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Time distribution of intense rainfalls at Campinas, Brazil

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Abstract— *the temporal variation of intense rainfalls is of great importance in hydrological analyses and prediction, which is required for dimensioning engineering projects. Therefore, this study has as objective to determine the temporal distribution of intense rainfalls with durations of 1, 2 and 4 h in Campinas, state of Sao Paulo, Brazil, for the period from 1997 to 2016. The rainfalls with duration of 1 h were subdivided in three intervals of 20 min. Rainfalls with duration of 2 and 4 h were subdivided in four intervals each, respectively of 1 h for the latter and of 30 min for the former. For rainfalls of 1, 2 and 4 h, the early rain distribution prevailed, i.e., the rainfall is more intense in the first period of time, regardless the total and duration of the event. Statistically, the intensive rainfall data adjusted to the Lognormal and Truncated Negative Binomial probability distributions.*

Keywords— heavy rainfalls, hyetograph, probability distribution, temporal distribution.

I. INTRODUCTION

The study of extreme climatic events is a topic of great interest in meteorology, because they are responsible for numerous social and economic impacts throughout the world (Vörösmarty et al., 2013; Swaminathan & Rengalakshmi, 2016). The analysis of these events provides important information on the behavior of watersheds from the point of view of floods (Beskow et al., 2015). Such skills are fundamental to the design of hydraulic structures and flood control (Cheng & AghaKouchak, 2014) and to the elaboration of strategies for soil conservation, since high-intensity rains have active participation in erosion processes (Vallebona et al., 2015; Martínez-Casanovas et al., 2002; Carvalho et al., 2009).

Severity and potential damages of storms depend on variables such as quantity of precipitation, intensity and duration, given that such information is crucial for practical and scientific purposes (Gaál et. al., 2014). Another characteristic to be considered in the analysis of these events is their temporal distribution, factor that can significantly influence the shape and the peak of the hydrograph. The knowledge of temporal distribution, besides being of great importance in the sizing of hydraulic structures, helps to understand the rainfall potential for causing flood and eroding the soil (Huff, 1967). In this context, engineers often need to establish flood control techniques and estimate the maximum discharge or design hydrographs for hydraulic structures scaling (Terranova & Iaquinta, 2011; Ghassabi et al., 2016; Dolšak et al., 2016; Back, 2011; Beskow, 2015).

Since this temporal distribution, which can vary in both space and time and also in relation to the type of precipitation, is unknown a priori, it is common to adopt empirical distributions that seek to represent the most critical conditions possible of temporal disaggregation of rainfall and thus define an equally critical hydrograph (Abreu et. al., 2017). It is in the disaggregation of precipitation for determination of the design hyetographs that the hydrologist's main problem lies, since each temporal distribution of rainfall has different hydrographs (Canholi, 2005).

According to the Manual of Rainwater Drainage and Management of the State of São Paulo (Manual de Drenagem e Manejo de Águas Pluviais de São Paulo – São Paulo, 2012), the kind and duration of temporal distribution of design rainfalls are subjected to several methodological guidelines, implying in results of maximum loads and flood volumes that can be quite discrepant.

Therefore, knowing the temporal distribution model of intense rainfalls of a locality makes the hydrological forecast in engineering projects in rural and urban areas more realistic, allowing the quantification of the effect of a hydrological event, which can be conducted by applying methods of hydrographs analysis (Sentelhas et al., 1998; Ahmed et al., 2012; Bonta, 2004).

Another important factor in intense rainfall analysis is to find the probability density function that best adjusts to the data, given that it is used for probability determination of stochastic variables, such as the prevision and estimate of precipitation (Mandal & Choudhury, 2015). Several probability distribution functions can be used for analysis of extreme events.

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According to Aksoy (2000), the most common distributions in hydrology are the normal, log-normal, gamma, Gumbel and Weibull.

Due to the importance of finding the probability distribution that best adjusts to the precipitation data, several studies for different localities are conducted aiming the best probability distribution (Amin et al., 2015; Li et al., 2014; Haddad & Rahman, 2011; Mamoon & Rahman, 2017; Zin et al., 2009; Sharma & Singh, 2010; Olumide et al., 2013).

Despite the literature being vast and diverse regarding rainfalls and its intensity, studies that report how the intense rainfall is distributed throughout its occurrence, i.e., its temporal distribution, are rare (Li et al., 2017; Syafrina et al., 2015; Forestieri et al., 2018; Douka & Karacostas, 2017). Thus, the objective of this study is to analyze data from hyetographs of the climatological station in Campinas, SP, Brazil, from 1997 to 2016, to determine the temporal distribution of intense rainfalls with duration of 1, 2 and 4 h. We also verified whether the analyzed data fit to a probability distribution.

II. METHODOLOGY

We used data from intense rainfalls with durations of 1, 2 and 4 h obtained from the climatological station, located in Campinas/SP, state of São Paulo, Brazil (22°49'07"S, 47°03'43"W and altitude of 635m). The climatological station, regarding the locality and equipment installation, is in accordance with the guidelines of the World Meteorological Organization (WMO). The pluviograph consists of a bascule model and records the precipitation every 10 minutes. The bascule to measure precipitation has a sensitivity of 0.5 mm.

We analyze isolated extremes events in the period between 1997 and 2016, from October to March, characterizing the rainy season, period of intense rainfalls, when approximately 80% of the total annual rainfalls occurs. The events, subdivided into intervals according to duration of rainfalls, were arranged in histograms.

After definition of rainfall duration, another issue addressed in this study was which value to adopt when considering a rainfall as intense. In practice, it is difficult to establish a value considering a rainfall as intense, as the impact can be different, depending on the characteristics of the local (Pinto, 1999). For example, in the urban area the problem is associated to the accelerated superficial runoff and low infiltration, causing floods and inundations, very common in major Brazilian cities that grow in a disorderly manner (Canholi, 2005). In rural areas, intense rainfalls can cause the erosive process in the soil (Kaufmann et al., 2012). For this study, the criterion adopted was based on basic infiltration rate in soils of the region, which according to Reichardt (1987), is equal to 15 mm/h. Thus, we selected events with potential for runoff generation following the same criteria by Cruciani et al., (2002) and Sentelhas et al., (1998), which were:

a) for intense rainfalls with duration of 1 h:

– Divided into 3 time intervals of 20 min each and precipitation equal to or higher than 12 mm.

b) for intense rainfalls with duration of 2 h:

– Divided into 4 time intervals of 30 min each;

– Precipitation equal to or higher than 15 mm in the first hour and total precipitation equal to or higher than 20 mm.

c) for intense rainfalls with duration of 4 h:

– Divided into 4 time intervals of 1 hour each;

– Precipitation equal to or higher than 15 mm in the first hour and total precipitation equal to or higher than 20 mm.

The events, subdivided into intervals, were arranged in histograms, and the most frequent cases of temporal distribution were selected for analysis. Within the intense rainfall records obtained from precipitation data, we divided the cases from 1 to n, representing the intensity of precipitation in each time interval. Rainfalls in which the highest rainfall event depth occurred in the first interval, we named as case 1; if the highest rainfall event depth occurred in the second interval, the rainfall was named as case 2, and so on.

After selection of events according to the criteria, precipitation data were analyzed considering the observed values, ordered so that the frequency distribution analysis and the search for a theoretical probability distribution that best adjust the sampling distribution were allowed. There are numerous probability models applied to continuous random variables, such as the annual maximum daily precipitation. In Brazil, the most used theoretical probability models are the Lognormal distribution of 2 and 3 parameters, and the Extreme Value Distribution Type I, also known as Gumbel (Mello & Viola, 2013; Caldeira et al., 2015). The probability distribution used in this study was the lognormal distribution with two parameters, widely used in hydrology and easily transformable into normal distribution (Mello et. al, 1994). The probability density function is given by:

$$f(x) = \frac{1}{\sigma . x . \sqrt{2.\pi}} . e^{-0,5\frac{(\ln x - \mu)^2}{\sigma^2}} \quad \text{for } 0 < x < \infty \qquad (1)$$

It's distribution function is given by:

$$F(x) = \int_0^\infty f(x).d(x) \qquad (2)$$

being:

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$$E(x)=e^{\mu+\frac{\sigma^2}{2}} \text{ and } Var(x)=\mu^2(e^{\sigma^2}-1) \qquad (3)$$

in which: σ is the standard deviation of the distribution, referring to the intense rainfalls; μ is the average intense rainfalls; x is the daily intense rainfall to be considered; E(x) the expected value and Var(x) the theoretical variance.

The truncated negative binomial distribution is given by:

$$p(x+1)=f(x)\left(\frac{K+x}{x+1}\right)(1-W) \qquad (4)$$

being:

$$W=\frac{\bar{x}}{S^2}\left(1-f\frac{1}{N}\right) \text{ and } K=\frac{W.\bar{x}-f\frac{1}{N}}{1-W} \qquad (5)$$

in which: x is the daily intense rainfalls to be considered; $\bar{x}$ is the average of the data grouped by class; S^2 is the sample variance; N is the sum of rainfall frequencies; W and K are parameters of the equation.

And the Gumbel distribution:

$$f(X)=\frac{1}{\beta}e^{-\frac{X-\alpha}{\beta}}e^{-e^{-\frac{X-\alpha}{\beta}}} \qquad (6)$$

in which: x is the daily rainfall to be considered; α and β are parameters of the equation. The cumulative probability function is:

$$F(X)=e^{-e^{\pm\frac{X-\alpha}{\beta}}} \qquad (7)$$

The double signal in the second exponent refers to the maximum (negative sign) and minimum (positive sign) values.

The adjustment of precipitation data for each of the distributions was evaluated through the χ^2 and Kolmogorov-Smirnov (KS) tests at a significance level of 0.01 (Assis et al., 1996).

III. RESULTS AND DISCUSSION

3.1 Temporal distribution of rainfalls

Table 1 shows a statistical description of the events of rainfalls with duration of 1, 2 and 4 h. The data indicate a distribution with strong asymmetry for the precipitation events. The mean is higher than the median and mode, and the coefficient of variation (CV) is high, 51.23%, 55.55% and 42%, for the rainfalls with duration of 1, 2 and 4 h, respectively.

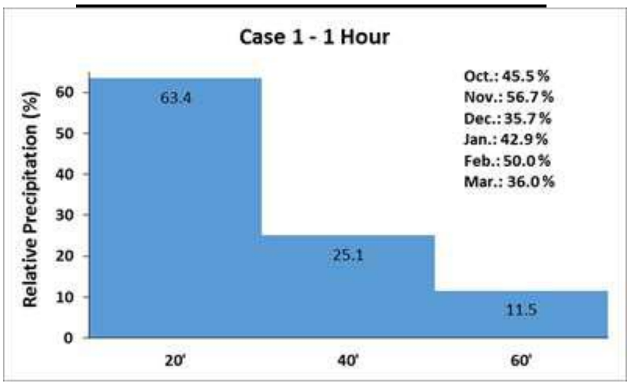
We identified 201 events of intense rainfalls with duration of 1 h, according to the distribution shown in Table 2. In this way, three histograms were prepared for the rainfalls with duration of 1 h (Fig. 1). One can see that the most frequent distribution model for the intense rainfalls with duration of 1 h was the type 2 model. Cruciani et al. (2002), analyzing precipitation data from Piracicaba, 65 km from Campinas, in the period from 1966 to 2000, found type 1 more frequently, in 85.7% of the events in the analyzed period.

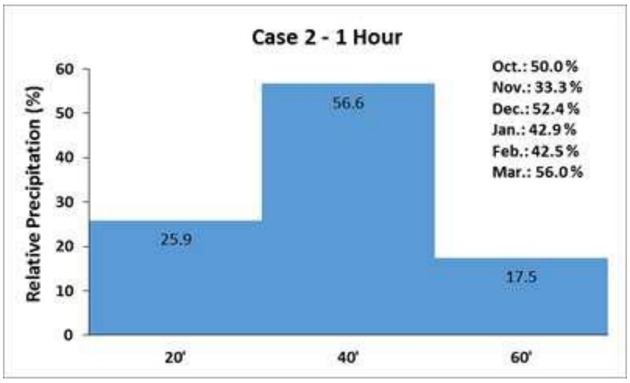
Table 1. Statistical description of the events of intense rainfalls with 1, 2 and 4 h duration, in Campinas/SP, in the period from 1997 to 2016.

	Rainfall (mm) 1 h	Rainfall (mm) 2 h	Rainfall (mm) 4 h
N	201	82	18
MEAN	21.7	37.8	49.9
STDEV	11.1	21.0	20.9
MAXIMUM	68.3	119.2	94.2
MINIMUM	11.2	17.8	25.8
MODE	12.7	23.3	-
MEDIAN	17.80	31.24	42.42
CV (%)	51.23	55.55	42.00

Table 2. Distribution of intense rainfalls with 1 h duration

Type	Frequency	Distribution (%)
Type 1	89	44.3
Type 2	92	45.8
Type 3	20	9.9
Total	201	100





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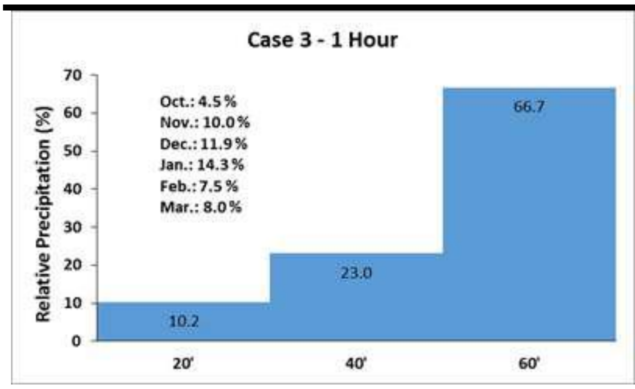
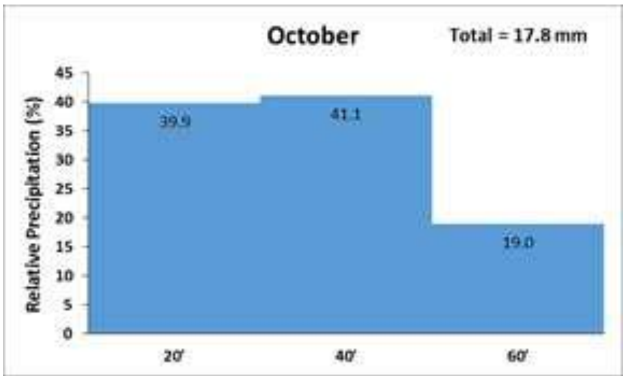
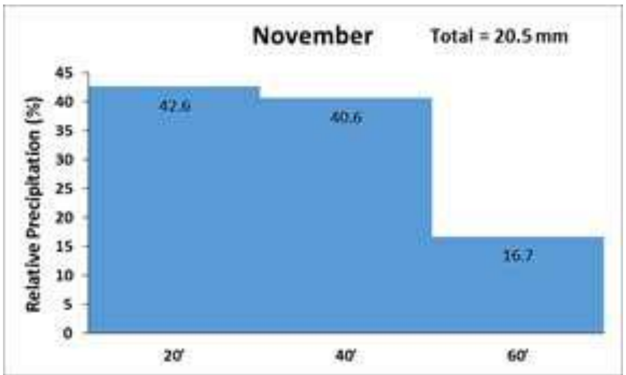
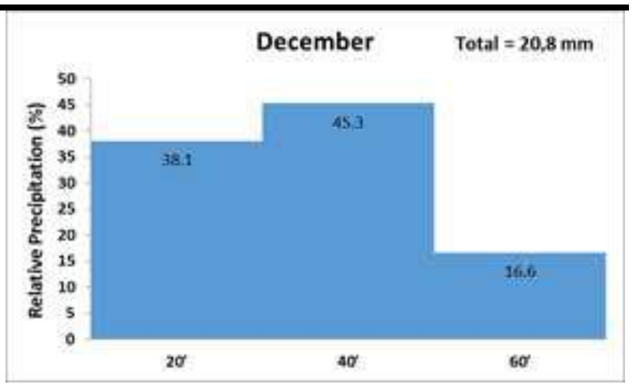


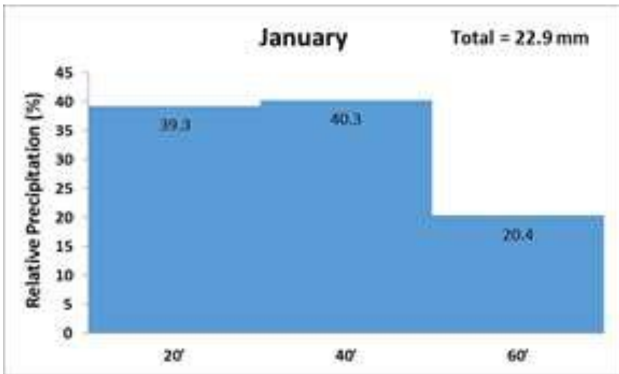
Fig. 1 – Distribution histograms of intense rainfalls with 1 h duration, in the period from October to March, for the city of Campinas/SP, from 1997 to 2016.

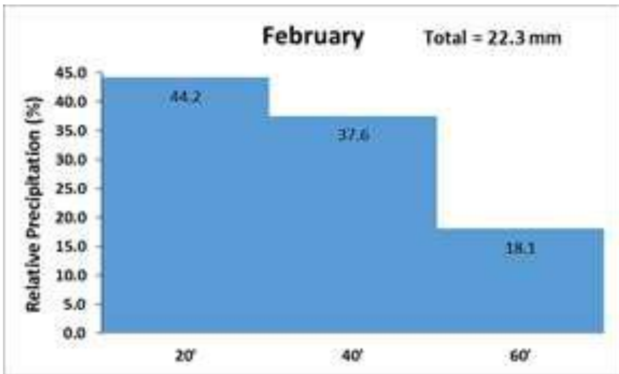
Distribution models of intense rainfalls with duration of 1 h for each month are shown in Fig. 2, in percentage. March was the month that showed the highest average precipitation, with 25.1 mm. A result similar to that achieved by Mello et al. (1994), in which March represents a critical state regarding the intensity of rainfall with duration of 60 min.











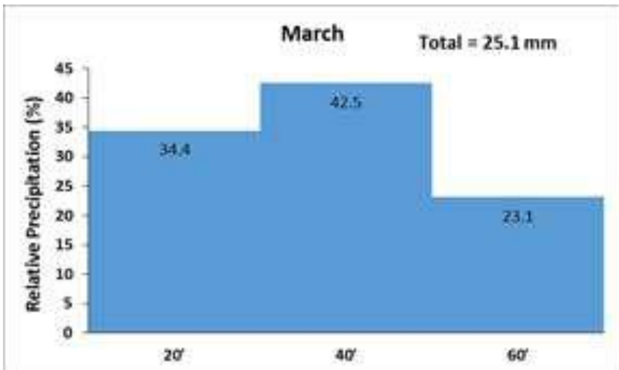


Fig. 2. Temporal distribution of intense rainfalls with 1 h duration, from 1997 to 2016, for the city of Campinas/SP, in the period from October to March.

The predominant distribution model of intense rainfalls with duration of 1 h showed an average of 21.7 mm (Fig. 3), with the following relative distribution:

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39.8% in the first-time interval, 41.1% in the second interval and 18.9% in the third interval.

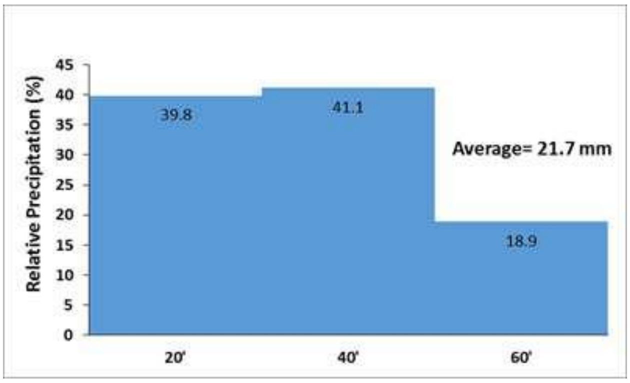
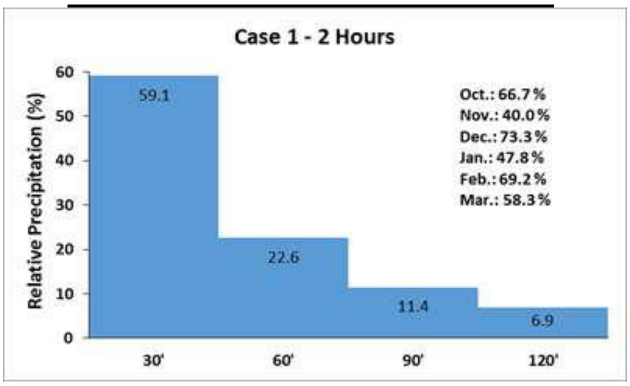


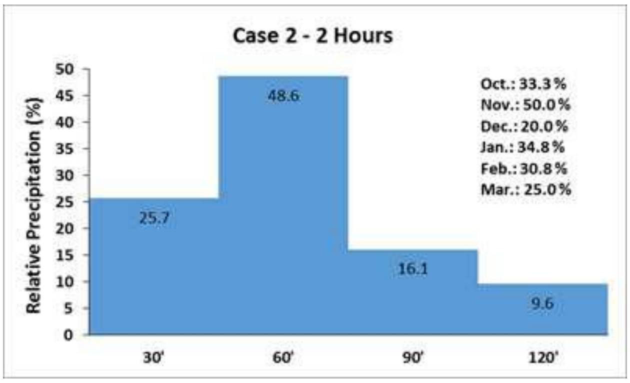
Fig. 3 – Distribution histograms of intense rainfalls with 1 h duration, from 1997 to 2016, for the city of Campinas/SP, in the period from October to March.

In the data analysis of the intense rainfalls with duration of 2 h, we found 82 events of intense rainfalls distributed according to Table 3. Thus, we observe that the most frequent distribution model was type 1. Fig. 4 shows the histograms generated for intense rainfalls with duration of 2 h for each case.

Table 3. Distribution of intense rainfalls with 2 h duration

Type	Frequency	Distribution (%)
Type 1	48	58.5
Type 2	26	31.7
Type 3	8	9.8
Total	82	100.0





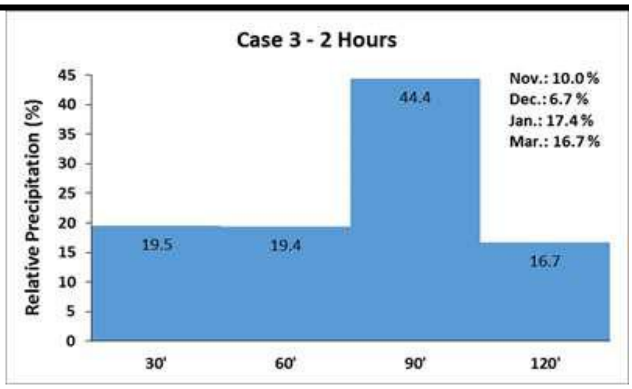
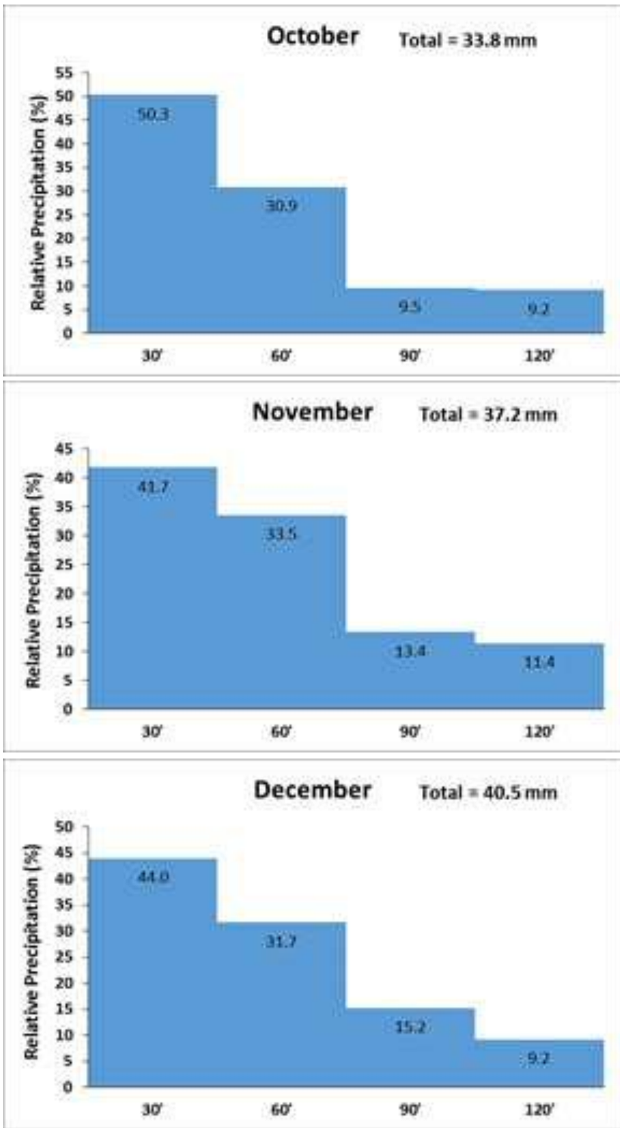


Fig. 4 – Distribution histograms of intense rainfalls with 2 h duration, in the period from October to March, for the city of Campinas/SP, from 1997 to 2016.

Distribution models of intense rainfalls for each month in the period studied are shown in Fig. 5, in percentage. The month with the highest rainfall levels in the first 30 min of precipitation was October, with 17 mm (50.3%). However, February was the month that showed the highest average precipitation, with 45.4 mm.



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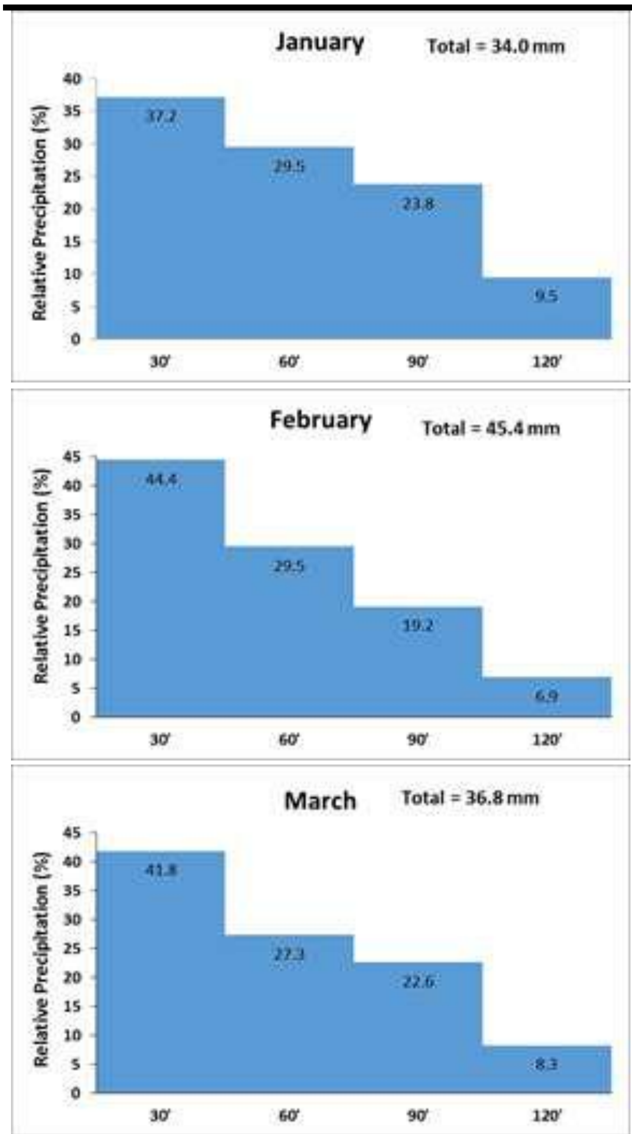


Fig. 5 – Temporal distribution of intense rainfalls with 2 h duration, from 1997 to 2016, for the city of Campinas/SP, in the period from October to March.

The representative model of intense rainfalls with duration of 2 h showed an average of 37.8 mm (Fig. 6), with the following temporal distribution: 42.3% in the first time interval, 30.2% in the second interval, 18.4% in the third interval and 9.0% in the fourth interval. This pattern is characteristic of convective rainfall, which predominate in the region during the period under examination.

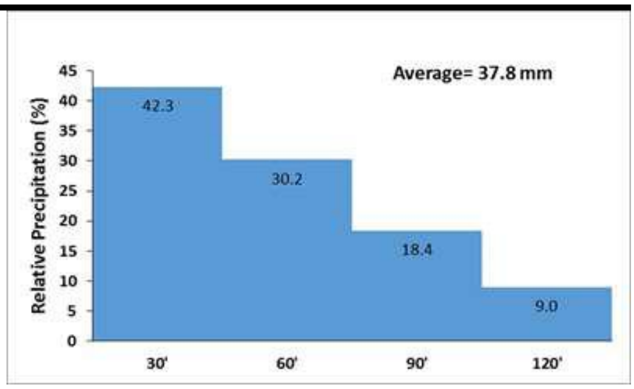


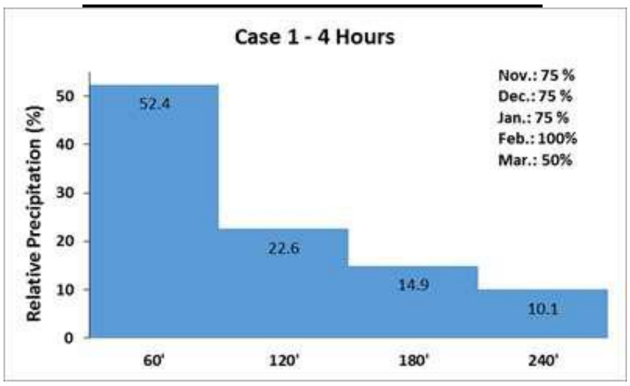
Fig. 6 – Representative model of distribution of intense rainfalls with 2 h duration, from 1997 to 2016, for the city of Campinas/SP, in the period from October to March.

For intense rainfalls with duration of 4 h, 18 events were found within the analyzed period, of which 72.2% were classified as type 1 (Table 4). With these data, the histograms for the intense rainfalls with duration of 4 h were generated (Fig. 7).

Distribution models of intense rainfalls with duration of 4 h for each month are shown in Fig. 8, in percentage. December was the month with the highest rainfall levels within the first hour, 52.4% (29.4 mm). However, the highest rainfall levels took place in March, with an average of 62 mm. For October, no events of intense rainfall with duration of 4 h were found.

Table 4. Distribution of intense rainfalls with 4 h duration

Type	Frequency	Distribution (%)
Type 1	13	72.2
Type 2	3	16.7
Type 3	2	11.1
Total	18	100.0



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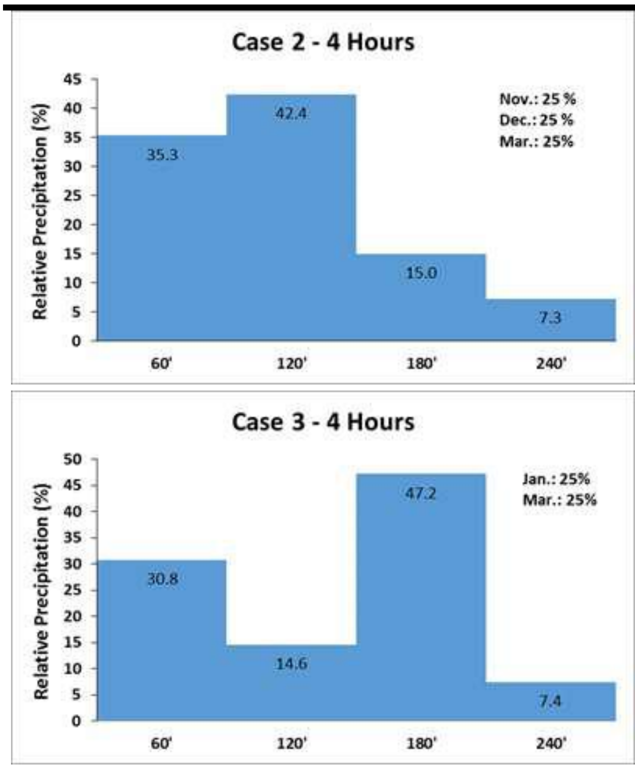
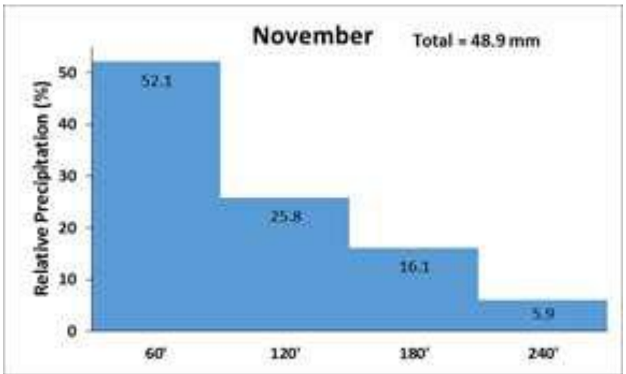


Fig. 7 – Distribution histograms of intense rainfalls with 4 h duration, in the period from October to March, for the city of Campinas/SP, from 1997 to 2016.

The representative model of distribution of intense rainfalls with duration of 4 h showed an average of 49.9 mm (Fig. 9), with the following temporal distribution: 46.4% at the first time interval, 26.3% in the second, 17.7% in the third and 9.5% in the fourth. Sentelhas et al. (1998), analyzing precipitation data from the agrometeorological station of the Luiz de Queiroz College of Agriculture, in Piracicaba, from 1966 to 1995, found type 1 more frequently, in 85% of the events in the analyzed period.



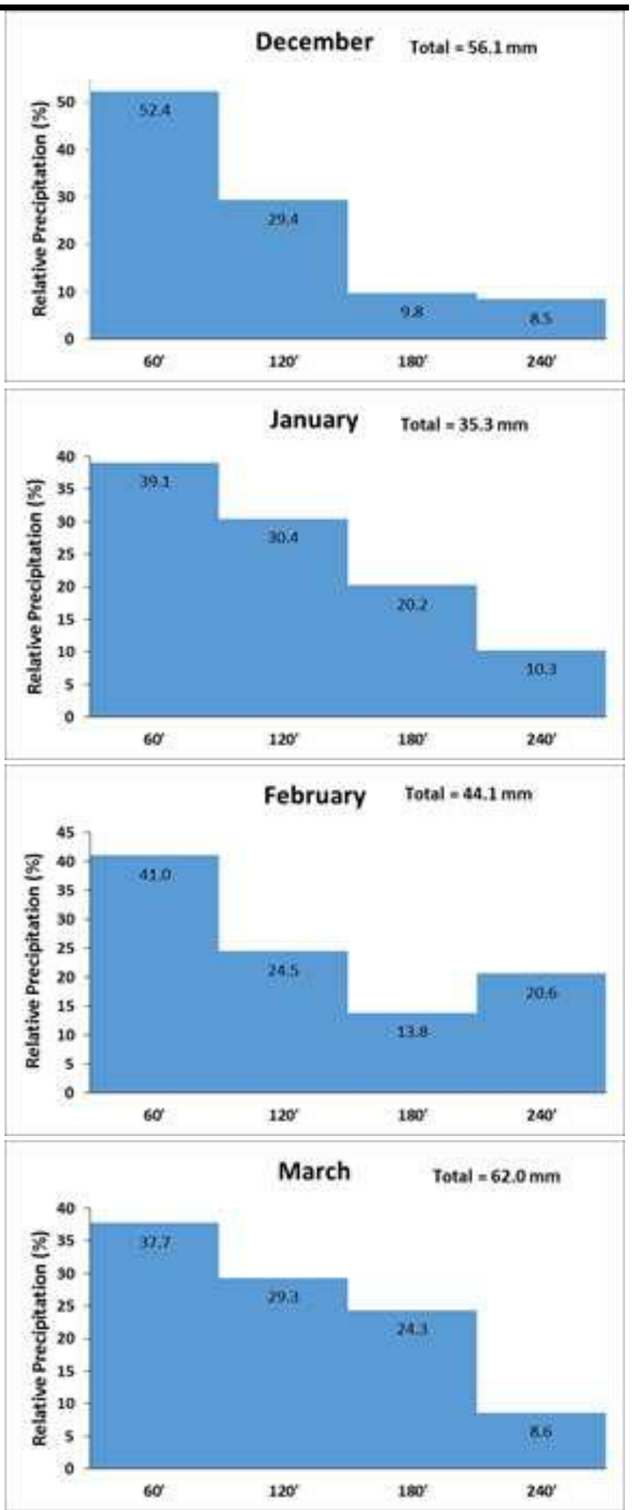


Fig. 8 – Temporal distribution of intense rainfalls with 4 h duration, in the period from November to March, for the city of Campinas/SP, from 1997 to 2016.

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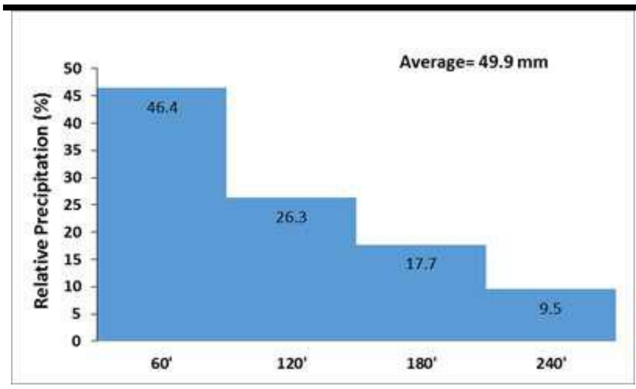

Fig. 9 – Representative model of distribution of intense rainfalls with 4 h duration, in the period from October to March, for the city of Campinas/SP, from 1997 to 2016.

The results found are typical of convective rainfall, also characterized as advanced, which predominates in the region during the study period. The convective events in Brazil suffer great influences of the South Atlantic convergence zone, but they can also, in some cases, occur because of the interaction of cold fronts with hot air masses (Vicente & Nunes, 2004). The predominance of this rainfall pattern can be found in other regions of the country, such as in the cities of Lajes (Cardoso et al., 2014) and Urassanga (Back, 2011), both located in the state of Santa Catarina, Southern Brazil.

In other countries, the prevalence of convective rainfall was found by Oñate-Valdivieso et al. (2018) in an Andean region in Southern Ecuador, where it's predominates during the rainy season and also by Syafrina et al. (2015), who found great contribution of convective rainfall in events that reach the west region of Peninsular Malaysia.

The type of precipitation is strongly related to soil erosion. In the study by Carvalho et al., (2009) the rains with greater intensity at the end of their duration were responsible for the greatest soil loss (58.3%), while the advanced and intermediate ones showed a loss of 35.1% and 6.6%, respectively. According to Sao Paulo (2012), rains with higher intensity at the end of their duration, cause greater floods.

3.2 Probability distribution

To view the data behavior of rainfalls with duration of 1, 2 and 4 h, we arranged them in histograms represented graphically (Fig. 10) together with the Lognormal probability (LogN), Truncated Negative Binomial (NTBin) and Gumbel distributions.

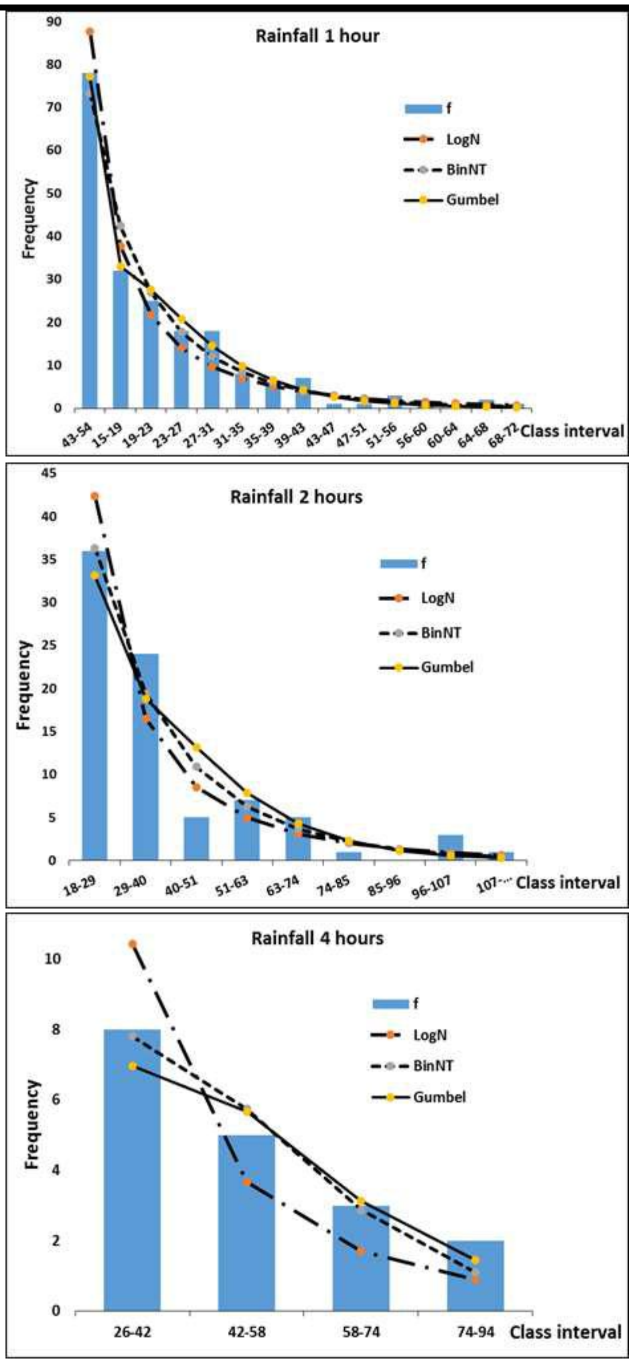

Fig. 10 – Empirical and theoretical probability (%) of maximum rainfall values greater than or equal the given value, using the LogNormal (LogN), Truncated Negative Binomial (NTBin) and Gumbel distributions, for rainfalls with 1, 2 and 4 h duration.

The distributions were fit to data related to hourly intense rainfalls. To corroborate with the graphical analysis, χ^2 and Kolmogorov-Smirnov (KS) statistical tests were conducted to verify if the precipitation data follow any of the distributions. The tests have the following hypotheses:

$$\begin{cases} H_0 = \text{Belongs to the tested distribution} \\ H_1 = \text{Does not belong to the tested distribution} \end{cases}$$

According to Table 5, both the lognormal distribution (LogN) and the Truncated Negative Binomial (NTBin) distribution were statistically adjusted to the sampling frequency distribution for the rainfalls with duration of 1, 2 and 4 h. The χ^2 calculated was lower than the one shown in the table. However, the BinNT distribution had a better adjustment. The same applies to the KS test. The Gumbel probability distribution was adjusted only for the rainfalls with duration of 4 h. However, despite the calculated χ^2 and KS being lower than those shown in the table for the LogN, BinNT and Gumbel probability distributions for the rainfalls with duration of 4 h in the analyzed period, it is not safe to affirm, with a non-representative sample number, the data adjustment to a sampling distribution for rainfalls with this duration.

Table 5. χ^2 and Kolmogorov-Smirnov (KS) statistical tests at 1% significance level applied to probability distributions for intense rainfalls with 1, 2 and 4 h duration for Campinas/SP.

Intense rainfalls	Distributions	χ^2_{calc}	χ^2_{tab}	KS_{calc}	KS_{tab}
1 h	LogN	19.249	21.666	-0.050	-0.115
	BinNT	16.491	20.09	-0.052	-0.115
	Gumbel	24.07	20.09	-0.996	-0.115
2 h	LogN	14.642	16.812	0.088	0.180
	BinNT	13.822	16.812	-0.073	0.180
	Gumbel	20.106	16.812	-0.985	0.180
4 h	LogN	3.362	6.635	-0.159	0.370
	BinNT	0.839	6.635	-0.056	0.370
	Gumbel	0.442	6.635	-0.852	0.370

IV. CONCLUSION

The temporal distribution model of heavy rainfalls with duration of 1, 2 and 4 h for the city of Campinas is very similar to the model of distribution of heavy rainfalls for Piracicaba. Early distribution rainfalls prevail in the region, regardless of the total and the duration of precipitation. However, as the climate phenomena are random, to determine the representative distribution model of heavy rainfalls in a determined region, one should consider the fact that a single rainfall may have other combinations of intensity and distribution throughout its duration. Lognormal (LogN) and Truncated Negative Binomial (BinNT) distributions were the ones best adjusted to the data collected for rainfalls with duration of 1 and 2 h. However, despite the Gumbel probability distribution being better adjusted for the rainfalls with duration of 4 h, few rainfall events with this duration occurred in the analyzed period. This article showed that the analysis of temporal distribution of design rainfalls is crucial to the numerous issues of interest to engineering, especially the control of surface runoff, in urban and rural areas.

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