# OPERATION OF THE HYDROLOGICAL WARNING SYSTEM IN THE CAÍ RIVER BASIN PRELIMINARY STUDIES

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**ABSTRACT** - This paper presents various issues that arose during the deployment and operation of the flood warning system in the Caí river basin, for which the answers were sought by the analysis of the historical series of river levels and of rainfalls. These analyzes included setting threshold river levels for the location for which flood warnings are required, research the most likely months of flooding, defining low, medium and high levels for certain gauging station, estimating the travel time of the flood wave between monitoring points, and the totals of rain that signal risk of flooding. Particularly, it is studied a simple criterion for setting the flood warning threshold level. The knowledge acquired has proved important for the understanding of flood events, providing relevant subsidies to the operation of warning systems.

Key Words: Flood Warning System, Characterization of Floods, Caí River Basin.

## 1. INTRODUCTION

In order to make predictions of levels for the cities of São Sebastião do Caí and Montenegro the CPRM - Serviço Geológico do Brasil began the implementation in 2010's of the project "Hydrological Alert System in the Caí River Basin" (Pedrollo et al., 2011).

The system consists in seven points for monitoring rain and levels, namely: Capão dos Coxos, Linha Gonzaga, São Vendelino, Nova Palmira, Barca do Caí, Costa do Rio Cadeia Montante e Passo Montenegro (Figure 1). These stations transmit data from 15 to 15 min to a central forecast, which have basically performed the following activities: monitoring data, forecasting levels with mathematical model and issuing alerts if necessary.

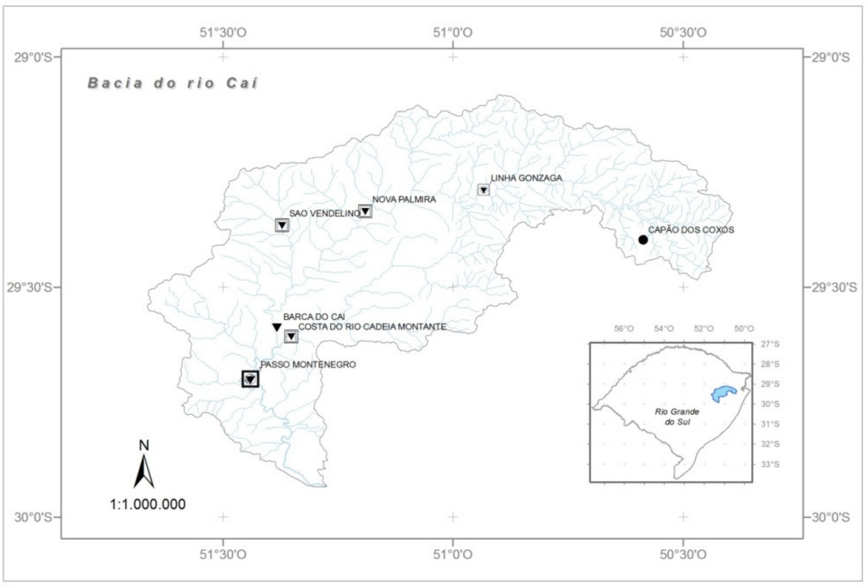


Figure 1: Caí River Basin with Gauges

With the implementation of the flood warning system of the Caí River a number of issues arose which responses were important to identify and manage emergency situations. We can mention, for example: (1) what are the values that characterize levels as low, medium and high?; (2) what is the flooding threshold (the gauge reading at which flooding impacts begin) at the location for which flood warnings are required?; (3) what is the flood warning threshold level (level from which more constant monitoring and maybe issuing alerts are required)?; (4) what is the magnitude that can reach flood events?; (5) what are the rainfall amounts which has the potential to cause flooding?; (6) what is the travel time of the flood wave between monitoring points?; (7) what is the frequency of flooding in the basin?

During flood events, under the pressures arising, time will be insufficient for analysis and discussion regarding the decision to issue an alert (Sene, 2008), so the previous answers to these questions are of great importance.

## 2. PRELIMINARY STUDIES

### 2.1 Flooding Threshold Level

The flooding threshold is the gauge reading at which flooding impacts begin (and for which a warning is required), such as property flooding, or flooding of roads, or overtopping of levees (Sene, 2008). It may be recognized by observation alone, if the locations for which flood warnings are required are gauged. It happens when the volume of water exceeds the carrying capacity of its river bed, respectively, to the cities of São Sebastião do Caí and Montenegro, for this river basin.

At São Sebastião do Caí this level was set from the observation of the cross section of the river at Barca do Caí gauging station and field observation, because the sections of the river on the river shore affected by the flood are not significantly different from the section of the river where the gauge station is installed. Thus, the flooding threshold level was set to 1000cm at Barca do Caí gauge station.

At Passo Montenegro gauge station, the river spills in higher levels than in riverside urban part of the municipality of Montenegro. Therefore, it is not possible to use this gauge station to establish the flooding threshold level. However, observations registered nearby (at Tanac Industry SA) were adjusted to establish a linear relationship which fitted well with the gauge readings. Thus, the flooding threshold level was set to 600cm at the gauge station of Passo Montenegro.

### 2.2 Quantitative Characterization of Levels

To characterize the river level as low, medium or high, the defined duration curves for three gauges (Nova Palmira, Barca do Caí and Passo Montenegro) of Caí River with historical data series were defined using daily mean levels.

Figure 2 shows the duration curves of Nova Palmira, Barca do Caí e Passo Montenegro defined respectively for a period from 1942 to 2009, 1947-2009 and 1939 to 2009.

According to the resulting duration curves, less than 5% of the observed levels correspond to floods, for both Barca do Caí and Montenegro sites.

By considering the gentle slope of the curves in this range, one may define the levels with durations between 20% and 80% (which means 60% of the historical observations), as the medium reach of the curves. Consequently, it sets, outside, the low and the high reaches. So, the flooding threshold does occur with much lower frequencies than the threshold to the high levels, according to this criterion.

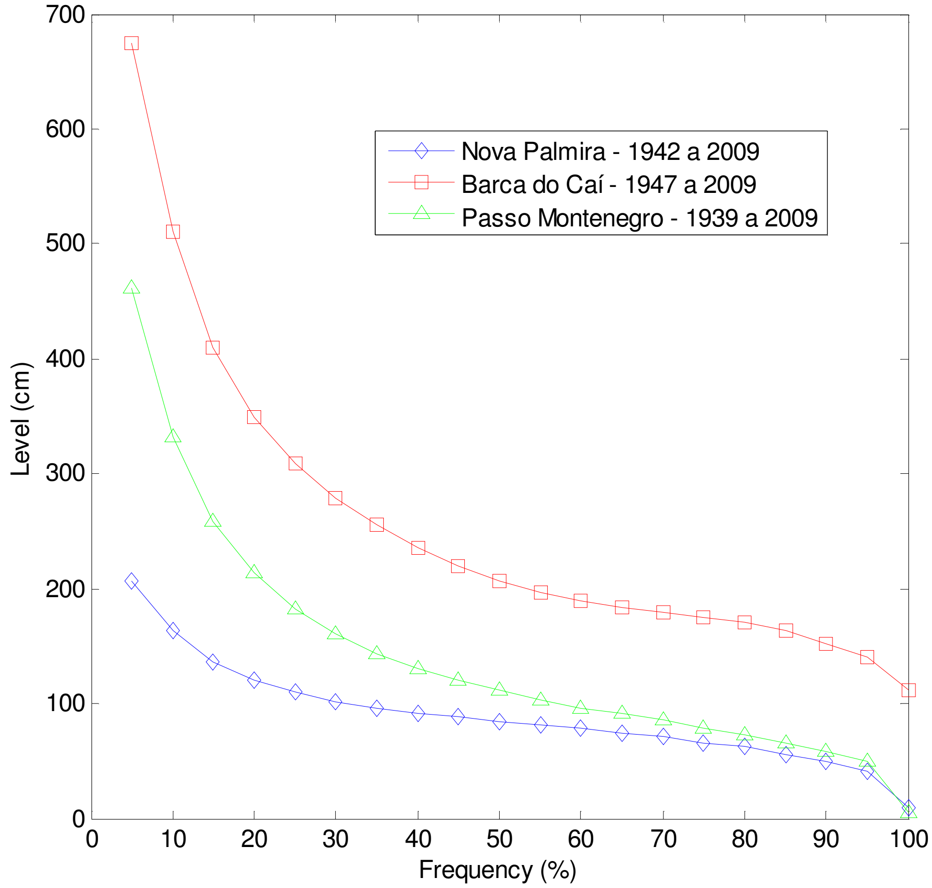


Figure 2: Level Duration Curves

### 2.3 Flood Warning Threshold Level

Flood warning threshold levels are important components in flood warning systems, defining the levels at which the decision to issue a flood warning should be taken. Threshold values may be defined based on a combination of experience and analysis of historical data.

The key issues in the definition of the flood warning level are: For the considered lead time, what is the level from which floods are likely to occur, and with which probability?

As the series of assessments were obtained from conventional stations, with data from 7 am and 5 pm, its range was 10 and 14 hours, considered, by simplification, as roughly 12 hours.

At first we thought of analyzing data from all events available, looking for the smallest level that occurred 12 hours before level has reached the flooding threshold level. For Barca do Caí gauge station this reading was 336cm, in December 2003 event, which is a level much frequent to be defined as an alert level. In Passo Montenegro this level was 440cm, observed in December 1991 event.

Whereas levels so frequent, relatively low, could not be used as a flood warning level, the following idea was to associate probability of occurrence of these values. In this sense, using all available data, level ranges were established and it was verified how many times the level of the river was in that range of dimensions. Counting only instance where the river was rising, it was selected those in which about 12 hours after the river reached the flood level. At these points it was adjusted to an equation relating levels to frequencies to approximate probabilities.

Figures 3 to 4 show the curves fitted to the point coordinates (h, cm), being the river rising to the frequencies in which the level reaches the flood threshold, respectively in Barca do Caí and Passo Montenegro.

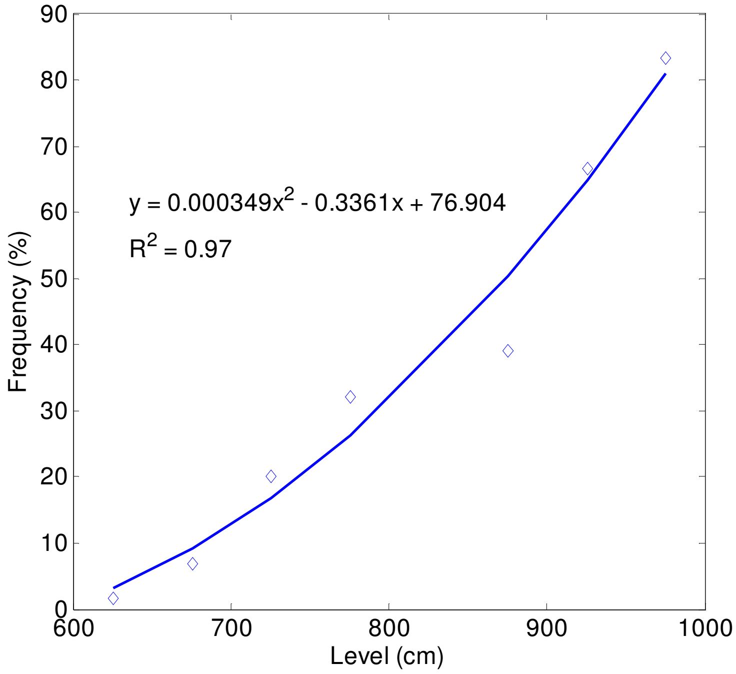


Figure 3: Curve of Frequency of the Foregoing Levels - Barca do Caí

For example, for the dimension 875cm, with the river on the rise, there is a probability round to 0.5 of the level reaches 1,000 at about 12 hours in Barca do Caí. On the other hand, the level for which the probability of surpassing the flood threshold level at Passo Montenegro is 0.3 results approximately 550cm, from the Figure 4.

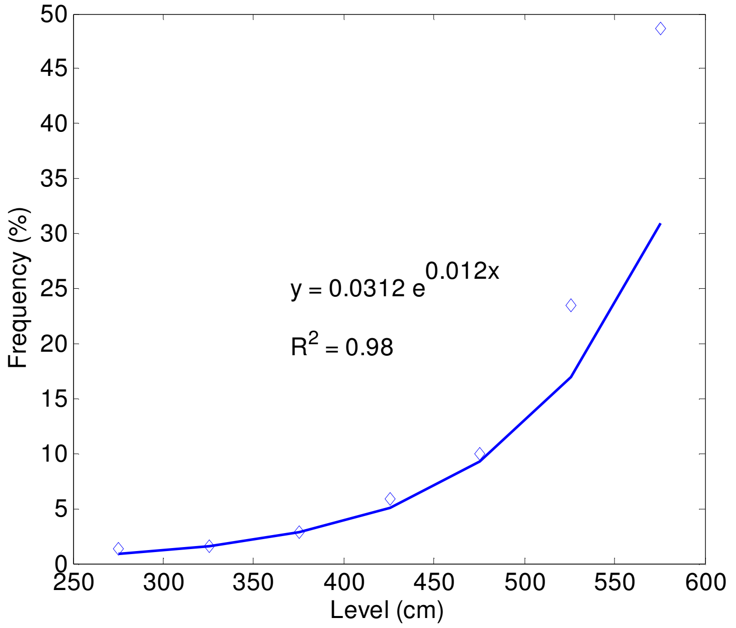


Figure 4: Curve of Frequency of the Foregoing Levels - Passo Montenegro

Thus, the definition of a flood warning threshold level depends on the adoption of a risk criterion to be accepted. Limiting the risk by adopting a flood warning threshold level too low may result in too many false alarms. Conversely, adopting too high flood warning threshold level, although reducing the occurrence of false alarms, it will imply in accept increased risks to endangered population and property. It is a compromise to be taken by decision-makers.

In the case of the frequency function adjusted to Passo Montenegro, since it is necessary a great additional increase in volume when they approach the overflow level, and not always occurring in quantity so pronounced, it is observed that the levels stop ascending or even regress often around 50%, even though almost reached the limit level.

## 2.4 Magnitude of Floods Events

In the period 1984-2013 the Caí River reached the maximum level of 1.475cm in Barca do Caí gauge on 11/10/2000 and for the period from 1991 to 2013, 870cm in Passo Montenegro gauge on 23/09/2007. In Figure 5 are presented for the period 1984-2013, all peak values events above the level of flooding in early Barca do Caí and Figure 6 analogously Passo Montenegro for the period 1991-2013.

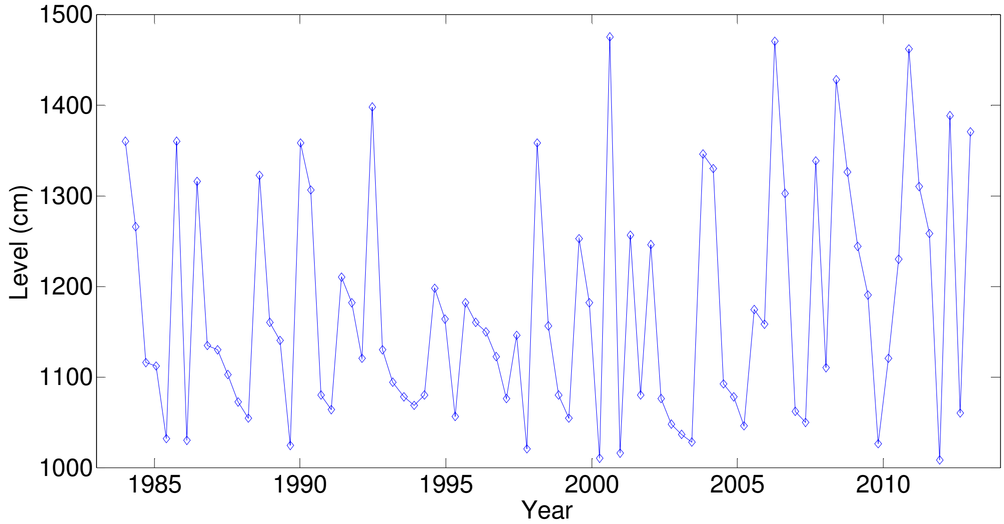


Figure 5: Maximum Level Hits in Barca do Caí

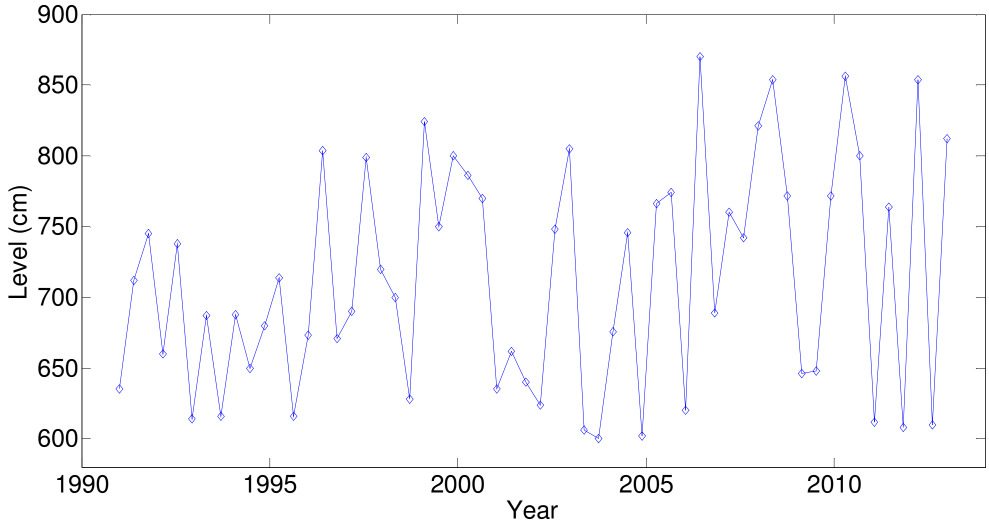


Figure 6: Maximum Level Hits in Passo Montenegro

The maximum levels reached almost five meters above the level of flood at Barca do Cai, and almost tree meters above the flood threshold level at Passo Montenegro. However, it is observed that about 70% of cases are below the level of 1.200cm and 750cm, respectively, for Barca do Caí and Passo Montenegro, which, however, already cause significant effects at both cities (Oliveira, 2010).

## 2.5 Rainfall Thresholds

Rainfall values alone do not provide a full indication of flooding potential, since the soil moisture state and other factors may also influence the magnitude and timing of flooding.

Rainfall threshold criteria may be expressed in terms of the quantity of rainfall in a given period which has the potential to raise the gauge readings above the flooding threshold.

On this analysis we used data of precipitation of rainfall gauge stations of Capão do Coxos, Nova Palmira and São Vendelino. In the period 1991-2009 the total daily rainfall that caused rise of the river level to the flood threshold level ranged between 59.5 and 209.3 mm. For the events where rainfall totals were less than 90mm and at the beginning of the event the river was around its average level, the readings has not reached peak values very higher than the flooding threshold level.

In the 2007 event, it rained a total of 209.3mm for 5 days, and at Barca do Caí gauge station, where the level was initially 166cm, the gauge reading reached 1.470cm. In October 2002, when it rained 59.5mm, its gauge level at the beginning of the event was 590cm and the maximum elevation was 1.048cm.

It is therefore very important the antecedent moisture condition of the soil, for the basin response is different when it rains after a dry period than after a wet one.

## 2.6 Travel Time of the Flood

The travel time between the monitoring points is important for the knowledge of the time available for actions based on the observations upstream, which is also related to the lead time of the forecast models that make use of this information.

The lead time requirement for flood warning may influence the network design, once a way of extending it would be to install a gauge further upstream, but this introduce additional uncertainties by increasing the rainfall lateral inflows (Pedrollo and Lanna, 1991).

Table 1 presents cross-correlations for the pairs of stations in Nova Palmira and Barca do Cai, and the Barca do Cai and Passo Montenegro, considering the possible combinations using 7am and 5 pm available gauge readings.

Table 1: Correlations of levels depending on the lags

| Lag (hours) | 0 | 10 | 14 | 24 | 34 | 38 | 48 |
|---|---|---|---|---|---|---|---|
| Nova Palmira x Barca do Caí | 0,845 | 0,878 | 0,863 | 0,833 | 0,769 | 0,729 | 0,687 |
| Barca do Caí x Passo Montenegro | 0,949 | 0,953 | 0,944 | 0,899 | 0,845 | 0,823 | 0,762 |

We observe that the travel time to the first reach is between 10 and 14 hours, and for the second, also about 10 hours, following the analysis. The times displacements are of the same order, although the distances are different (46.6km from Nova Palmira to Barca do Cai, and 19.9km between Barca do Cai and Passo Montenegro), mainly due to influence of differences in slopes (1.12 cm/km and 0.15 cm/km, respectively, for the two river reaches).

## 2.7 Frequency of Floods in Caí River Basin

In Barca do Cai, along the 30 years analyzed (1984-2013), 82 flood events occurred, being the period among July and October, the one with the largest number of events (around 13 and 14 events). In Passo Montenegro, along 23 years of observations (1991 to 2013), 57 events occurred, being July the months with the highest number of events (12 events). Table 2 and Figure 7 show the distribution of flood events for the Barca do Cai and Table 3 and Figure 8 for Passo Montenegro.

Table 2: Occurrence of levels greater than 1.000cm in Barca do Caí

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1984 | | | | | 1 | 2 | | 1 | | 1 | | | 5 |
| 1985 | | | | | | | | 1 | 1 | | | | 2 |
| 1986 | | | | | 1 | | | 1 | | 1 | 2 | 1 | 6 |
| 1987 | | | | | | | 1 | 1 | 1 | 1 | | | 4 |
| 1988 | | | | | | 2 | | | 2 | | | | 4 |
| 1989 | | | | | | | 1 | | 2 | | | | 3 |
| 1990 | | | | 1 | 1 | 1 | | | 1 | 1 | | | 5 |
| 1991 | | | | | | | | | | | | 1 | 1 |
| 1992 | | | | | 1 | | 1 | | 1 | | | | 3 |
| 1993 | | | | | | | 2 | | | | | | 2 |
| 1994 | | | | | 1 | 1 | | 1 | | | | | 3 |
| 1995 | | | | | | | 1 | | | | | | 1 |
| 1996 | | | | | | | | | | 1 | | | 1 |
| 1997 | | | | | | | | 2 | | 2 | | | 4 |
| 1998 | | | | | | | | 1 | 1 | | | | 2 |
| 1999 | | | | | | | | | | 1 | | | 1 |
| 2000 | | | | | | 1 | | | | 1 | | | 2 |
| 2001 | | | | 1 | | | 1 | | | | | | 2 |
| 2002 | | | | | | 1 | 2 | | | 1 | | 1 | 5 |
| 2003 | | 1 | | | | | 1 | | | 1 | | 2 | 5 |
| 2004 | | | | | | | | | | | | | 0 |
| 2005 | | | | | | | | 1 | | 1 | | | 2 |
| 2006 | | | | | | | | | | | | | 0 |
| 2007 | | | | | | | 2 | | 1 | | 1 | | 4 |
| 2008 | | | | | | | | 1 | | 1 | | | 2 |
| 2009 | | | | | | | | 1 | 2 | | 1 | | 4 |
| 2010 | | | | | | | 1 | | | | | 1 | 2 |
| 2011 | | | 1 | 1 | | | 1 | 1 | | | | | 4 |
| 2012 | | | | | | | | | 1 | | | | 1 |
| 2013 | | | | | | | | 2 | 1 | | 1 | | 4 |
| Total | 0 | 1 | 1 | 3 | 5 | 8 | 14 | 14 | 14 | 13 | 5 | 6 | 84 |

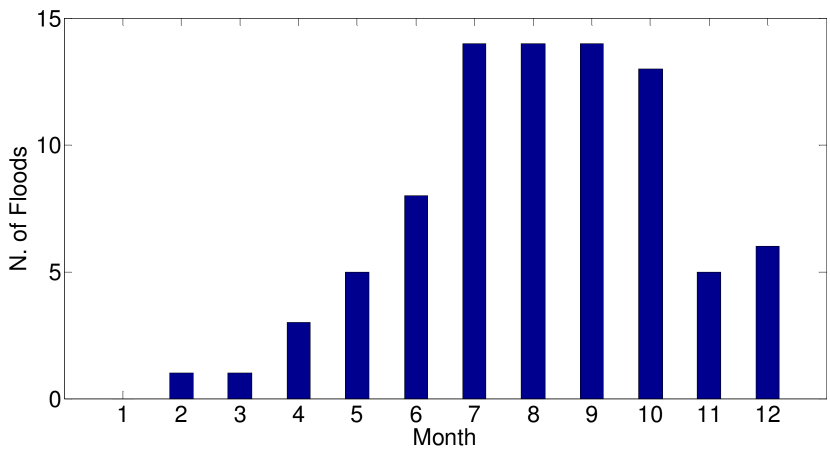


Figure 7: Number of Floods by Month in Barca do Caí

Table 3: Occurrence of levels greater than 600cm in Passo Montenegro

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1991 | | | | | | | | | | | | 1 | 1 |
| 1992 | | | | | 1 | | 1 | | 1 | | | | 3 |
| 1993 | | | | | | | 1 | | | | | | 1 |
| 1994 | | | | | 2 | 2 | 1 | 1 | | | | | 6 |
| 1995 | | | | | | | 1 | | | | | | 1 |
| 1996 | 1 | | | | | | | | | 1 | | | 2 |
| 1997 | | | | | | | | 2 | | 1 | | | 3 |
| 1998 | | | | | | | | 1 | 1 | | | | 2 |
| 1999 | | | | | | | | | | 1 | | | 1 |
| 2000 | | | | | | | | | | 1 | | | 1 |
| 2001 | | | | 1 | | | 1 | | | 1 | | | 3 |
| 2002 | | | | | | 1 | 2 | | | 1 | | 1 | 5 |
| 2003 | | 1 | | | | | 1 | | | 1 | | 2 | 5 |
| 2004 | | | | | | | | | | | | | 0 |
| 2005 | | | | | | | | | 1 | 2 | | | 3 |
| 2006 | | | | | | | | | | | | | 0 |
| 2007 | | | | | | | 2 | | 1 | | | | 3 |
| 2008 | | | | | | | | 1 | | 1 | | | 2 |
| 2009 | | | | | | | | 1 | 2 | | 1 | | 4 |
| 2010 | | | | | | | 1 | | | | | | 1 |
| 2011 | | | 1 | 1 | | | 1 | 2 | | | | | 5 |
| 2012 | | | | | | | | | 1 | | | | 1 |
| 2013 | | | | | | | | 2 | 1 | | 1 | | 4 |
| Total | 1 | 1 | 1 | 2 | 3 | 3 | 12 | 10 | 8 | 10 | 2 | 4 | 57 |

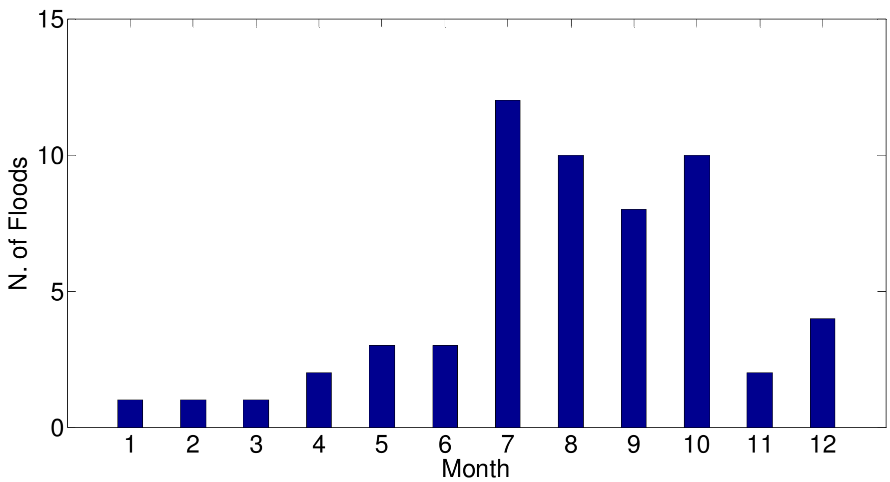


Figure 8: Number of Floods by Month in Passo Montenegro

Tables 2 and 3 show that floods are common, and that only in 2004 and 2006 the levels of the Caí River did not reach at least once the flooding threshold level at Barca do Caí and Passo Montenegro gauge station.

The identification of months with a high frequency of occurrence contributes to the individualization of the months that will require greater involvement, affecting the mobilization of staff involved with the operation, and moving to an increased frequency of monitoring river condition.

## 2.8 Conclusion

The set of acquired knowledge proved to be important for understanding the flood events, providing relevant information for the operation of the warning system.

Although by the duration curves developed, it should be noted that the levels of flood constitute less than 5% of the records, it was found that almost every year suffer from at least one occurrence, and they are concentrated in the months from July to October, which constitutes an important tool for managing the operation, mainly with respect to the concentration of human resources.

It was found that the flooding threshold level should be investigated based on the flooding area, and then related to the gauge readings.

The proposed criteria for definition of the flood warning threshold still depends on subjective decisions (acceptable risks), but is an important starting point. In addition, the study may be improved with the inclusion of additional conditions, such as the occurrence of rainfall forecasts.

Knowledge of the magnitude of events, represented by peak levels, is important to the warning system operation, as it allows taking into account the possible futures short term scenarios, during the events. Rainfall threshold is an issue that deserves a more detailed approach, and it was presented an example of its importance.

Travel times of flood waves were approximated by cross-correlation analysis, but it is assumed that the accuracy of this analysis can be improved by providing the highest frequency acquisition of the telemetry data.

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