend the highest rainfall in a consecutive period of 24h. After this conversion, the obtained 24h precipitation

Table 3.4: Conversion factors from daily rainfall values to smaller time frames.

Time Relation	24 h/ 1d	12 h/ 24 h	6 h/ 24 h	1 h/ 24 h	30 m/ 1 h	15 m/ 1 h	5 m/ 1 h
Correction Factor	1.14	0.85	0.72	0.42	0.74	0.7	0.34

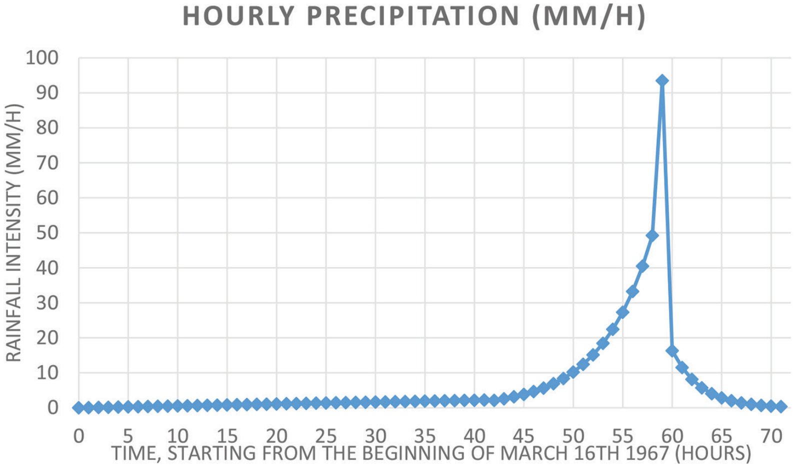

Figure 3.7: Graph of hourly rainfall during the previous days and the day (March 18, 1967) of the catastrophe.

intensity must be multiplied by the 1h/24 h factor in order to estimate the hourly peak rainfall of this day.

Based on the values shown in Table 3.3 and on the conversion factors shown in Table 3.4 as well as on the qualitative description of the event described in Cruz (1974), an hourly hyetograph was created for the specific event, referencing zero as the milestone hour of the beginning of March 16, 1967 (Figure 3.7).

3.2.3.3 Debris Flow and Flooding Modeling

When in possession of sufficient data for modeling the terrain, the computer program FLO-2D (O'Brien 1989) can be used in order to build, calibrate and validate a simulation model. The model used in this program can simulate the spread of a water-sediment mixed flow on terrains of complex topography and roughness, by following the principles of conservation of mass and momentum. The model uses dynamic equations from hydraulics and a finite mesh to predict the progression of a system flow over a grid of elements representing topography and buildings.

For the modeling of a complex hydraulic system, the program uses a set of components and routines, which are calculated for a number of discrete units, called grid cells. Its code contains elements that can simulate rainfall, channel flows, the flow from external sources and along watercourses, infiltration, the effect of dams, bridges, and many other items that can interfere or spread the flood /debris.

The program simulates the channels as a one-dimensional flow through the known geometry of its cross sections while the surrounding areas is a simulated two-dimensional flow, and the inflow exceeds the capacity of the channel bed (full in rough elements). The two-dimensional simulation is performed using numerical integration of the equations of motion and conservation of fluid volume.

In order to input the terrain model, a data transformation was made from the scanning of paper-formatted documents to the AutoCAD program, and later tracing the contours of the images. For each of them the elevation was defined, and the data was then exported to the FLO-2D.

The rainfall hydrogram was input into a HEC-HMS model of the basin and the resulting discharge at the floodplain’s mouth was then input into FLO-2D model as a hydrograph.

Other necessary input values like terrain roughness, sediment coefficients and solid concentration were calibrated on the basis of the results of the model comparison with the real event which happened on 18th March 1967.

3.3 Results and Discussion

Some more relevant results from the rainfall and tide level relationships were obtained on the basis of the methodology described in paragraph 3.2.2. Figure 3.8 shows the graphical result from the statistical analysis of the previous paragraph.

From this graph, Table 3.5 summarizes the main useful values for both maritime and fluvial hydraulic projects in the region; in addition, these values can be considered as input in the deterministic model.

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) with accumulated heavier daily rainfall ($P > 100$ mm/day) a lower Mean Sea Level (40.59 cm) must be assumed; hence, an elevated sea level along with heavy rain is less likely to occur. Another important concept, for example, is that when days with the same rainfall characteristics are considered (i.e.: $P > 0$ mm/day), as larger Return Periods (less likely to occur) are selected, higher sea levels must be adopted. According to the explanation in paragraph 3.2.2.3, only the MSL values are shown in Figure 3.7 and Table 3.5, given that these results are most commonly used in engineering applications, which is based on the fact that sea behavior (tide levels) is constantly changing during the day. Moreover, the daily tidal cycle (Figure 3.6) is larger than other natural events (precipitation), meaning that MSL is used properly for the drainage purposes. Notwithstanding the fact that MSL is most commonly applied,

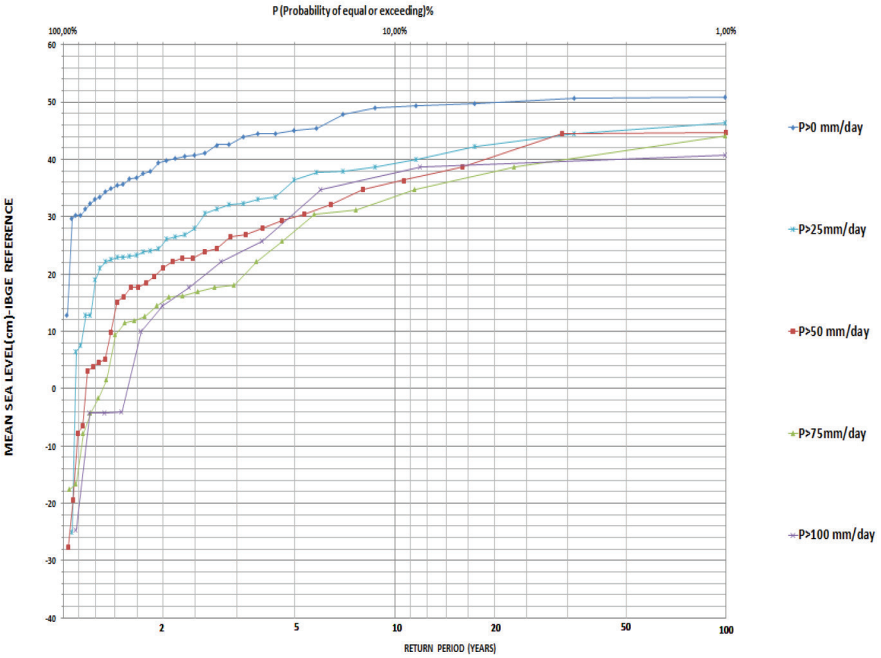

Figure 3.8: Graph of probabilities (Rainfall × Mean Sea Level).

Table 3.5: Results applicable to engineering projects (Rainfall × Mean Sea Level).

Rainfall (mm/day)	**Return Period (TR)-Years**							
	2	**5**	**10**	**20**	**50**	**75**	**100**	
>0	38.56	46.11	49.18	50.28	50.69	50.75	50.77	Mean Sea Level (cm)-IBGE Reference
>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	

the extreme analyses (High and Low tides) are important to specific situations, such as flooding and navigation. As an example, in a harbor project, the statistical results using high tide are important to determine the vessel draught in the access channel, jointly with precipitation parameters for drainage and discharges.

By combining the tide level and rainfall analysis, FLO-2D results were obtained for a defined rainfall data input, as described in paragraph 3.2.3, for two situations: debris flow and flooding occurrences.

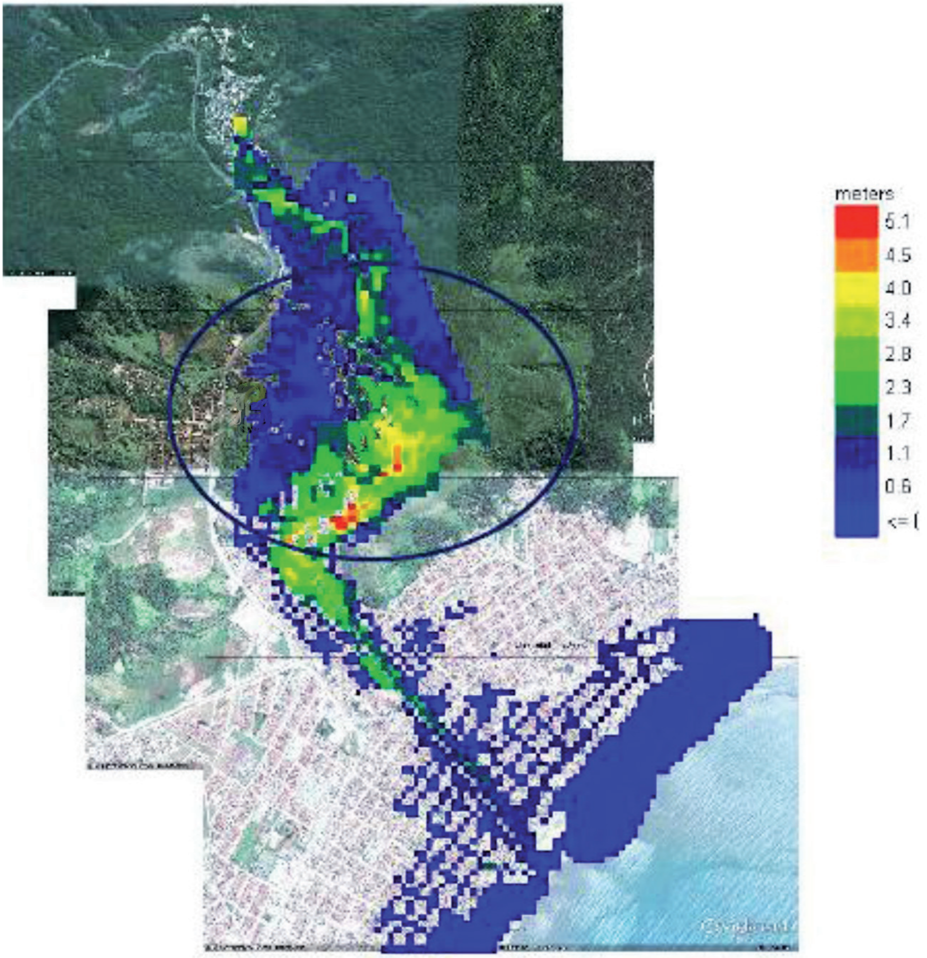

Figure 3.9: Flood depth and affected areas.

The areas affected were defined for these situations and plotted on a map, in order to facilitate understanding of the results.

Finally, by combining these results with the results presented in Figures 3.7, 3.8 and Table 3.5, the real catastrophic scenario of an event of this size is fully characterized (Figure 3.9 and Figure 3.10).

According to Brigatti and Sant'Anna Neto (2008), regarding the occurrence of floods, flooding and debris flow, the north coast has unique characteristics, mainly due to its physical make-up and land use. The land occupation beside the river banks and their mouths (Figure 3.11), together with peculiar atmospheric dynamics and tidal fluctuations, commonly causes serious socio-environmental damage.

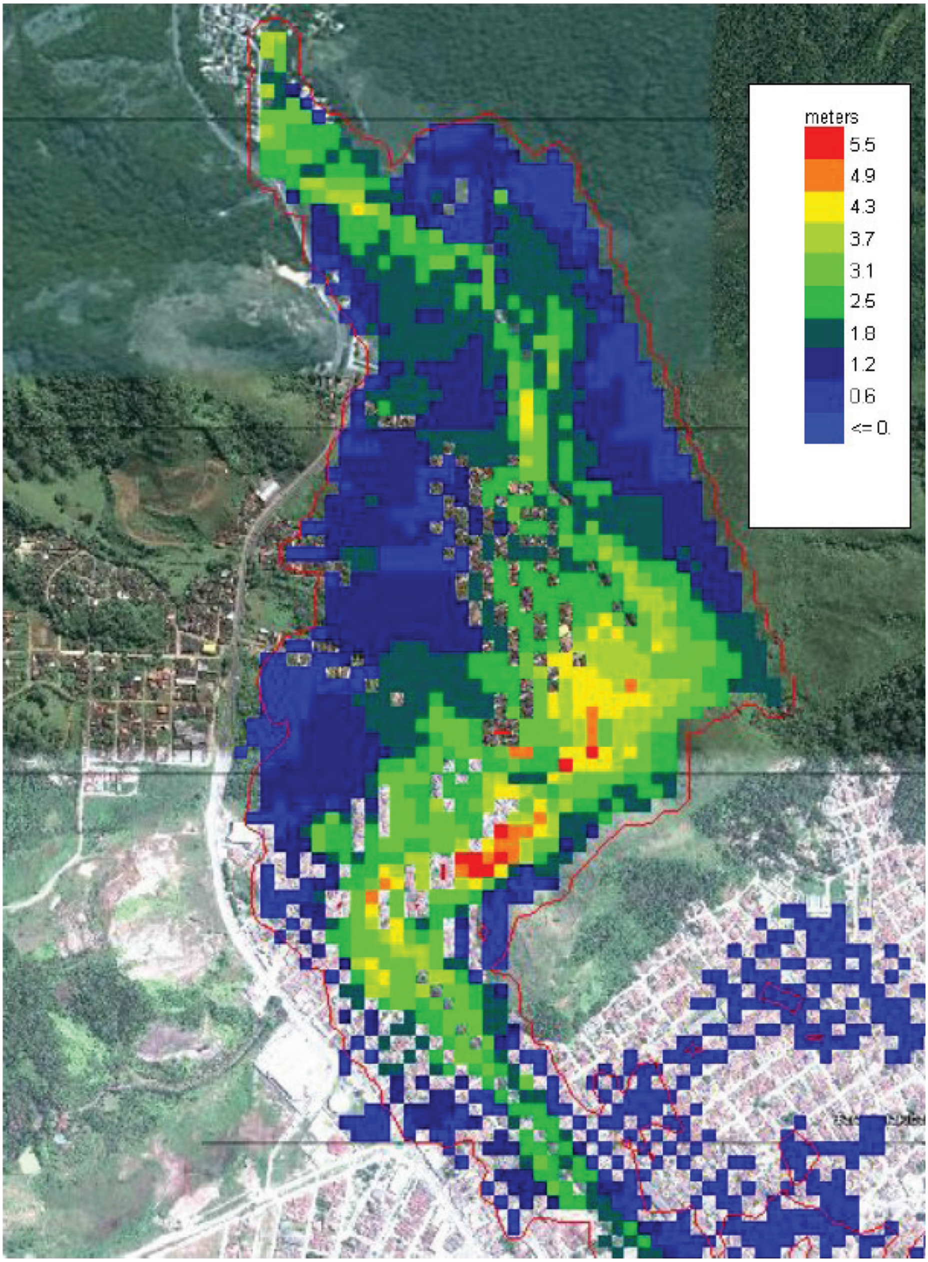

Figure 3.10: Debris-flow depth and affected areas.

Figure 3.11: Occupation by the river flooding area in the northern coast of São Paulo State, Brazil.

The ocean-atmosphere-continent interrelationship is extremely complex and leads to an area of uncertainty. In the specific case of the episodes related to floods, flooding and debris flow, 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) (Cartacho 2013);
- 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 tide episodes) (Cartacho 2013);
- 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 their presence gives the region a complex configuration in relation to rainfall, as noted by Conti (1975), and the orographic effect greatly participates greatly in this dynamic (Cruz 1974).

The climatic characteristics, coupled with steep slopes, the small extension of the coastal plain, the shapes of the basins of major rivers and the ocean dynamics, characterize a fragile region. This is aggravated by irrational occupation and the construction of numerous roads, with the presence of irregularly occupied areas and poor projects carried out in areas susceptible to extreme episodes (Souza 1998; Fúlfaro *et al.* 1976).

3.4 Conclusions

The coastal regions of Brazil have constantly been subjected to extreme events caused by 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 must be based on collection, storage and processing of natural variables data (tidal levels, rainfall heights, waves, currents, etc.), in order to examine phenomena statistically, linking them to the probabilities of occurrence. This research is involved in this initial process.

From statistical studies, the results can be applied to Engineering practices. The coastal projects should consider the lessons learned from past events, both with the direct application of statistical analysis, and by using mathematical models, such as data input for simulations of natural events.

In recent decades, an advanced branch of Engineering has been committed to discussing, from the analysis of databases and mathematical models, whether the projects already built will be affected by climate changes, such as the increase of the Mean Sea Level, more frequent heavy rainfall and debris flow events that destroy cities in the coastal floodplain. If this is the case, repair work will become increasingly more frequent in these regions.

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