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PLUVIAL FLOODING IN SANTO ANDRÉ CITY - SÃO PAULO: OBSERVATION AND PREDICTION

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ABSTRACT: The goal of this paper is to analyze the pluvial flooding that occurs in Santo André region caused by extreme rainfall as well as to propose a statistical model for rainfall flood forecasting. Santo André being located in the São Paulo metropolitan area, it has developed in the floodplains of the Tamanduateí River, and for this reason it has a history of recurrent floods. In this study, three points of the highest frequency of flooding were selected: the river Tamanduateí and its tributaries Meninos and Oratório. The dataset includes daily rainfall data of three rain gauges closest to the rivers. So we carried out a statistical analysis involving the accumulated daily rainfall with flood records on the three rivers. On the other hand, multi-linear regression (MLR) approach is used to construct the daily extreme rainfall prediction model. The results showed that the highest frequency of rains and flooding occurs in the months of January and February with an average of 2 flood events in January. The floods identified as extreme by the number of affected districts occurred in 15 December 2011, where the rainfall intensity exceeded the daily value of 120 mm. On the other hand, the higher frequency of flood events was associated with the overflow of the river Tamanduateí followed by that of Meninos. The maximum daily rainfall associated with these events reached values of 152 mm. In addition, it was confirmed that the rains, both in their mean values, as in their extremes, have increased. The MLR model showed difficulty in capturing the peaks of extreme rainfall that cause floods, underestimating their value. We believe that the MLR model cannot follow the inherent non-linearity of rain. However, the best prediction model was found for the river Meninos, where the model followed the variability of daily rainfall.

Key Words: Pluvial Flooding, Tamanduateí River, extreme rainfall.

1. INTRODUCTION

Santo André is a Brazilian city, part of the Paulista ABC, located in the metropolitan area of São Paulo (MASP). Santo André developed in the floodplains of the Tamanduateí River, having been wrongly "planned", without respect for the nature of hydrologic processes, with the town and its main streets bordering the rivers and brooks built on top of these bodies of water and of the areas naturally destined to contain their overflow in the periods of heavy rains (Santos, 2002).

The urban area of Santo André (Figure 1a) is inserted in the urban hydrographic basin of the Tamanduateí, with its main affluents the Oratorio and the Meninos streams (Figure 1b). The Tamanduateí river basin encompasses 53% of the urban area's hydrography and the remainder of the urban area is divided between the sub-basins of the Oratorio and Meninos streams (CTO, 1997).

Since the 19th century great floods occurred in the floodplains of the Tamanduateí River and, as the years went by, the advance of the urban spot over the territory resulted in a worsening of the problem. A survey made by the Santo André Civil Defense on occasion of the floods during the summer of 2005 showed that around 5,000 people were affected and damages amounted to one million reais (DDC, 2005). Das Neves (2008) documented that during the days of constant rains in the summer of 2005, the peaks of rain and the pluviosity indices were such that the city's and the region's main traffic corridors, which cross the main streams belonging to the Tamanduateí river basin, were immobilized.

The MASP can currently count on a Flood Warning System (SAISP), which provides rain and flooding forecast maps (Fernandes et al., 2000), based on two main data sources: the Ponte Nova meteorological radar and a telemetric network of the Upper Tiete basin. The SAISP helps Civil Defense in preventing or mitigating Natural Disasters in the RMSP. However, few studies exist that have focused on the forecast of rains associated with floods in the Tamanduateí river (Santos and Pereira Filho, 2003; Fernandes et al., 2000), in spite of the fact that these are the most frequently observed causes of disasters in the city of Santo André.

Whereas the impact of urban flooding, i.e. the extent of the flooded areas, is directly related to the intensity of the rain, the degree of soil impermeability through roofs, paved streets and yards, among others, and the town drainage system, in this study we will only focus on the triggering factor i.e. rain intensity.

In this context, this work proposes to evaluate the history of urban flooding in the region of Santo André, analyzing the variability and the frequency with which these events have occurred over the last 14 years, and to develop a statistical tool for the forecasting of extreme rains associated with floods in the city of Santo André. The study is justified by the impact a flood has, mainly on the population, in terms of material and human losses, interruption of economic activities in the flooded areas and contamination by water-transported diseases such as leptospirosis and cholera, among others (Das Neves, 2008).

2. DATA AND METHODOLOGY

We used daily rainfall data from three rainfall stations (E3-159, E3-160 e E3-161), for the period 1999-2013, which are located in the basin of the Tamanduateí river and its tributaries, within the municipality of Santo André (Table 1 - Figure 1b). These data were provided by the Department of Water and Power (DAEE / CTH). Additionally we used historical data of floods, obtained from historical media, newspapers, and the Fire Department of Santo Andre, as well as the work of Valverde and Cardoso (2012). With these data, we constructed a climatology of flooding and frequencies, and the number of districts affected were evaluated and related to the intensity of rainfall. For the analysis of rainfall as well as construction of the climatology, we used the technique of percentiles (Neter et al., 1989) to determine the maximum daily rainfall during the study period.

The forecast tool was based on the data series of daily rainfall at each station and the statistical technique of multiple linear regression (MLR). The MLR model uses a variable to be predicted, the dependent variable, which is expressed by a linear function of the independent variables, dependent variables which are referred to as predictands and independent variables as predictors (Neter et al., 1989). The data set was divided into two periods, one for training (1999-2011) and another for validation (2012-2013). The training period is used to determine the weights of MLR equations. The validation set was used to evaluate the performance of the forecast tool. Three experiments were done, and three models were built, where rain flooding would be provided by the rain that occurred two, three and four days respectively before the event.

Table 1 – Geographic locations for the ground stations in the city of Santo André

Prefix station rainfall	Name	Lat	Long	Basin	Period
E3-159	PB - Campestre	23^o38'53"	46^o32'47"	River Tamanduateí	1999-2013
E3-160	PB - Lucinda	23^o37'33"	46^o31'06"	Rib. Oratório	1999-2013
E3-161	PB - Jardim do Mar	23^o41'15"	46^o33'36"	Rib. Dos Meninos	1999-2013

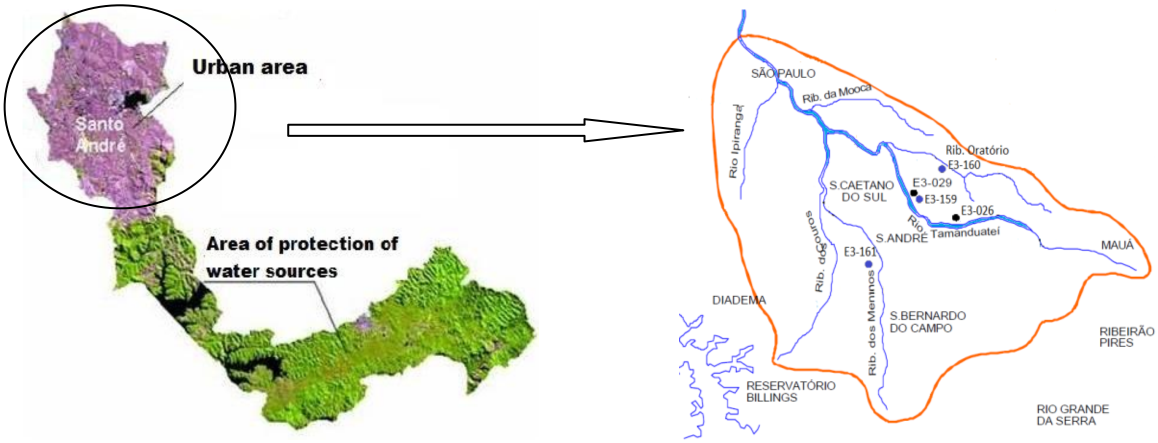

Figure 1 - Map of Santo André (a) and contour (▬) of Tamanduateí River (▬) basin with the location of the rain gauge stations (●) near Tamanduateí River and its tributaries Meninos and Oratorio (b). Figure adapted from Santos and Pereira Filho (2003).

3. RESULTS.

Figure 2 shows the pattern of the annual cycle of flooding events (Figure 2a). The months of most occurrences are January and February, accounting for an average of 16 events in January and 13 in February. In the inter-annual analysis of flooding events (Figure 2b) a substantial variability can be observed, with the years of 2010 and 2011 standing out with the largest number of floods, followed by the year 2008. The red line in Figure 2b, which indicates the number of districts hit, also shows a great variability, not always matching the behavior of the number of floods. E.g., the years 2004, 2008, 2009 and 2010 present the same number of districts hit by the floods. However, the year 2010 showed a higher frequency of events, meaning that the majority of flooding events in that year hit less districts compared to the events that occurred in 2009, 2008 and 2004. In the year 2009, the flooding rain was more intense, causing a larger number of districts to be flooded. On the other hand in 2011 a greater frequency of flooding events was observed, same being intense, as also a larger number of districts were flooded.

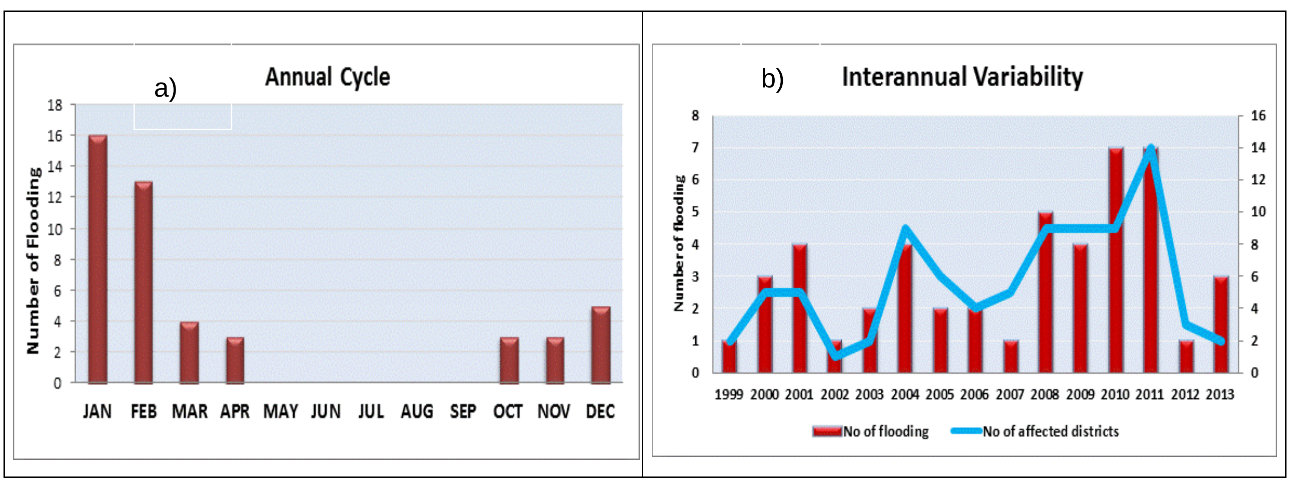

Figure 2 - (a) The annual cycle of occurrence of floods for the period 1999-2013, and (b) inter-annual variability of flood events, and number of affected districts (▬).

Figure 3 shows the frequency of flooding events due to the overflowing of the rivers studied over the period 1999-2013. One observes a great variability, and also that there were years (2004 and 2005) that floods in Santo André were associated with the overflowing of three rivers: the Meninos and Oratorio streams and the Tamanduateí river. On the other hand, the flooding caused by the Meninos stream and by the Tamanduateí river occurred practically every year. The years 2005 and 2008 stand out with a higher frequency of floods due to the overflow of the Meninos stream. Besides, the occurrence of floods associated with the overflow of the Tamanduateí river increased significantly in the years 2010 and 2011.

It should also be pointed out that since 2007 no floods occurred associated with overflow of the Oratorio stream. This may be related to the construction of the Oratorio containment pool, which started in October, 2005 and was concluded in April, 2007. This pool was constructed in Jardim Elba and benefits mainly the districts of Vila Prudente, Coral and California. Before being built the consequences of floods in these areas were serious: people and houses carried away by the rains, and the spreading of diseases, aggravated by the great volume of water that invaded the homes. After the construction of the containment pool floods in this area were considerably reduced.

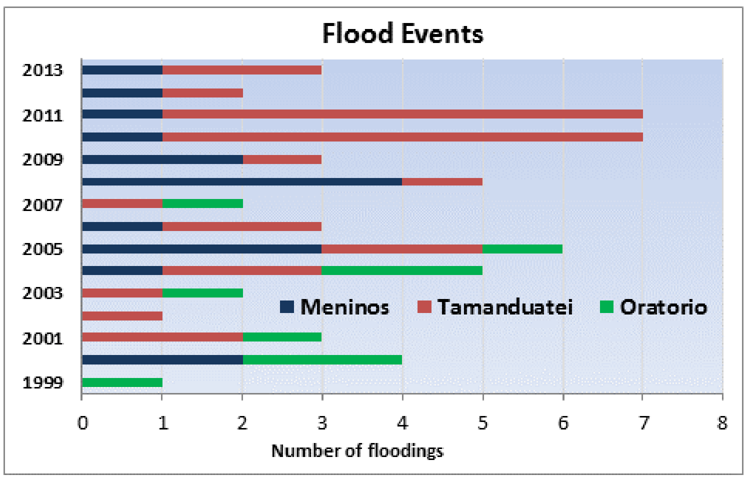

Figure.3 - Events of flooding associated with the overflow of Meninos and Oratorio streams and Tamanduateí River.

Figure 4a shows the monthly distribution of the averages of historical series at the three rain gauge stations near the rivers (Figure 1b)). We can observe the similarities in the monthly distribution of the averages of the historical series at the three stations, presenting a well defined seasonality, with a rainy and a dry period. In regard to rain intensity, the month of January shows the greatest precipitation index, followed by the month of February, which explains the greater occurrence of floods in these months, as demonstrated in Figure 2. Station E3-161, near the Meninos stream, showed the most intense rains in January, with an average difference of 12 mm compared to the other stations. On the other hand, in the month of August the lowest precipitation was registered at the three rain gauge stations, station E3-160 near the Oratorio stream presenting the least rains.

The 95 percentile rains which characterize extreme rains associated with flooding events are shown in Figure 4b. Rain gauge station E3-161, near Meninos stream, shows the largest accumulated extreme rainfall for January, with a monthly value of 459 mm. The month of March also stands out at rain gauge station E3-160, near the Oratorio stream, with a 95 percentile value of 490 mm, indicating that in this month extreme rains must have caused extreme flooding events.

The daily rain intensity values for seven flooding events are shown in Figure 5a. The March 18, 2009 flood event stands out, when accumulated daily precipitation was 152.5 mm at station E3-161, causing the Meninos stream and the Tamanduateí river to overflow, affecting six districts: Jardim Bom Pastor, Principe de Gales, the Center, Vila Palmares, Valparaiso and Jardim Santo André. Figure 5b illustrates this event of March 18, 2009, with the overflow of the Tamanduateí river flooding the Avenue of Estados.

The flood event of January 12, 2005 was also an intense event which affected a large part of the ABC region. In terms of daily rain intensity, the E3-161 station, near the Meninos stream, had the highest reading: 120.7 mm. The districts of Vila Luiza, Jardim Utinga, Vila Pires, Center and Vila Floresta were the most hit. This flooding event was characterized as very intense due to the number of districts affected. In the February 1999 and January 2004 events, the rain gauge station E3-160, near the Oratorio stream, showed the greatest daily rain intensity: 100 mm. Specifically during the January 30, 2004 event, the districts of Jardim Utinga, Parque Novo Oratório, Parque das Nações, Parque São Lucas and Vila Homero Thon were most hit by floods and overflows.

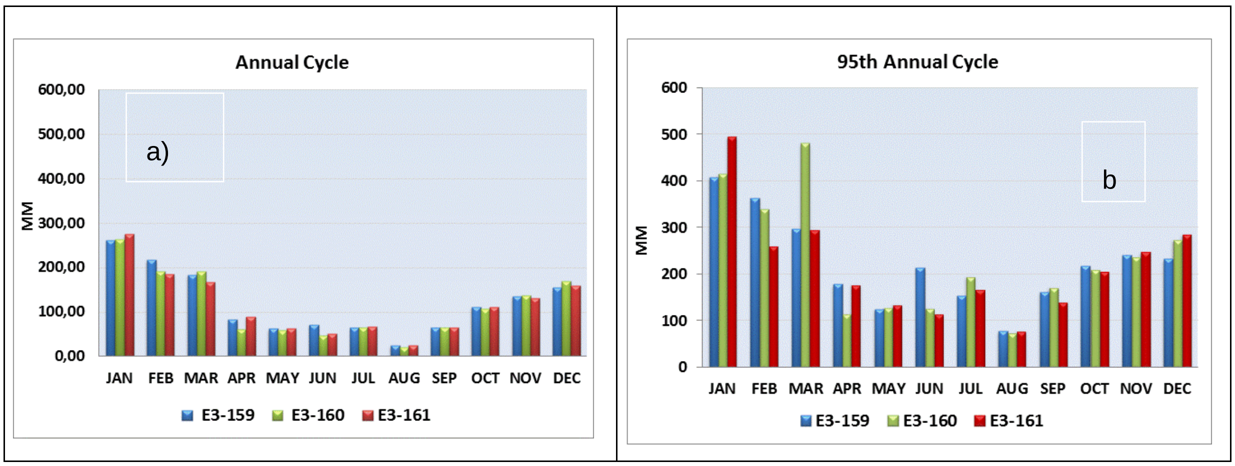

Figure 4 – Annual climatologic cycle of precipitation (a) and 95 percentile (b) for the three rain gauges E3-159, E3-160 and E3-161.

Another important aspect to be highlighted in Figure 5a is the great variability of rainfall among the three rain gauge stations. When the rains are localized or convective, their variability is greater and the effect of islands of heat and urban pollution should contribute to the increase or decrease in rainfall. On the other hand, when the rains are associated with more persistent atmospheric systems, such as the South Atlantic Convergence Zone or cold fronts, the rains at the three rain gauge stations tend to show less variation in intensity rates.

The performance results of the MLR forecast model for the three experiments evaluated by the correlation coefficient (ρ) and by the bias are shown in Figures 6a and 6b. The ρ values show that the best results were obtained for rain gauge station E3-161, near Meninos stream, with the highest correlation for test #3 (including, as predictors, the rainfall occurred four days before the forecast rain) (Figure 6a). The bias shows, however, that the average value of the rain was overestimated, mainly associated with the values that occur in the period of little rain (Figure 6b). For station E3-159, near the Tamanduateí river, the lowest correlation and low negative bias were obtained, which clearly shows the underestimation of the maximum rain data (Figure 6a).

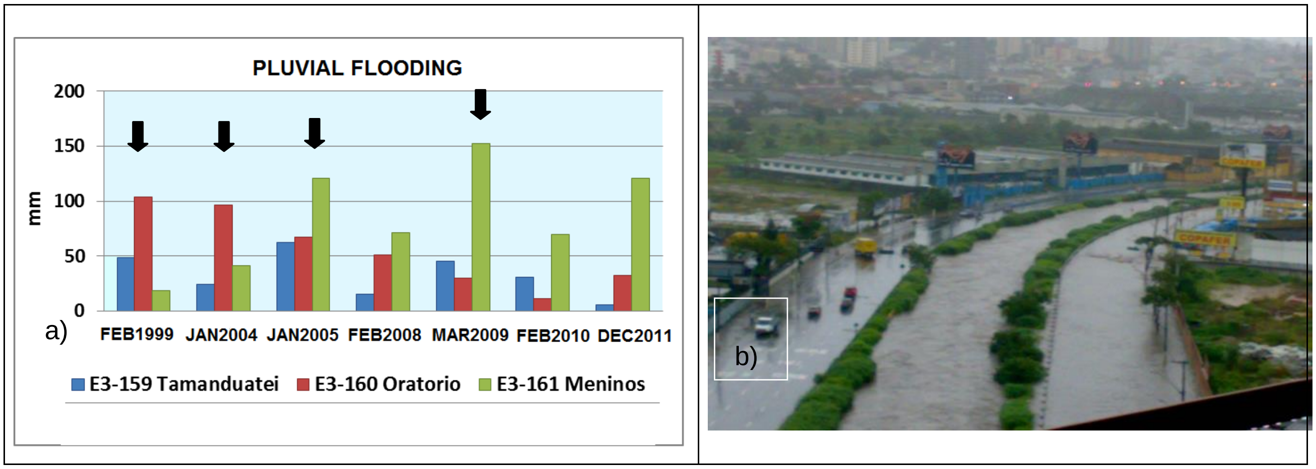

Figure 5 - (a) extreme rainfall events associated with floods, and (b) Images illustrating the flood occurred on March 18, 1999, with the overflowing of the river Tamanduateí.

In general, in the three experiments and at the three rain gauge stations, the model manages to capture the rain's variability in the training phase, but it underestimates the high intensity peaks associated with the occurrence of flooding. On the other hand, it overestimates in less intensity the periods of minor rains. This result influences the forecast performance, as shown in figure 6.

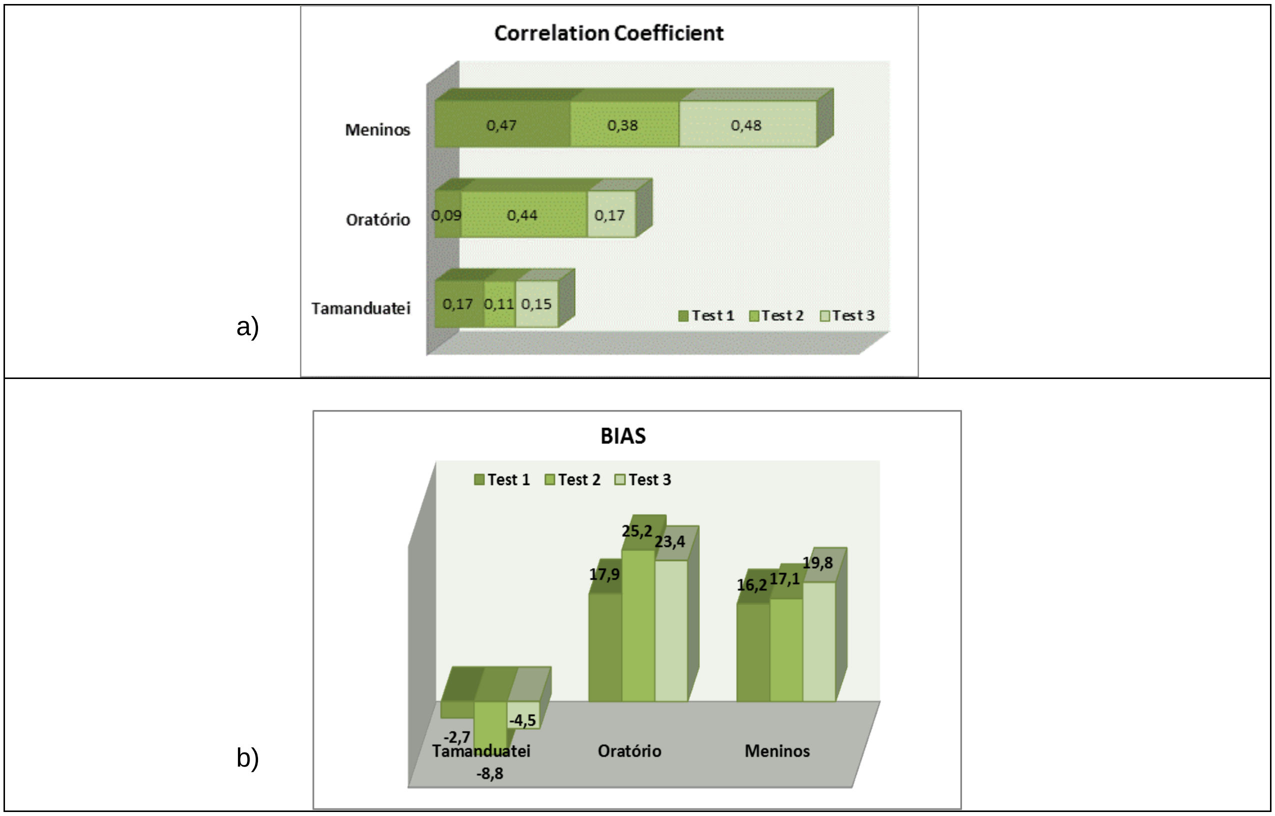

Figure 6 - Correlation coefficients (a) and Bias (b) for the forecasts using MLR for the three stations: E3-159, E3-160 and E3-161 close to the Tamanduateí River and its tributaries Oratório and Meninos, respectively.

4. FINAL CONSIDERATIONS

This work presents the results of the behavior and frequency of flood occurrences in the city of Santo André, as well as the intensity of the events, evaluated by the number of streets and districts affected, also related to the intensity of the rains. The analysis focused on the hydrographic basin of the Tamanduateí and its main tributaries, the Meninos and the Oratorio streams, and on the intensity of the rains that were associated with the overflowing of these rivers. It was determined that the rains were more intense in the areas located near the Meninos stream, and that 2011 was the year with most frequent and extensive flooding, measured by the number of districts hit and by the intensity of the rain which exceeded 120 mm per day. It was further found that the greater frequency of floods was associated with overflow from the Tamanduateí river, followed by that of the Meninos stream.

On the other hand, the MLR forecast model showed difficulty in forecasting peak intensities of rain associated with the occurrence of flooding, but the best results were obtained for the rain gauge station near the Meninos stream. It is believed that the forecasting model may be improved by including other predictors, such as flow and water level in the river. In addition, information about the characteristics of the urban areas which modify the morphologic characteristics of the Tamanduateí basin may also be helpful in improving the forecasting model.

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