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Representative rainfall thresholds for flash floods in the Cali river watershed, Colombia

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Abstract

In the 21st century, societies face a significant increase in the number of extreme hydrometeorological events associated with climate variability (CV) and/or climate change (CC). Research has recently focused on establishing adaptation and mitigation measures to counteract the effects of CV and CC, especially those associated with precipitation, such as flash floods and flooding. In this study, 27 floods, listed in the historical database of natural disasters (DesInventar), occurring between 1980 and 2012, were analyzed. Using the daily hydrometeorological data, representative rainfall thresholds were defined to predict flash floods in the hydrographic basin of the Cali River, Colombia. Antecedent rainfall (AR), or short-term rain (1, 3, 5 and 7 days), and accumulated antecedent rainfall (AAR), or long-term rain (5, 7, 10, 15, 20, 25, 30, 60 and 90 days), levels were defined. The analysis showed that the greatest determinant for the occurrence of floods is AAR, with thresholds greater than 73, 95, 124, 170, 218 and 273 mm, for 5, 7, 10, 15, 20 and 25 days, respectively. Additionally, the data showed that, historically, the greatest number of flash floods (81.7 %) occurred in the Cali River basin in the months of April, May, and June.

1 Introduction

In global terms flash flooding ranks first among natural disasters in terms of both the number of people affected and the proportion of individual fatalities (Milinski et al., 2008). Moreover, flash floods are potentially disastrous events causing human and economic losses worldwide (Gaume et al., 2009). There are different definitions of flash flooding, but that which best represents the hydrological characteristics of a mountainous region such as Cali River basin in Colombia, is that published by the United States National Weather Service, i.e., a flash flood is a rapid increase in the water level of a river or creek above the predetermined flood level that generally occurs within 6 h of the event that caused it.

Tropical regions, such as the South America Andes and mountainous countries, are highly susceptible to floods and flash floods due to environmental and socio-economic characteristics (Sedano et al., 2013). In Europe and America, floods are rarely associated with fatalities except in cases of levee failures. In contrast, flash floods often cause loss of life. For instance, thirteen people lost their lives in the town of Cardoso, Italy, in June 1996, when more than 400 mm of rain fell in less than six hours, at rates up to 88 mm in 30 min. Thirty-five casualities occured in the Aude flood in France in 1999 (Gaume et al., 2009). In, 2003, in the state of Kansas-USA, a total of 150–200 mm of precipitation fell during three hours in a basin with a catchment area of 5 km^2. Six people died in the resulting flood.

In September 2009, in İkitelli Istanbul, Turkey, flash floods destroyed a commercial district causing the deaths of 20 people. In January 2010, in Aguas Calientes, Peru, authorities estimate that floods destroyed 2000 houses (University Corporation for Atmospheric Research, 2010). In 2010, 178 million people were impacted by floods. The monetary losses in high-flood years, such as 1998 and 2010, exceeded USD 40 billion (The Word Bank, 2012). Therefore, an in-depth analysis of such potentially disastrous phenomena in real time has become a key element in early warning systems (Aristizábal et al., 2010a). It has been very useful to define thresholds of extreme natural events to reduce human and economic losses, insofar the prediction of landslides or mass movements are concerned (Aleotti, 2004; Aristizábal et al., 2010a, b, 2011; Dahal and Hasegawa, 2008; Guzzetti et al., 2007; Larsen, 2008).

Recently a new agent has emerged as a potential contributor to increase the strength and frequence of floods and flash floods. Although climate variability (CV) and climate change (CC) can induce frequent precipitation anomalies, globally, more frequently, human intervention in ecosystems leads to prominent social risk. Hence, increasing the impact of the disaster when the threat of continued or intense rain appears (Milinski et al., 2008; Vincent, 2007; Brown and Funk, 2008).

The characterization of CV and CC is difficult because of the marked influence of CV under present day weather conditions. In particular, South America has been punctuated by more frequent extremes events of intense precipitation (Dereczynski et al., 2013; Marengo et al., 2009). This situation has been attributed to the influence of the El Niño–Southern Oscillation (ENSO) phenomenon and to Sea Surface Temperature (SST) changes in the Atlantic Ocean (Poveda and Mesa, 1997; Poveda and Salazar, 2004; Poveda et al., 2011; Puertas et al., 2011). During the ENSO cool phase, namely La Niña, an increase in extreme river flooding occurs in Colombia. A recent episode includes the 2010–2011 rainy seasons which impacted 5.2 million people. The flooded cultivation areas exceeded more than one million hectares and economic losses exceeded USD 4870 billion (Sedano et al., 2013).

These conditions impose serious threat to the livelihood of vulnerable population. It is important to stress that human induced CC is expected to increase the frequency and intensity of extreme hydrometeorological events. Colombia is a country prone to disasters, including severe events such as erosion, landslides, torrential floods, avalanches, flooding, droughts and forest fires. Among all these occurrences floods are the most recurrent (The Word Bank, 2012; Sedano et al., 2013). Located in the equatorial region, the country is influenced by the intertropical confluence zone (ITCZ), which is tightly linked to dynamical processes occurring in the Atlantic and Pacific oceans, and in the Amazon rainforest. Additionally, three mountain ranges and flood plain areas in Colombia play an important roles in the occurrence of flash floods and flooding. These regions have historically housed groups of human settlement.

In this regard, studies focussing on flash floods and flooding forecast in real time and the definition of critical rain-based thresholds have become essential tools for the implementation of early warning systems. The advantages of systems based on critical rain thresholds are supported by the fact that rainfall is relatively simple and inexpensive to measure (Aristizábal et al., 2010b, 2011). In this study, critical thresholds of daily accumulated rainfall (AR) for the prediction of flash floods in the Cali River basin are proposed. The thresholds are derived from the daily records of hydrometeorological events and extreme natural events (flash floods and flooding) reported over the past 32 years in the historical database of natural disasters (DesInventar). The results can shed some light on hydrologic behavior, and provide decision-making criteria for water resource planners to aid in the prevention and mitigation strategies, before the occurrence of flash floods and floods.

2 Methodology

2.1 Description of the study area and data

The current socio-economic, cultural, and physical characteristics of the Cali River basin comprise the latent risk conditions that for years have been manifested in natural disasters. The urban and industrial expansions, and population increase have all progressed with inappropriate planning and occupation of the territory. Moreover, the region experiences high amount of precipitation in April and May by about 190 mm, adding to higher vulnerability. These levels generate risk scenarios that can cause landslides, sudden damming of natural channels or flash floods in urban areas.

Precipitation is an important climatic parameter, and its variability severely affects regional hydrological processes and water resource management (Wang and Li, 2015). In order to explore temporal characteristics of precipitation on local scale, (Fig. 1 and Table 1). We shown the temporal variability of extreme climate indices based on daily precipitation data, for three rainfall stations located in the upper (Peñas Blancas), middle (Brasilia) and lower part (Planta Río Cali) of the Cali river basin insofar altitude is concerned. This is evaluated for the 1980–2010 interval. Data were analyzed using the RClimDex package (http://etccdi.pacificclimate.org). We selected a set of four indices of rainfall extremes (Table 1). The statistical significance of the calculated trends are achieved by using a Mann–Kendall test. This method has been applied because it is more suitable for non-parametric distributions (Burić et al., 2015; Tramblay et al., 2013). The values in boldface are considered statistically significant at a confidence level of 95 % (Table 1).

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The results demonstrated that the majority of precipitation-related indices exhibited an upward trend, with a regional average of 11.56 mm yr^{-1} in terms of the annual precipitation (Fig. 1a). Moreover, the number of days with precipitation ≥ 20 mm (Fig. 1b), the maximum amount of rain in 5 consecutive days (Fig. 1c), and heavy precipitation (Fig. 1d) (annual total precipitation from daily rainfall > 95th percentil) experienced increasing trends. It is interesting to note that these are characteristics of all stations analyzed, but higher have been detected to the area of higher altitude. These conditions are more favourable for flash flooding in the basin.

The flash floods analyzed in this study caused loss of life and material losses, primarily in the low-lying areas of the basin, where the hydrologic characteristics generated large volumes of runoff before the intense and continuous rains began. The events were compiled from various sources, e.g., the hydrometeorological records of the Autonomous Regional Corporation of the Cauca Valley (CVC) and DesInventar. The DesInventar database system includes the conceptual and methodological tools to access the data to analyze loss, damage, or effects caused by emergencies or disasters (available at http://www.desinventar.org/).

The occurrence of flash floods and flooding in watersheds that do not have weather stations means that there are no direct measurement data or formal records of the magnitude of the event. For this reason, the Cali River basin was selected as the pilot basin (coordinates 03°26′ N, 76°31′ W). It is one of the best equipped in the Valle del Cauca area. The Cali River basin is located in south-western Colombia, as shown in Fig. 2, on the eastern slopes of the Western Cordillera and has an approximate area of 215 km^2. Annual precipitation ranges between 1300 and 2700 mm in the upper and lower part of the basin, respectively. Overall precipitation is orographic and the influence of humid winds from the Pacific Ocean results in an annual average precipitation exceeding 1500 mm. The mean annual flow of the Cali River is 3.7 m^3 s^{-1}, with instantaneous maximum and minimum values ranging between 0.2 m^3 s^{-1} in severe droughts and 193 m^3 s^{-1} in periods of intense rain (Ávila et al., 2014).

Information collected from the database was filtered according to the following criteria: (i) only events that occurred between 1980 and 2012 were used because the hydrometeorological data collection at most of the stations began operation in 1980. To ensure data quality, the following additional criteria have been applied. (ii) Flows with a return period equal to or greater than three years at the Bocatoma limnigraphic station were considered the terminal point of the basin. The Bocatoma limnigraphic station is the only limnigraphic station in the area with a continuous record of data. (iii) The maximum flows were confirmed to vary $\geq 90\,\%$ from the multiannual monthly mean flow in which the event occurred. (iv) The event must be seasonal, continuous and accurate.

The hydrometeorological database is based on records obtained from 19 pluviometric stations and one limnigraphic station, located in the basin or near the basin, which belong to the CVC and to the Institute of Hydrology, Meteorology and Environmental studies of Colombia (Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia-IDEAM – IDEAM) (see Fig. 2). The altitudes of the stations range between 960–2158 m a.s.l. Information recorded from the stations included year, month, day, precipitation and flow rate on the day of the event.

2.2 Definition of critical rain thresholds

According to Guzzetti et al. (2008) rain critical thresholds for predicting flash floods can be defined in two ways; (i) using empirical or statistical methods applied widely to early warning systems because of their easy implementation (Glade et al., 2000; Aristizábal et al., 2011), and (ii) using numerical physical models which are more complex to define and apply (Iverson, 2000; Crosta and Frattini, 2003). In this study, the methodology proposed by Aristizábal et al. (2011) is used to predict mass movements in the Aburrá Valley, Colombia. This is the first study to focus on understanding the hydroclimatology of flash floods in Colombia.

The rain threshold is defined as the minimum or maximum level of a certain amount of precipitation, after which a process occurs (Reichenbach et al., 1998). In accordance with the minimum and maximum thresholds defined by Glade et al. (2000) and adapted for this study, the minimum threshold is the amount of rain greater than which the probability of occurrence of a flood increases drastically, and the maximum threshold is the amount of rain which causes the highest percentage of flash floods.

In this analysis, AR = 1, 3, 5 and 7 days, and the accumulated antecedent rainfall (AAR) = 5, 7, 10, 15, 25, 30, 60 and 90 days for each of the selected flash flood events are used. The AR is the short-term rain and represents the amount of rain in the days immediately prior to the occurrence of the event, including the 24 h of the day that the event occurs. The AAR is the long-term rain, corresponding to the amount of rain in the days preceeding those that were considered in the AR. Critical rainfall thresholds were visually determined from the dispersion patterns or concentration of data points, taking into account the layout of the boundary lines below the rain conditions that caused the event. This has been drawn in a semi-logarithmic or logarithmic Cartesian coordinates for different combinations of rain and antecedent rain. Evaluation of the relation between the occurrence of the events and the antecedent rain has also been determined as suggested by Guzzetti et al. (2007) and Aristizábal et al. (2011). For this purpose, it has been used the matrix plot tool of the Minitab 16 statistical software (www.minitab.com), which permits selection of precipitation values within the thresholds. If the number of events with respect to the total is known the result is shown as a percentage in each graph in the upper right corner.

3 Analysis and results

According to the DesInventar data, 300 floods were identified that occurred in the period from 1950 to 2012; more detailed information about the events is available at the historic inventory of losses at the Cali Municipal office.

Figure 3 shows the intra-annual behavior of the precipitation. Two rainy periods appear in the data corresponding to the March–May and October–December quarters. This semiannual harmonic is explained by the seasonal migration of the ITCZ. This also coincides with the historical monthly averages of instantaneous flow (1951–2011) represented by the dotted line in Fig. 3. These two quarters are the times with the highest probability of flash floods. It should be noted that the interannual variability of precipitation is primary related to changes in Ocean Pacific SSTs. The seasonal maximum southward displacement of the ITCZ takes place in January (summer in the Southern Hemisphere), while in April–May, the ITCZ is located northward, migrating toward its southern position in the month of July (summer in the Northern Hemisphere) (Poveda and Mesa, 1997; Waylen and Poveda, 2002; Poveda and Salazar, 2004; Poveda et al., 2011).

The hydrological and climatological regimes are closely related; however, the months of greatest rainfall do not coincide with the months of greatest flow, i.e., there is a one-month delay, as shown by the data in Fig. 3. This is because, after a dry period, the initial rainfall recharges the soil matrix, causing higher volumes of river flows one month later. By the end of wet period, the average monthly flow decreases significantly when the water reserves in the soil begin to run out. Of the total number of events found, 27 were selected which successfully met the quality criteria described by the applied method. Table 2 shows each of the events with the date (day-month-year), the maximum flow rate and the return period.

Table 2 shows that the percentage of flash floods compared to the total for each month is as follows: March 3.7 %, April 22.2 %, May 29.6 %, June 25.9 %, July 3.7 %, October 3.7 %, November 7.4 % and December 3.7 %. The highest occurrence of flash floods was in the April–June quarter, at 81.5 % of the total. This result coincides with the results shown in Fig. 3, where April, May, and June exhibit the highest averages of instantaneous maximum flow rates of 32.9, 42.6 and 31.4 $m^3 s^{-1}$, respectively.

This may also be associated with the control exerted by the Pacific Ocean on the hydroclimatology of the basin. Indeed, maritime wind from the Pacific Ocean transports large amount of moisture to the Colombian territory, interacting with the topography of the Western Andes and the trade winds in the East. Subsequently, the wind convergence contributes to increase precipitation due to ascending motion (Poveda and Salazar, 2004; Poveda et al., 2011).

To define the thresholds, the AR = 1, 3, 5 and 7 days is shown for AAR = 5, 7, 10, 15, 20, 25, 30, 60 and 90 days. In the figures that follow, the solid black lines represent the interval in which the maximum probability of flash floods occured, adjusted by the greatest concentration of points. The upper right image shows the value as a percentage relative to the total number of flash floods within the threshold. Figures 4 shows AR for 1 day plotted for AAR = 5, 7, 10, 15, 20, 25, 30, 60 and 90 days. The results show that accumulated precipitation value equal to 80 mm for all combinations is required to achieve the highest probability to the occurence of the event. For AR = 1 day and AAR = 15, 20 and 25 days, the results show a minimum threshold (or accumulated precipitation) by about 10 mm. Evaluations for 30, 60 and 90 days (Fig. 4g–i) demonstrated that this minimum value increases to 100, 200 and 300 mm. However, Fig. 4g–i also shows that when AR = 1 day and AAR = 30, 60 or 90 days flash floods are less likely to occur as can be seen from the probability values. This has also been observed for AR = 3, 5 and 7 days i.e. the lower percentages of the total number of flash floods.

Figure 5 shows AR = 3 days for AAR = 5, 7, 10, 15, 20 and 25 days. One may note that the highest probability of flash floods is related to accumulated precipitation up to 100 mm, below which more than 86 % of the flash floods occurred. At AAR = 10 and 15 days (Fig. 5c and d), the maximum threshold increases 20 mm in both cases. For AAR = 25 days, the minimum is 50 mm. However, in the latter case, the scatter is slightly increased, and the percentage of events within the threshold decreases to 72.4 %.

Figure 6 shows the results of AR = 5 days and AAR = 5, 7, 10, 15, 20 and 25 days. The highest percentage of occurrence of flash floods, 85.2 % occurred at AAR = 7 days (Fig. 6b). This combination also exhibits the maximum AR limit value for all the combinations at 120 mm. It is intersting to note that from the AAR = 15 days, the minimum threshold increases from 10 to 50 mm for AAR = 25 days. Interestingly is to observe that AAR = 20 days delivered the lowest percentage of flash floods (67.8 %, Fig. 6e).

The AR = 5 days evaluation also shows that for probability between 82 and 67 % to the occurence of flash floods is associated with upper limits varying between 60 and 290 mm, respectively.

Figure 7 shows the results for AR = 7 days for AAR = 5, 7, 10, 15, 20 and 25 days. This condition delivered more favourable threshold by about 150 mm accumulated in 7 days. The minimum thresholds gradually increase from 10 mm for 15 days (Fig. 7d) to 50 mm at 25 days (Fig. 6f). The maximum thresholds is equal to 80, 100, 120, 180, 250 and 300 mm, respectively.

Figure 8 shows that from AAR equal to 15 days and more closer to the occurence of the event the percentage are larger than 78 %. In addition, one may note that most of flash floods in the Cali River basin during the studied period is linked to AAR between 5 and 7 days. Indeed, the percentage based on the total number of flash floods for the four different combinations of AAR = 5 days range between 84 and 88 %, and for AR = 7 days, from 81 to 85 %. Aristizábal et al. (2011) based on landslides analyses argue that the condition of exceeding the rainfall threshold does not guarantee a flash flood, but provides the antecedent moisture conditions for one to occur. Different values of AAR for AR = 7 days were those that were more likely can be used to predict flash floods because the probability range is reduced as compared to other AR values (Fig. 8).

The discussion above differs from previous studies related to landslides which take into account preceeding precipitation values, such as Aleotti (2004) that selected 7, 10 and 15 days, and Terlien (1998) tested 2, 5, 15 and 25 days, found appropriated results for longer periods of rain (AAR). Pasuto and Silvano (1998) tested periods of rain from 1 to 120 days, and found a better correlation of the occurrence of landslides with AAR = 15 days. This variability can be attributed to various factors, including: (i) lithological and morphological diversity, vegetation and soil conditions, (ii) different climatic regimes and weather circumstances that lead to slope instability, (iii) and the heterogeneity and the incomplete nature of rain data and landslides used to determine thresholds (Guzzetti et al., 2007).

Throughout this study, significant Pearson correlation coefficients were obtained for all combinations of the AR. This result is similar to that found by Aleotti (2004). Low correlations (by about 0.3) are explained by the fact that short term precipitation is not entirely related to long term accumulated rainfall occurring before the flash flood.

4 Concluding remarks

Based on analysis of precipitation associated with 27 flash floods events, it has been concluded that combinations of antecendent rainfall between 5 and 7 days are those that can best represent rainfall thresholds. Specifically, this includes combinations with long-term antecedent rainfall or AAR = 5, 7, 10 and 15 days. The results can be used, in first approximation, as thresholds for the prediction of flash floods. However, due to the complexity involving the event more research is still needed.

The influence of the antecedent conditions of soil saturation on the occurrence of flash floods was analyzed by considering the AAR and the AR up to 90 days prior to the event. The analysis of the data demonstrated that the antecedent conditions of precipitation and indirectly of the soil moisture have a significant impact on the cases studied, strengthening the assumption that antecedent soil moisture is important in the characterization of a flash flood and/or flooding (Marchi et al., 2010). One of the outstanding results of this study is the analysis of the long-term rain for AAR = 25 days, because for other combinations such as AAR = 30, 60 and 90 days, the percentage of events within the thresholds was less than or equal to 75 % with respect to the total flash floods. This reflects the worst case scenarios for a prognosis. It is importamnt to stress that future investigations should include other climatological variables such as evapotranspiration.

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Table 1. Summary of observed changes of rainfall indices in the Cali river basin as observed for three rainfall station during the period 1980–2010. A wet day has precipitation ≥ 1 mm. A dry day has precipitation < 1 mm. Rx5day stands for annual maximum consecutive 5 day precipitation; R20mm is the annual count of days when precipitation ≥ 20 mm; R95p: annual total precipitation from daily rainfall > 95th percentile; PRCPTOT: annual total precipitation in wet days. The values in boldface are considered statistically significant at a confidence level of 95 %.

Rainfall Station Elevation (meters) Index	Peñas Blancas 2158	Brasilia 1864	Planta Río Cali 1070
Rx5day (mm yr^{-1})	**1.70**	0.02	−0.32
R20mm (day yr^{-1})	**0.51**	0.13	0.09
R95p (mm yr^{-1})	**11.26**	**5.48**	3.42
PRCPTOT (mm yr^{-1})	**23.16**	**6.85**	4.67

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Table 2. Date of occurrence of the 27 analyzed events.

Id	Date	Maximum streamflow ($m^3 s^{-1}$)	Tr* (Years)	Id	Year	Maximum streamflow ($m^3 s^{-1}$)	Tr (years)
1	23 May 1981	57.8	3.0	15	28 Mar 1998	81.1	5.0
2	23 Jun 1981	64.1	3.0	16	28 May 1998	81.1	5.0
3	9 Apr 1983	64.9	3.0	17	2 Apr 1999	68.0	3.0
4	1 Jul 1984	193.0	100	18	15 Jun 1999	58.0	3.0
5	23 Oct 1986	91.3	7.0	19	18 Nov 1999	61.6	3.0
6	17 Nov 1986	143.0	50	20	21 May 2000	71.3	4.0
7	2 Dec 1987	76.6	4.0	21	25 Apr 2003	108.7	10.0
8	1 Jun 1989	59.2	3.0	22	12 May 2003	95.6	7.0
9	12 Apr 1994	59.0	3.0	23	17 Jun 2003	76.1	4.0
10	8 May 1994	57.0	3.0	24	7 May 2006	128.8	15.0
11	29 May 1994	62.0	3.0	25	24 Jun 2008	62.1	3.0
12	8 Aug 1994	59.0	3.0	26	15 Apr 2009	84.3	5.0
13	29 Jun 1994	62.0	3.0	27	23 Apr 2011	70.0	4.0
14	30 May 1997	62.9	3.0				

* Return period-Tr.

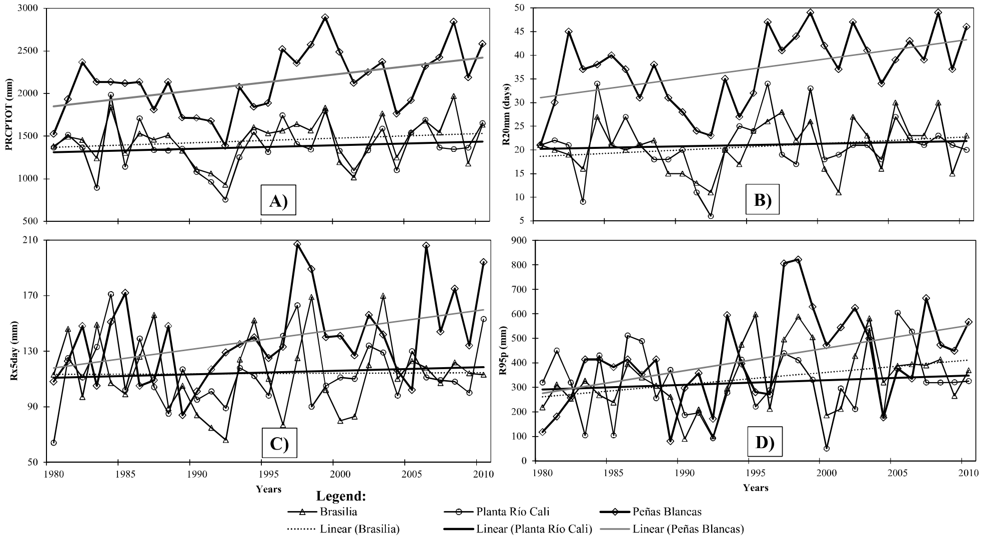

Figure 1. Time series of indices of extremes for three rainfall station. We assume a linear fit to the observed trends.

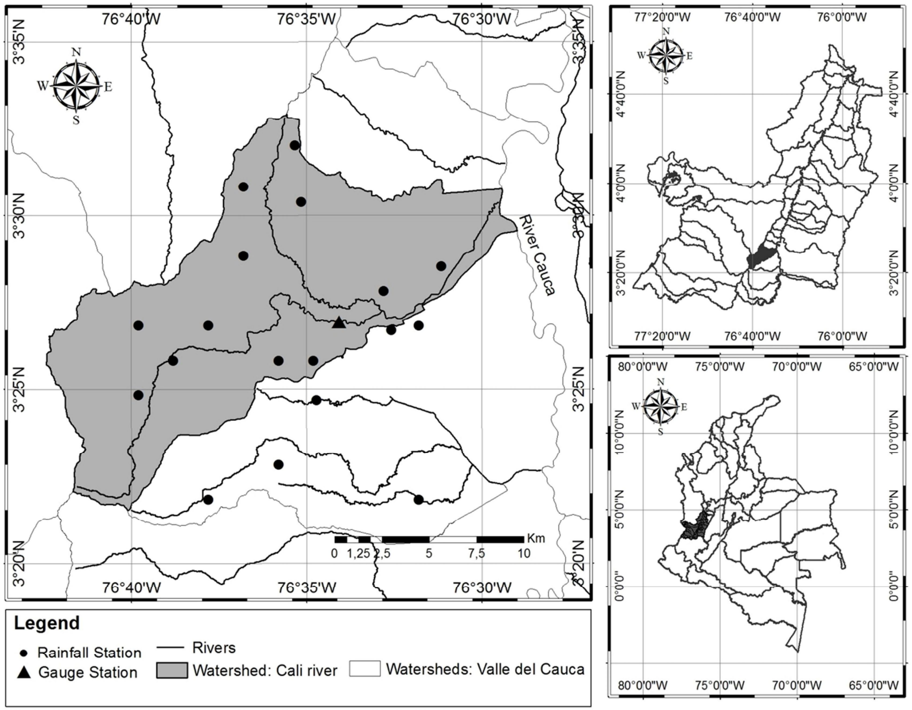

Figure 2. Location of the study area and position of the measurement stations.

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Representative rainfall thresholds for flash floods, Colombia

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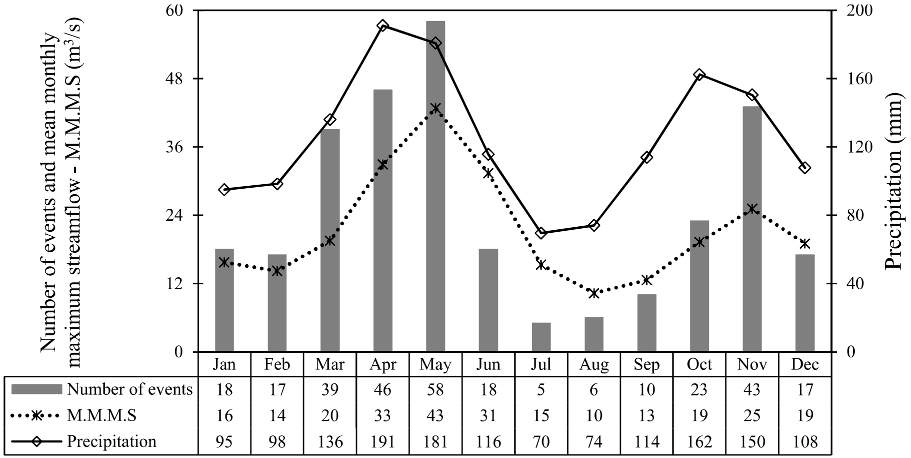

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
▬ Number of events	18	17	39	46	58	18	5	6	10	23	43	17
···✳··· M.M.M.S	16	14	20	33	43	31	15	10	13	19	25	19
—◇— Precipitation	95	98	136	191	181	116	70	74	114	162	150	108

Figure 3. Relation between the monthly mean precipitation in the basin of the Cali River, maximum flow and events denoted by rainfall in the Cali municipality in the period 1950–2012.

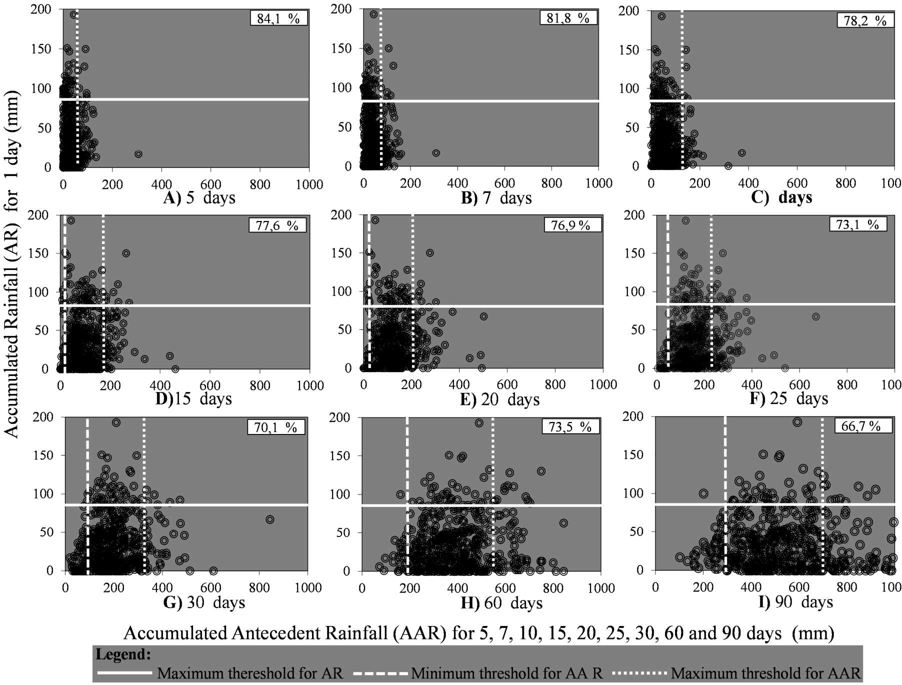

Figure 4. AR for 1 day for AAR = 5, 7, 10, 15, 20, 25 30, 60 and 90 days.

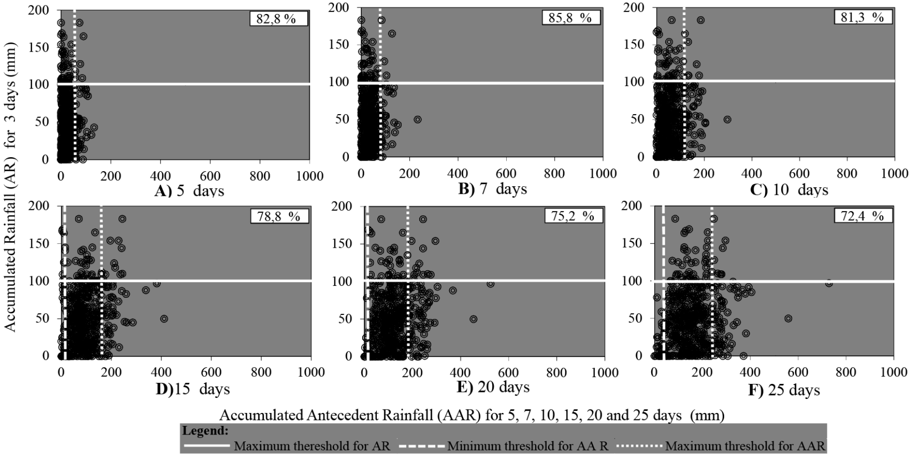

Figure 5. AR for 3 days for AAR = 5, 7 10, 15, 20 and 25 days.

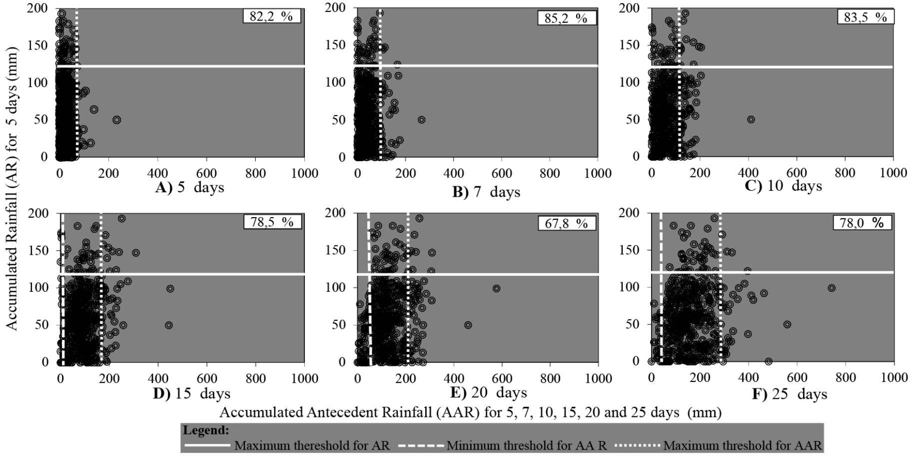

Figure 6. AR for 5 day for AAR = 5, 7, 10, 15, 25 and 30 days.

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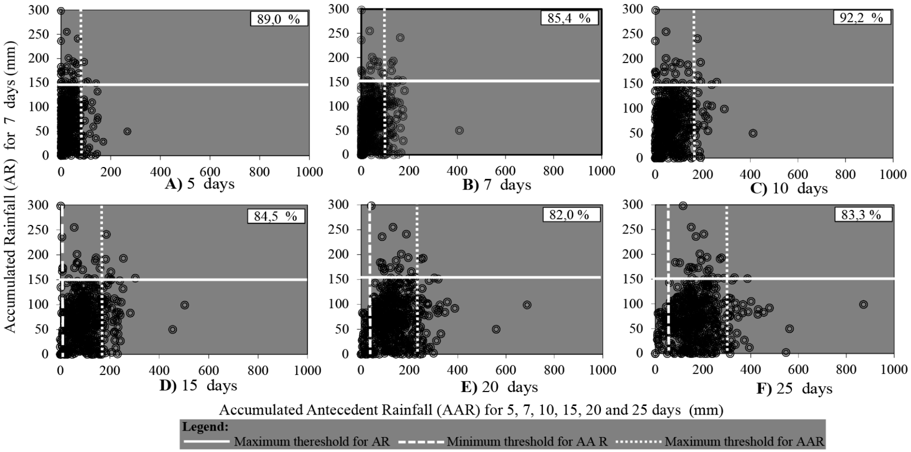

Figure 7. AR = 7 days for AAR = 5, 7, 10, 15, 20 and 25 days.

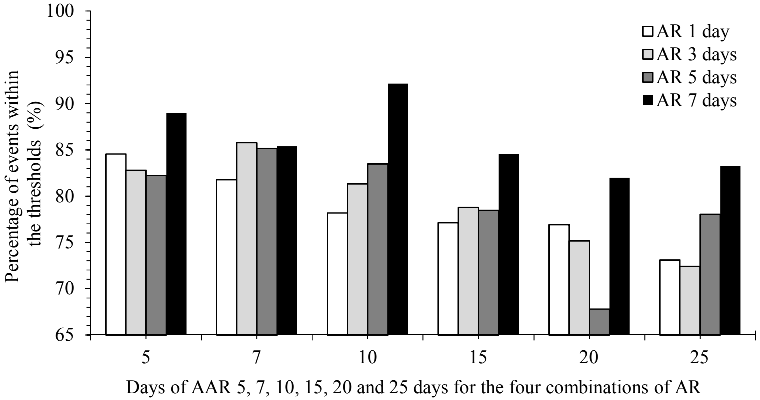

Figure 8. Percentage of events within the thresholds for the four combinations of AR.