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Simple rainfall indices for forecasting hazardous events of hydrologic and geologic nature

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Abstract

Heavy rains are the main natural trigger agent of floods and slope movements responsible for significant economic and social losses in many regions of the Brazilian territory. The affected municipalities are generally scarce in technical and economic resources to invest in mitigation actions. This work aimed to define readily available rainfall indices to predict the occurrence of these dangerous events. The main pluviometric parameters used were the daily rainfall and the mobile cycle coefficient (MCC). MCC is defined as the ratio between the total amount of rainfall accumulated over a certain period and the accumulated rainfall considered normal for this period. The analyses were based on a spatial database containing daily rainfall, flood and landslides events that occurred from 1965 to 2016 in the São Carlos municipality (São Paulo, Brazil). The structuring of this database and the subsequent spatial analyses were performed using a geographic information system software. The results indicated good potential for the combined use of MCC and daily rainfall indices to predict floods in the study area. The correlations with landslides presented some incongruities that can be mainly explained by not considering the accumulated rainfall before the triggering of landslides and the small number of events available. The simplicity and easy access to these rainfall indices favor their use to subsidize Civil Defense preventive measures, while more detailed studies are not available.

1 Introduction

Heavy rains are the main natural trigger agent of dangerous hydrologic and geologic events in the dynamics of the Brazilian environment. These events are responsible for significant economic and social losses, and the affected municipalities are generally scarce in technical and economic resources to invest in mitigation actions. Ninety-four flood disasters

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were recorded between 1960 and 2015 in different Brazilian cities, causing 4604 deaths and affecting more than 12 Mio. people (EM-DAT 2016).

Among the dangerous processes of geologic nature that are common in the Brazilian territory should be highlighted: rainfall erosion (laminar and linear), river erosion, coastal erosion and slope movements. Slope movements, in particular landslides, are the ones that have caused the most fatalities. In 2011, in the mountainous region of Rio de Janeiro, slope movements were responsible for 947 deaths and for making 50,000 people homeless (Dourado 2012).

Christofoletti (1980) identifies two main types of hydrologic events associated with fluvial channels: floods and inundations. According to the author, the elevation of the river level above its average but without the overflow of water from the main riverbed area is denominated flood or high stage. In inundations, water overflows from the main riverbed, leading to the partial or total submersion of alluvial plains. Another common hydrologic process is the urban flood in urbanized areas, resulting from the localized accumulation of surface water after intense rainfall in topographic depressions and/or by deficiencies in rain drainage systems.

The distinction between floods and inundations is not always clear when using these criteria, especially in urbanized areas where natural drainage systems have been modified by civil constructions. In the scope of this work, the hydrological processes were differentiated only between floods and urban floods and the landslides were the main slope movement considered.

The close relationship between rainfall and the dynamics of these hazardous events, coupled with the higher availability and lower investments required for measuring and monitoring rainfall indices in comparison with other variables (tension, displacement, groundwater level, run off, etc.), has led to the development of studies aimed at establishing empirical and theoretical correlations and defining critical indices and rainfall thresholds that can trigger these processes.

This work investigated the relationship between the rainfall regime and the occurrence of floods and landslides. The spatial and temporal distribution of rainfall was analyzed based on maps generated using historical series of daily rainfall. We also aimed at identifying critical rainfall indices for the triggering of these hazardous processes, using daily rainfall and the mobile cycle coefficient (MCC) index proposed by Tatizana et al. (1987). These indices are more commonly used for forecasting landslides, whereas for floods, other theoretical models related to rainfall and river discharge are more frequently applied. We decided to test the use of these empirical indices for predicting floods events as a possible alternative to subsidize mitigation actions while more detailed hydrologic studies are not available.

2 Background

The correlation with rainfall parameters can be made using calculation methods that convert rainfall amounts to peak flow rate of the watershed for floods or inundations. The flow rate in a watershed at a given time depends on the intensity, duration and frequency (return period) of rainfall, expressed by the IDF equations, so that different temporal distributions of precipitation are related to different peak flows. The flow rate generated by rainfall also depends on characteristics of the watershed, such as drainage area, shape, slope, type of land use and occupation, soil and drainage network pattern.

Rainfall is also the main natural agent responsible for triggering landslides in the dynamics of the Brazilian environment. Precipitation can act in a progressive or instantaneous manner on the instability of slopes, resulting in the unfavorable alteration of soil parameters (elevation of specific weight and reduction of apparent cohesion) and/or in the increase of internal stress by the generation of positive pore pressure caused by the elevation of water level.

For landslides, the correlation with precipitation is generally made based on empirical relationships considering the hourly (or daily) rainfall intensity and the accumulated rainfall amount before the landslide triggers. Then, these empirical relationships are used to define the threshold values above which the triggering of these processes is likely to occur.

The investigation of correlations between rainfall and landslides is well established internationally and in Brazil, with several works published on the topic, such as Guidicini and Iwasa (1977), Tatizana et al. (1987), Chleborad et al. (2006), Guzzetti et al. (2007), Norbiato et al. (2008), Montesarchio et al. (2009), Parizzi et al. (2010) and Amaral et al. (2015).

Regardless of the mathematical model adopted, the correlations between rainfall intensity and the triggering of floods and landslides should be based on climatic characteristics, in particular on the rainfall regime of the investigated region and characteristics of these hazardous processes, as rain has a different effect on each one of them.

Characterization of rainfall based on its intensity and the temporal and spatial distribution is fundamental for supporting theoretical and applied studies aimed at the investigation, prevention and mitigation of floods and landslides. A common pluviometric analysis is the representation of continuous surfaces of rainfall indices on maps, using deterministic and geostatistical methods for interpolating specific data collected from rainfall stations. Examples of deterministic interpolation methods frequently employed in the regionalization of rainfall data are Thiessen polygons, the spline method, polynomial interpolation and inverse-distance weighting (IDW).

Regarding IDW, it is common to use the value 2 for the distance-weighting coefficient, being the method then referred to as inverse squared-distance weighting, expressed by Eq. 1 (Ly et al. 2013). Several works have been performed applying this method for the regionalization of rainfall data with satisfactory results (Tabios and Salas 1985; Naoum and Tsanis 2004; Magalhães et al. 2013).

$$z = \frac{\sum_{i=1}^{n} \frac{1}{d_i^2} z_i}{\sum_{i=1}^{n} \frac{1}{d_i^2}} \tag{1}$$

where z is the interpolated value, n the number of observed values, z_i the observed value, and d_i the distance between interpolated and observed values.

Guidicini and Iwasa (1977) proposed one of the first indices for correlating rainfall and the triggering of landslides in Brazil, in a study that analyzed nine regions of the country. These authors defined an indicator called the cycle coefficient (CC), obtained by calculating the ratio between the amount of rainfall accumulated up to the date of the event and the average annual rainfall amount. The authors observed that landslides were more likely to occur when CC values ranged from 1.08 to 1.17 (a cumulative pre-event precipitation of 8–17% above the average annual precipitation).

Tatizana et al. (1987) proposed the mobile cycle coefficient (MCC) in an attempt to improve the CC index. Currently, MCC is used by several municipalities in the state of São Paulo as one of the basic parameters for the implementation of preventive measures against

slope movements by the Civil Defense Department. MCC calculation considers that the hydrologic or rainfall year (comprising the dry and rainy seasons) goes from June of a given year to May of the following year, according to Eq. 2:

$$MCC = \frac{\text{Rainfall accumulated from June to day i}}{\text{Normal accumulated rainfall for the same period}} \qquad (2)$$

The accumulated rainfall is calculated by the sum of the rainfall amounts from June 1 to the considered day i. The normal accumulated rainfall corresponds to the sum of the normal daily rainfall from June 1 to the considered day i. The normal daily rainfall is calculated by dividing the average monthly rainfall by the number of days of the respective month.

MCC serves as a medium-term indicator of the triggering of landslides, whereas daily and hourly rainfall values serve as short-term indicators.

The occurrence of landslides is more likely to occur for MCC values above 1, that is, when the cumulative rainfall is greater than the average expected for that period. At the beginning of a hydrologic year (in the dry season), MCC values should be carefully analyzed, as even a slightly more intense rainfall can result in very high values, given the typically low average rainfall amounts of the dry period. This distortion tends to disappear throughout the year.

For the elaboration of preventive measures by the Civil Defense Department of the state of São Paulo, it is common to adopt an MCC equal to 1.2 (accumulated rain 20% above the normal amount) as the threshold value from which actions must be adopted to prepare for the occurrence of landslides. For daily rains, it is customary to adopt threshold values between 100 and 120 mm of 3-day accumulated rainfall (Macedo et al. 1999).

3 Study area

Figure 1 presents the study area, the rainfall stations considered for analysis and the main watersheds of the São Carlos municipality. The municipality is located in the central region of the state of São Paulo, between coordinates 47°30′ and 48°30′ west and 21°30′ and 22°30′ south. The total area of the municipality is 1132 km², and its urban area comprises 67.25 km² (Prefeitura Municipal de São Carlos 2016).

The São Carlos municipality is part of the Tietê-Jacaré Water Resources Management Unit (UGRHI-13) of the state of São Paulo, and ten watersheds can be delimited in its territory. The studied urban area occupies the Monjolinho watershed, including the Monjolinho River and the Gregório, Mineirinho, Tijuco Preto, Água Quente, and Água Fria streams (Fig. 1). The climate is temperate, with high altitudes, dry winters and rainy summers, being classified as Cwa by the Köppen system. Average annual rainfall varies from 1100 to 1600 mm (Prefeitura Municipal de São Carlos 2016).

Regarding the geological context, the studied area is located within the Paraná Sedimentary Basin, including the Botucatu Jurassic–Cretaceous Formations (sandstones), Serra Geral Formations (basalts), basic tabular intrusions related to the Serra Geral Formation, and Itaqueri Cretaceous Formation, composed of sandstones with clay-cement soil. The typical alteration profile is formed by thick residual soils with sandy, sandy-clayey or clayey texture, depending on the bedrock (sandstone, basalt, and diabase). There are also shallower residual soils in the more prominent relief areas, colluvial-transported soils and alluvial deposits on the banks of the main rivers and streams (Bartolomeu 2012).
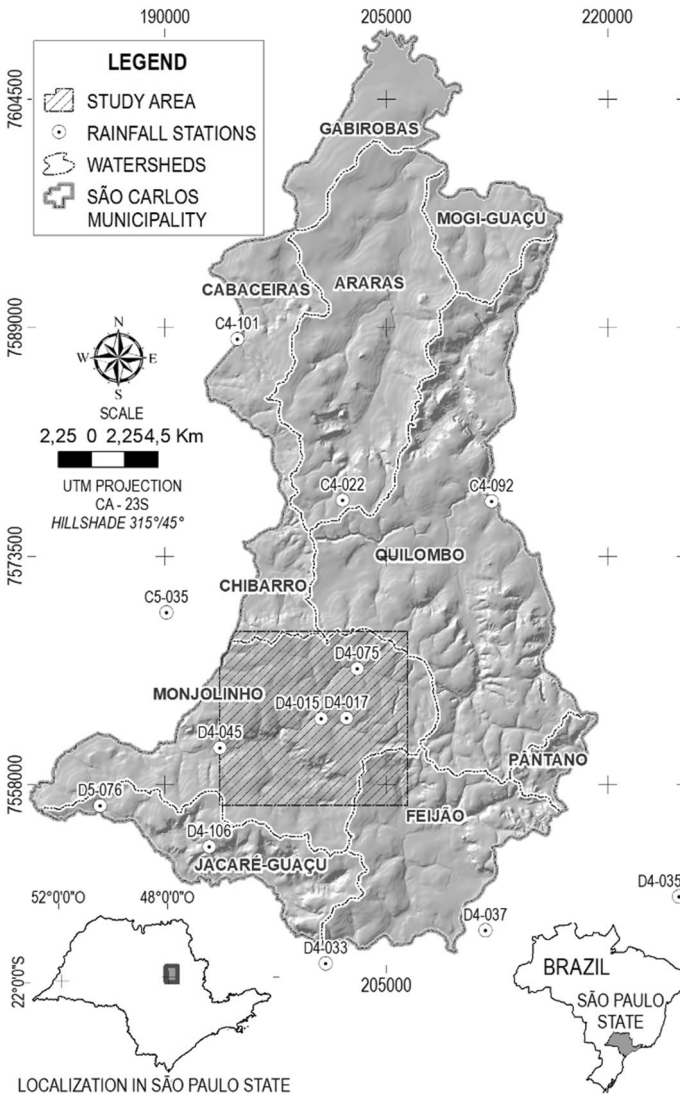
Fig. 1 Study area

Local relief is characterized by the predominance of a system of medium hills with slopes lower than 15% and local amplitudes lower than 100 m. There is also a more restricted occurrence of large hills (slopes lower than 15% and local amplitudes between 100 and 300 m) and hillsides with parallel valleys with slopes of 15–30% and local amplitudes of more than 100 m. The slope map (1:10,000-scale topographic base with 5-m interval contour lines) of the studied region indicates that 54% of its total area has slopes lower than 6% and only 3% of its area has slopes higher than 30% (Eiras 2017).

The geological and geomorphological characteristics of the studied municipality combined with its climatic characteristics propitiate the occurrence of dangerous events

of hydrologic and geologic nature. The urban area of the municipality of São Carlos is expanding and has experienced a significant increase in the frequency of floods and the production of sediments in its main drainage areas (Tucci and Collischonn 1998). IPT 2015 identified one high-risk site for landslides, and four high-risk and four medium-risk sites for floods in the area under study.

4 Material and methods

The study was developed according to two main research lines: characterization of the temporal and spatial dynamics of rainfall in the study area and the correlation between daily rainfall, MCC (Tatizana et al. 1987), and the occurrence of floods, urban floods and slope movements. The ArcGIS/ArcMap 10.1 geographic information system (GIS) software integrated with spreadsheets (Microsoft Office, Excel 2010) were the basic computational tools used for storing data, calculating rainfall indices, and for spatial analysis. Data from historical records of flood and landslide events in the São Carlos municipality were gathered from news reports, the Civil Defense Department, Google Earth images and field surveys. The digital topographic base on a 1:50,000 and 1:10.000 scales of the São Carlos municipality was used for mapping and spatial analysis in GIS. The research was developed following five major steps, as described below.

4.1 Structuring of the rainfall database

Thirteen rainfall stations internal and external to the urban area were selected to ensure that the study area be completely inserted in the interpolation region (Fig. 1). Being two stations located near each other, the one with the longest historical series was selected. Data on the stations and their respective historical series of daily rainfall were obtained from the Integrated Water Resources Management System (SIGRH) of the Department of Water and Electricity (DAEE) of São Paulo (SIGRH 2016). Data from the D4-017 rainfall station for the period of July 2007 to May 2016 were provided by the National Meteorological Institute (INMET 2016) since data provided by DAEE for this station accounted for records only up to 1971.

Daily rainfall data of the historical series were stored in electronic spreadsheets. Subsequently, a preliminary treatment of these data was performed, filling gaps and discarding periods with no records. This procedure was validated by calculating the percentage differences between the monthly averages obtained with the treated data and those provided by the DAEE. Finally, the treated and validated rainfall data were linked to a vector file with the location of the rainfall stations in the digital cartographic base in GIS, resulting in a rainfall database used for spatial analyses.

4.2 Calculation and spatial analysis of rainfall indices

The analysis of the spatial variability of rainfall in the studied region was carried out based on four rainfall indices: annual average, daily maximum, average monthly, and monthly daily maximum rainfall. The indices were calculated for each rainfall station considering their respective historical series and were regionalized through the deterministic interpolation method of inverse squared-distance weighting (Eq. 1, "Background"). The interpolation limit was defined by the position of the outermost rainfall station and the limits of

the municipality. A 10-m square interpolation cell was adopted. The interpolated values were divided into five classes of relative intensity (very low, low, medium, high and very high rainfall intensity), using the natural breaks statistical method, which identifies the best groups of similar values in a data population and maximizes the differences between the classes (Smith et al. 2015).

4.3 MCC calculation

The accumulated daily rainfall and the daily MCC were calculated according to Eq. 2 ("Background") and using the data of the 13 rainfall stations selected to the study.

4.4 Selection of hazardous events

A total of 179 flood, urban flood and slope movement events triggered in the study area between 1965 and 2016 were selected to be correlated with the daily MCCs and the daily rainfall amounts calculated in the previous steps. The date, location and description of events were obtained from news reports, the Civil Defense Department, Google Earth images and field surveys conducted by Eiras (2017). The D4-017 rainfall station data were used for this correlation study due to the reach of its historical series and its position at lower mean distance of the location of the majority of the considered events. The MCC analysis considered the threshold values of 1, 1.1 and 1.2, whereas threshold values of 10, 20 and 40 mm were used for daily rainfall. These values of MCC and daily rainfall amounts were defined based on the characteristics of the rainfall regime of the studied area and considering the thresholds adopted for the landslide prevention plans of the state of São Paulo (Macedo et al. 1999).

The daily rainfall amounts are the values accumulated between 7 am of the previous day and 7 am of the day considered. Thus, for events occurring in the early hours of the day, it is appropriate to consider the rainfall amounts of the current day, whereas, for events occurring at later periods, it is more appropriate to consider rainfall amounts recorded in the next day. As it was not possible to accurately identify the timing of all events, we adopted the highest value recorded between the day of the event and the day after. For MCC values, this procedure was not necessary since it is a cumulative and continuous index.

4.5 Data integration and analysis

First, we sought to understand the rainfall regime of the studied area, considering the spatial distribution of the calculated rainfall indices (average annual, daily maximum, average monthly and monthly daily maximum). Then, the distribution of the 179 flood, urban flood and slope movement events investigated was also considered. The results of the correlations between MCC, daily rainfall values and the triggering of the analyzed hazardous events were summarized in tables and graphs. The period from 2014 to 2016 was detailed, as it presented several well-documented events. These analyses converged to the goal of defining threshold values for the triggering of floods, urban floods and landslides in the studied area.

5 Results and discussion

5.1 Rainfall maps

Table 1 presents the registration periods of the 13 rainfall stations used to produce the rainfall maps and Fig. 1 their spatial distribution in the São Carlos municipality. Seven rainfall stations presented historical series comprising periods greater than 50 years, considered the ideal minimum period, whereas the six stations presented record periods varying from 22 to 36 years. Some of the stations had data gaps and one of them stopped operating in 1961 (C4-022, São Carlos). Among those located within the urban area of the municipality, only the D4-015 station, near the stream Gregório, had a historical series of over 50 years. Station D4-017, used in the analysis of hazardous events, had 25 years of operation, with a gap between 1972 and 2007.

Five rainfall stations were located at elevations between 610 and 690 m, five above 800 m, one at 760 m, one at 789 m and one at 598 m. No significant differences were observed between the monthly averages of the treated data and the averages provided by the DAEE (78% of the total with a difference of less than 5%, highest difference was 15%), indicating that the general characteristics of the data were not altered with the consolidation procedures used for structuring the rainfall database (Table 1).

The limits of the rainfall maps were defined by the interpolation area generated by the selected rainfall stations in the limits of the São Carlos municipality and its main watersheds (Material and Methods). With this procedure, part of the north and the extreme west of the municipality were not covered by the maps, including the Mogi-Guaçu and Gabirobas watersheds and part of the Cabaceiras, Araras, and Quilombo watersheds. The urban area, the area of greater interest for this study, was totally contained within these limits.

5.2 Annual rainfall map

Annual rainfall values varied between 1091 and 1588 mm, totalizing a difference of almost 50% between the least and the rainiest areas. Figure 2 illustrates the annual rainfall map produced. Table 2 shows the percentage areas of average annual rainfall zones by watersheds in the region of interpolation of rainfall data.

Jacaré-Guaçu, Pântano, Monjolinho and Feijão watersheds have, respectively, 100%, 98%, 83% and 76% of their areas in rainier locations (with high and very high intensities of annual precipitation), while the Araras watershed has about 50% of its area in drier locations (low and very low intensities of annual precipitation).

The headwaters of the Jacaré-Guaçu, Monjolinho and Cabaceiras watersheds, located in the southwest, central, and northwest regions of the municipality, were classified as having very high rainfall intensity (1469–1588 mm). A zone of very low rainfall intensity (1091–1229 mm) was delimited in the headwaters of the Araras watershed, at the north of the municipality. Another less rainy area, characterized as having low rainfall intensity (1229–1334 mm), was identified in the lower part of the Monjolinho watershed, at the extreme west of the urban area (Fig. 2).

The urban area has 89% of its territory located in the rainy region, of which 19% is located in a zone of very high rainfall intensity, in the headwaters of river Monjolinho. The main streams of the urban area, Gregório, Tijuco Alto, Mineirinho, Água Quente, and Água Fria, are located in regions with high average annual precipitation (Fig. 2).

Table 1 Rainfall stations (see Fig. 1), registration periods, elevations (m) and percentage differences between the monthly averages obtained with the treated data and those provided by the DAEE

| Rainfall stations	Registration periods	Years	Elevations (m)	Percentage differences between the monthly averages provided by DAEE and obtained from the study (%)											
				Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
C4-022	1939–1961	22	800	1.3	4.0	7.3	8.8	0.0	0.9	3.5	1.8	6.3	0.9	9.5	15.6
C4-092	1960–2014	54	610	4.2	4.5	3.9	5.6	1.3	1.7	0.8	1.4	1.0	2.6	1.6	2.8
C4-101	1972–1996 1998–2000	26	620	2.3	0.2	11.5	4.2	0.4	3.8	1.8	0.8	2.8	2.3	2.7	1.9
D4-015[a]	1937–1994 1997–1998	58	820	4.5	5.9	0.9	2.8	2.7	1.6	1.7	2.8	0.9	0.2	1.6	1.8
D4-017[a]	1954–1971 2008–2016	25	830	12.0	3.0	0.6	2.2	8.1	4.6	5.9	7.6	7.9	4.5	1.8	15.2
D4-045[a]	1940–1968	28	660	9.2	3.8	11.4	6.5	1.5	1.4	1.8	3.7	1.4	3.6	7.7	2.4
D4-075[a]	1970–1995 2014–2015	26	815	3.4	4.7	6.4	4.1	0.9	6.8	5.8	6.2	2.1	1.1	1.2	1.7
D4-106	1979–2015	36	789	9.5	1.2	4.9	4.2	2.6	3.4	0.0	0.4	4.2	5.7	1.9	1.3
D5-076	1961–2015	54	598	2.2	11.3	6.1	2.3	2.3	1.0	3.8	3.0	1.9	2.4	1.8	0.7
C5-035	1939–1999	60	830	0.3	1.1	5.0	4.9	1.2	5.0	2.2	3.0	2.1	2.3	8.5	1.8
D4-033	1938–1997	59	690	8.5	7.1	0.1	2.0	1.1	2.0	4.6	3.3	0.8	1.2	3.4	3.7
D4-037	1937–1999 2004–2015	73	760	3.3	1.7	3.9	3.6	0.4	1.3	2.4	4.2	1.3	0.8	5.3	5.1
D4-035	1937–2015	78	643	4.4	6.1	5.9	0.7	0.3	1.2	1.9	0.2	0.6	0.1	2.2	0.4

[a] Rainfall stations located inside study area
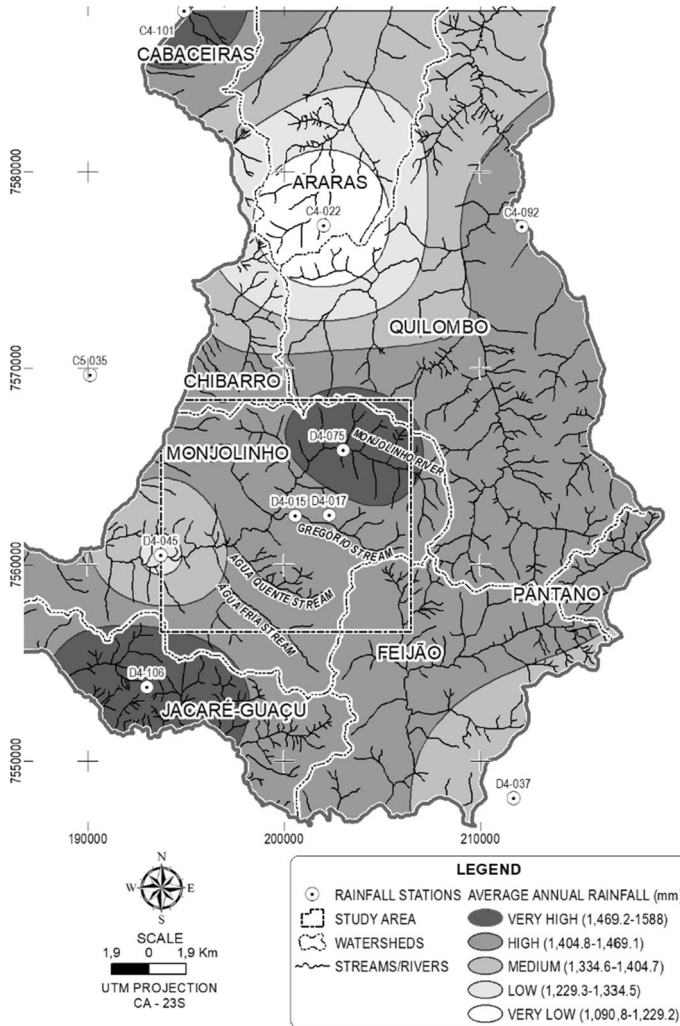
Fig. 2 Average annual rainfall map

5.3 Maximum daily rainfall map

Regarding the maximum daily rainfall, values ranged from 106 to 186.1 mm. Two zones of very high intensity (166.1–186.1 mm/day) were identified in the Jacaré-Guaçu watershed and in the lower portion of the Quilombo watershed, in the southwest and northeast limits of the municipality. Three zones of very low intensity (106–128.6 mm/day) were identified in the Cabaceiras watershed, to the right of the Gregório stream, and in the lower portion of the Monjolinho River, at the extreme west of the urban area (Fig. 3).

Two zones of very low intensity of maximum daily rainfall were identified in regions of the municipality classified as having very high intensity of average annual precipitation (Figs. 2, 3). This apparent contradiction can also be associated with the differences

Table 2 Percentage areas of average annual rainfall zones by watersheds

Average annual rainfall (mm)	Watersheds percentage areas (%)							
	Cabaceiras	Araras	Quilombo	Chibarro	Monjolinho	Feijão	Pântano	Jacaré-Guaçu
VL (1090.8–1229.2)	1	29	3	2	0	0	0	0
L (1229.3–1334.5)	19	26	8	21	2	0	0	0
M (1334.6–1404.7)	11	37	26	31	15	24	2	0
H (1404.8–1489.1)	39	8	60	45	67	76	98	49
VH (1489.2–1588)	30	0	1	0	16	0	0	51

VL very low, *L* low, *M* medium, *H* high, *VH* very high
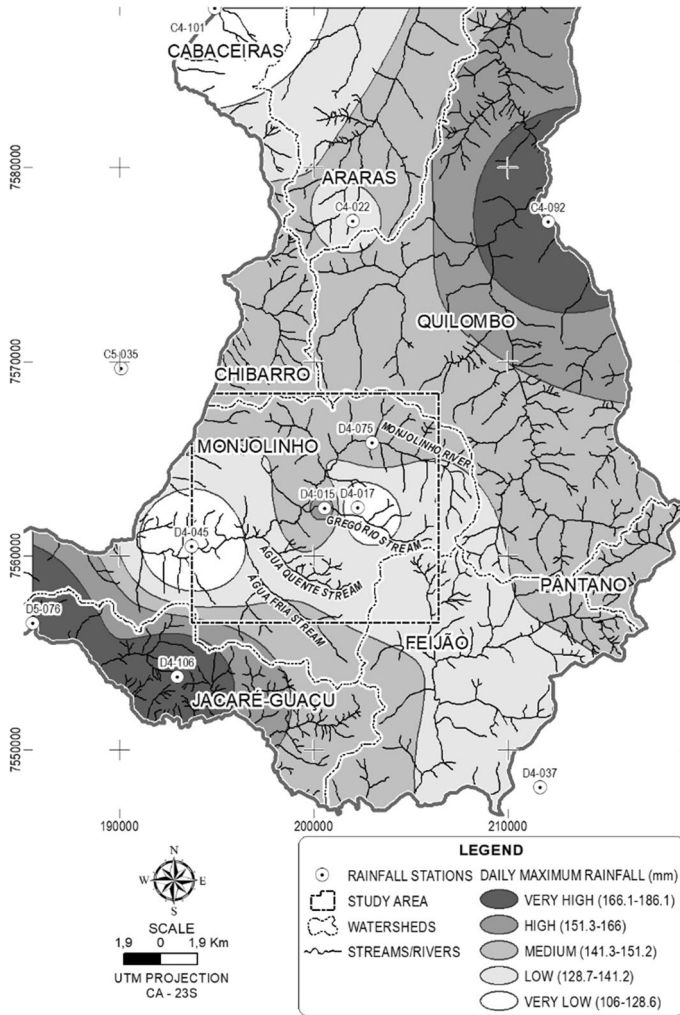
Fig. 3 Maximum daily rainfall map

in the periods and duration of the historical series used, which can interfere in the definition of the daily maximum value of rainfall (Table 1).

On average and for long periods of time, the most intense daily maximum rainfall should occur preferentially in the regions with the highest average annual rainfall, as verified for the two very high intensity zones identified in the Quilombo and Jacaré-Guaçu watersheds, which were also identified as zones of high and very high intensity of annual rainfall (Figs. 2, 3).

The urban area of the municipality was predominantly classified as low and medium maximum daily rainfall. It should be emphasized that the classification of rain intensity zones is comparative (natural method breaks, see Materials and Methods). Thus, in this study, areas classified as very low intensity of maximum daily rainfall had a minimum

value of 106 mm/day, which is considered high in absolute terms for the historical series of the rainfall stations used in the study.

5.4 Average monthly rainfall map

The average monthly rainfall ranged from 14.2 to 291.6 mm throughout the hydrologic year (dry and rainy seasons), as illustrated for the months of July and January in Figs. 4 and 5. There was a tendency for the more and less rainy zones to be approximately coincident throughout the year, only differing in the intervals of the intensity classes regarding the dry and rainy periods. There was also a general tendency for areas of very low, high and very high average monthly rainfall to be approximately coincident with those with the lowest
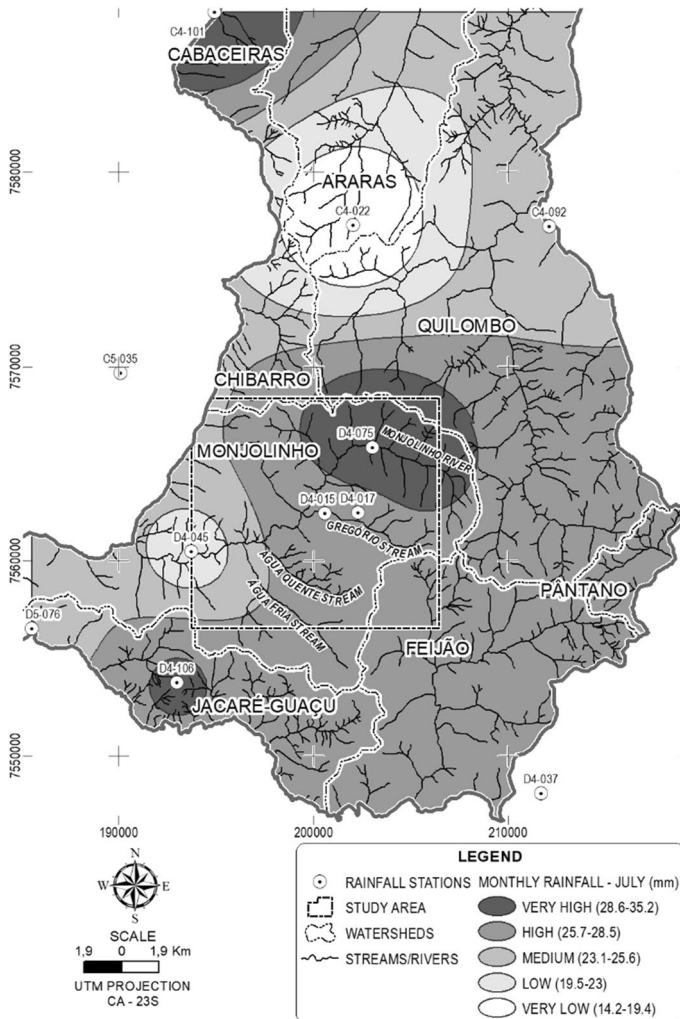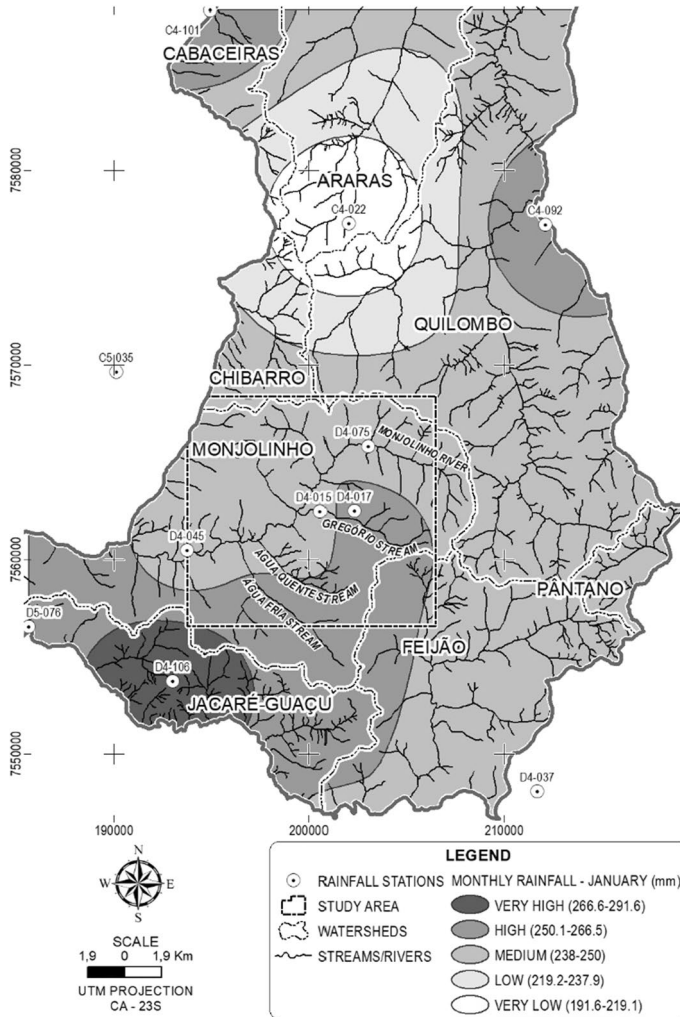

Fig. 4 Monthly rainfall (July) map

Fig. 5 Monthly rainfall (January) map

and highest average annual rainfall, respectively, both in the dry and rainy seasons (Figs. 2, 3, 4, 5).

The values for the monthly daily maximum rainfall ranged from 34.9 mm (August) to 186.1 mm (January). The values of monthly daily maximum are higher than the respective average monthly rainfall from April to September (drier season) and lower than the monthly averages of the wet season (October–March). This result is expected since average monthly rainfall values tend to be high in the rainy season and are unlikely to be reached by daily rainfall amounts. The highest monthly daily maximum rainfall (186.1 mm) corresponds to 95% of the minimum and 64% of the maximum average monthly rainfall, both obtained for January.

The urban area of the municipality presents a predominance of zones of high and very high intensity of average monthly rainfall. In the wet season, this trend is maintained, with

the exception of January, when in the entire northwestern portion of the urban area there is a medium intensity zone, with values ranging from 238 to 250 mm/month, which in absolute terms are also high, 15–16% of the annual maximum precipitation of the historical series considered (Fig. 2). Regarding the monthly daily maximum rainfall, the urban area presents a predominance of medium- and high-intensity areas during the dry period, whereas in the wet season, the medium intensity zone predominates, with some months presenting significant areas of low intensity (120.8–133.6 mm/day), as is the case of January. That is, even in this case, the daily rainfall amounts are also high in absolute terms.

5.5　Spatial and Temporal distribution of hazardous events

Of the 179 hazardous events of hydrologic and geologic nature registered between 1965 and 2016 in the municipality of São Carlos, 103 (58%) were floods, 65 (36%) urban floods and only 11 (6%) landslides. All selected events occurred in areas characterized as high and very high intensity of average annual rainfall. Several flood and urban flood events are recurring in the same place (Fig. 6).

In terms of distribution throughout the hydrologic year, about 80% of these events occurred in the months of November to March (rainier months), with emphasis to January and November, with 20% and 17%, respectively. About 8% of the events occurred in October and April (transition between dry and rainy periods). In the dry period, only three events were recorded in May and one in June, all of them urban floods.

All the considered events occurred in the upper and middle portions of the Monjolinho watershed (Mineirinho, Tijuco Alto, Gregório, Água Quente, and Água Fria streams), being 95% and 23% of them located within a radius of 5 and 1 km of the rainfall station D4-017, respectively, used as the reference for the correlation of daily rainfall amounts and MCC. Floods were recurrent in the region of the Municipal Market (Gregório stream) and in the Rotatória do Cristo (middle Monjolinho, downstream of the Mineirinho and Gregório streams).

Urban flood events are recurrent in the Praça Itália, Municipal market and Cristo roundabout. Many of these urban floods are not directly associated with the natural drainage channels. Landslides are more frequent in the steep slopes supported by sandstones of the Botucatu and basic tabular intrusions (diabase dikes and sills), located on the left bank of the headwaters of the stream Água Quente, in the district of Cidade Araci (Fig. 6).

5.6　MCC, daily rainfall and hazardous events

It was observed that most of the floods (78%) and the urban floods (72%) were related to MCC values above 1, while only 36% of the landslides occurred under these conditions. MCC values above 1.2 occurred for 51% of the inundations, 35% of the urban floods and 9% of the landslides. Only 23% of the inundations and 28% of the urban floods occurred with an MCC below 1, whereas this condition occurred in 64% of the landslide events analyzed. In the analyzed historical series, MCC was over 1 for half of the time (Table 3).

The evolution of MCC during the hydrologic year of 2015–2016 is detailed in Fig. 7, highlighting the dates of occurrence of floods, urban floods and landslides. At the beginning of the hydrologic year, the index began below 1 and so remained until the beginning of July, with a flood event recorded on June 5 (dry season). MCC then peaked in early July, rising to 1.4, and decreased until early September, when it was again below 1. Thereafter, a new peak occurred and a new flood was observed on September 9, with
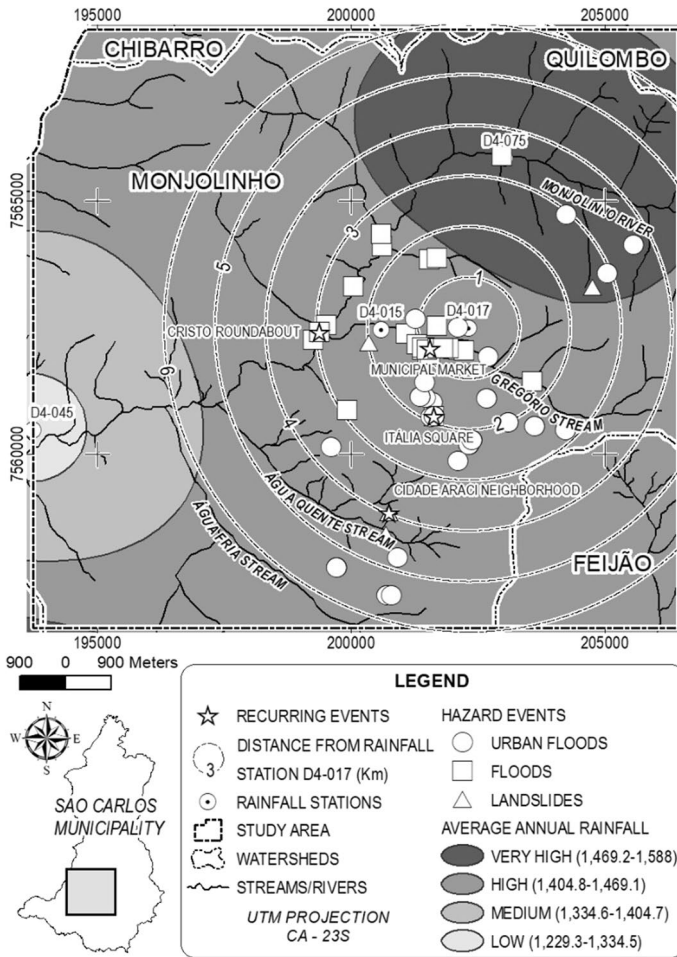
Fig. 6 Spatial distribution of the hazard events in the study area

Table 3 Mobile cycle coefficient (MCC) and hazard events

MCC	Frequency (%)—period of 25 years				
	Registration period	Floods		Urban floods	Landslides
< 1	54	23	28		64
> 1	46	77	72		36
> 1.2	24	50	35		9

an MCC of about 1.2. There was an oscillation in the chart for the remainder of the year, but with the MCC always above 1, approaching 1.4 on certain dates. Many floods, urban floods and a landslide occurred from the beginning of November to the end of March. An isolated flood event was observed at the end of May (2016), with an MCC value approximate to 1.
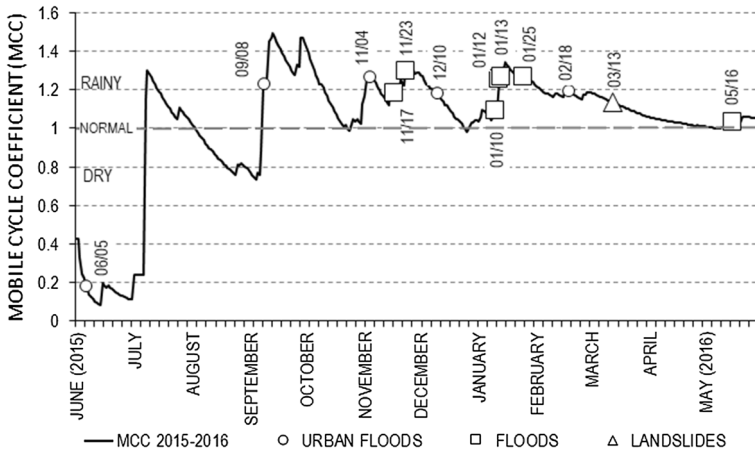
Fig. 7 Mobile cycle coefficient (MCC) for 2015–2016 and hazardous events

Table 4 Daily rainfall values and hazard events

Daily rainfall (mm)	Frequency (%)—period of 25 years			
	Registration period	Floods	Urban floods	Landslides
≤20	93	18	58	64
20< and <40	5	31	6	27
≥40	2	51	36	9

It was observed that 82%, 42% and 36% of flood, urban flood and landslides events occurred with daily rainfall above 20 mm. Notably, daily rainfall between 20 and 40 mm and greater than 40 mm represented only 5% and 2% of the whole historical series considered (Table 4). The results obtained for urban floods can be considered normal since these processes can be triggered by smaller volumes of rain in relation to floods or inundations. On the other hand, the landslides presented an anomalous result, with the majority of events (64%) occurring with daily rainfall below 20 mm.

The frequency of flood events (103 in total) was also analyzed in relation to MCC in combination with daily rainfall in order to define thresholds for the triggering of these processes. The smallest and largest CCM associated with the registered flood events was 0.75 and 1.85, with daily rainfalls of 0.2 and 10 mm, respectively (Fig. 8).

Figure 9 shows the distribution of the 65 urban flood events registered according to the CCM and daily rainfall values. The smallest and largest CCM associated with these events was 0.2 and 1.7, with daily rainfalls of 0.2 and 23 mm, respectively.

The highest frequency of floods (75% of events) occurred with an MCC ≥ 1 and daily rainfall above 10 mm. Floods frequency remained very high with an MCC ≥ 1.1 and daily rainfall above 10 mm (73% of events). All other combinations with an MCC above 1.1 or MCC above 1 and daily rainfall above 20 mm presented lower frequencies of
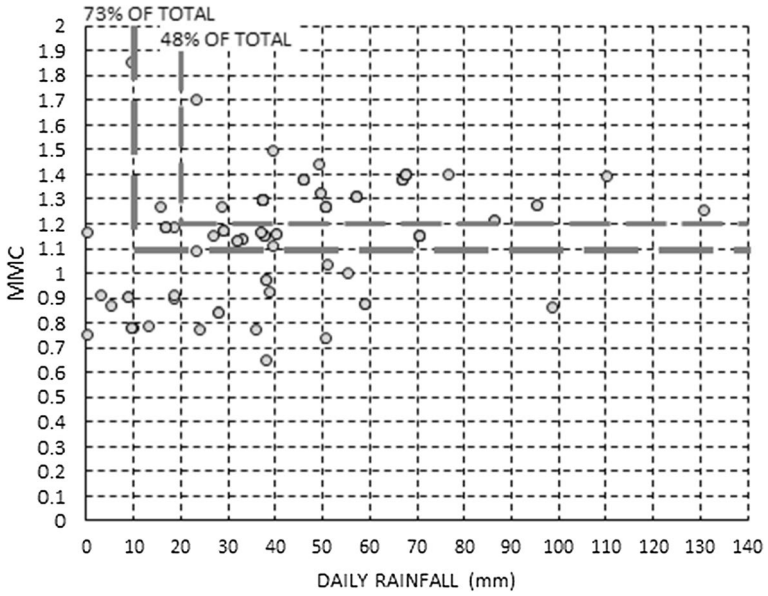
Fig. 8 Flood events by mobile cycle coefficient (MCC) and daily rainfall
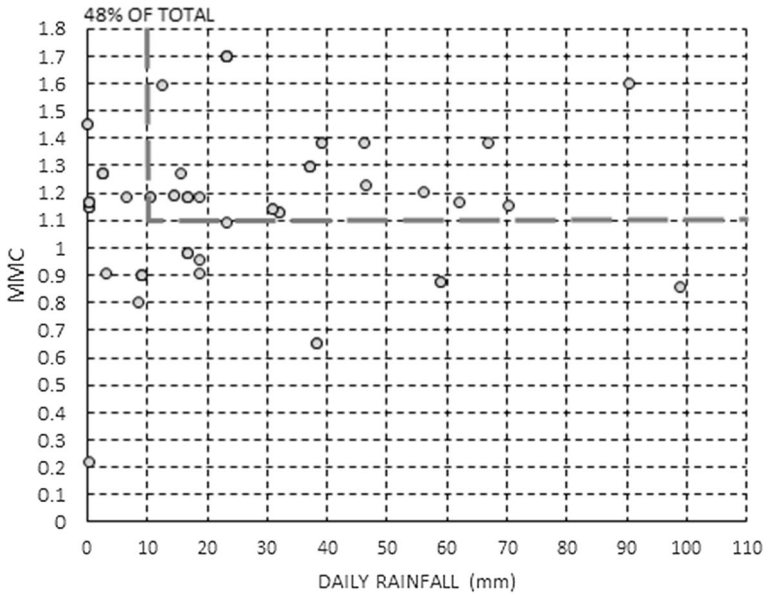

Fig. 9 Urban flood events by mobile cycle coefficient (MCC) and daily rainfall

Table 5 Frequencies of mobile cycle coefficient (MCC) and daily rainfall (DR)

MCC and DR (mm)	Frequency (%)—period of 25 years
MCC ≥ 1 and DR > 10	7
MCC ≥ 1.1 and DR > 10	6
MCC ≥ 1.2 and DR > 20	2

floods. For example, less of 50% of the floods occurred for MCC ≥ 1.2 and daily rainfall above 20 mm (Fig. 8).

Flood and urban flood events with very low CCM and daily rainfall values should be related to inaccuracies in data records, localized rains not registered by the station D4-017 (adopted as the reference in the analyses) or specific determinants (anthropogenic modifications).

In defining the threshold values for the mobile cycle coefficient (MCC) and daily rainfall, it is also important to know the frequency of these values in the historical series. If the values adopted are very frequent, there is a risk of structuring a preventive action plan with a low success rate and little efficiency. Table 5 presents these frequencies considering the combinations of MCC and daily rainfall with more events of floods.

Considering that 73% of all flood events occurred for values of MCC ≥ 1.1 and daily rainfall above 10 mm and that this combination of values occurred in only 6% of the entire period analyzed (Table 5), it is believed that these values could be tested as threshold values to predict the occurrence of floods in the urban area of São Carlos to subsidize preventive measures by the Municipal Civil Defense Department.

The combined values of MCC ≥ 1.1 and daily rainfall > 10 mm can also be preliminarily adopted as thresholds for the triggering of urban flood events in the study area but with a lower recorded frequency than the observed for floods (48%, Fig. 9). For landslides, it is necessary to expand and improve the registration of events.

6 Conclusions

The rainfall maps produced proved to be good tools for spatialization and characterization of rainfall dynamics. They indicated that the urban area of São Carlos is one of the rainiest zones in the municipality and has favorable conditions for the occurrence of intense rainfall able to trigger floods, urban floods and landslides.

In spite of data limitations on registration of some events and the available historical series of daily rainfall, the study indicated a good potential for the combined use of MCC and daily rainfall indices as indicators of floods and urban floods in the study area. The combined use of MCC values above 1.1 and daily rainfall above 10 mm could be tested as indices to predict the occurrence of floods in the urban area of São Carlos.

Landslides presented an anomalous behavior in relation to rainfall indices, with 64% of the events being recorded with MCC < 1 and daily rainfall < 20 mm. This apparent incongruence can be explained by the small number of landslides events considered; not considering the accumulated rainfall prior to the event (increase in the degree of saturation and hydraulic conductivity of the soil); the greater distance of these events in relation to station D4-017; the fact that a part of these events are associated with cut and embankment slopes

and, therefore, may have been triggered by influence of other agents; and inaccuracies on the day of the occurrence of these events since some records were based on the interpretation of image areas and not on news reports.

The results also confirm that MCC cannot be used as the sole indicator of hydrologic and geologic events since in almost half of the time of the historical series considered (46%, Table 3), it presented values above 1, being necessary to use the index in combination with rainfall intensity values. The simplicity and easy access to these rainfall indices indicate their potential use to subsidize Civil Defense preventive measures while further studies are not available.

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