Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 23, e16, 2018
Scientific/Technical Article

http://dx.doi.org/10.1590/2318-0331.231820170155

Relationships between rainfall and throughfall in a secondary forest in southeastern Brazil: an evaluation of different statistical models

Relações entre precipitação em aberto e precipitação interna em uma floresta secundária no sudeste brasileiro: uma avaliação de diferentes modelos estatísticos

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Received: September 22, 2017 - Revised: January 31, 2018 - Accepted: March 9, 2018

ABSTRACT

Throughfall (TF) is influenced by different meteorological conditions, which can result in high spatial and temporal variability, when interacting with vegetation and mutually with each other. This study aimed to evaluate rainfall (RF) influence on TF, as well as to describe the behavior of these variables in an area dominated by *Pinus elliottii* in southeastern Brazil, by exploring different statistical models proposed in the literature. For this, RF and TF data were recorded in 24 rainfall events by 180 gauges distributed in six 10 x 10 m plots. The results indicate a significant influence of RF volume on response variables [TF volume (TF_{mm}), TF fraction ($TF_{\%}$) and coefficient of variation of TF (CV_{TF})]. While the linear model presented the best fit for TF_{mm}, the non-linear models had better results for $TF_{\%}$ and CV_{TF} as a function of RF, allowing the identification of distinct behaviors for different RF volumes. In general, it was verified that RF is the main source of variability in TF estimates in the study area. However, it should be noted that other variables may be acting simultaneously on $TF_{\%}$ and CV_{TF}, in which 45.4 and 38.1% of the variation, respectively, remain unexplained, requiring complementary studies to identify and quantify the influence of other factors.

Keywords: Throughfall; Forest hydrology; Modelling; Spatial variability.

RESUMO

A precipitação interna (PI) é influenciada por diferentes condições meteorológicas, que, ao interagirem entre si e com a vegetação, podem resultar em elevada variabilidade espacial e temporal. Este estudo teve como objetivo avaliar a influência da precipitação em aberto (PA) sobre a PI, assim como descrever o comportamento dessas variáveis em uma área de vegetação com predominância de *Pinus elliottii* no sudeste brasileiro, explorando diferentes modelos estatísticos propostos na literatura. Para isto, foram registrados dados de PA e PI em 24 eventos de chuva por 180 pluviômetros distribuídos em seis parcelas de 10 x 10 m. Os resultados indicam influência significativa do volume de PA sobre as variáveis resposta [volume de PI (PI_{mm}), fração de PI ($PI_{\%}$) e coeficiente de variação da PI (CV_{PI})]. Enquanto o modelo linear apresentou o melhor ajuste para PI_{mm}, os modelos não-lineares tiveram melhores ajustes para $PI_{\%}$ e CV_{PI} em função de PA, permitindo identificar comportamentos distintos para diferentes volumes de chuva. De forma geral, verificou-se que a PA é a principal fonte de variação nas estimativas de PI na área de estudo. No entanto, destaca-se que outras variáveis podem estar atuando simultaneamente sobre a $PI_{\%}$ e CV_{PI}, nas quais 45,4 e 38,1%, respectivamente, da variação permanecem inexplicados, demandando estudos complementares para identificar e quantificar a influência de outros fatores.

Palavras-chave: Atravessamento; Hidrologia Florestal; Modelagem; Variabilidade espacial.

INTRODUCTION

In forest ecosystems, the volume of water from rainfall is partitioned into canopy interception, stemflow and throughfall, which are influenced by the meteorological factors that characterize rain events. In these ecosystems such factors control both the water flow, due to their effects on partitioning and storage of rainfall fractions (CROCKFORD; RICHARDSON, 2000), and the nutrient flow by leaching, dissolution and transport of compounds in the atmosphere and plant surfaces (LEVIA JUNIOR; FROST, 2006; OZIEGBE; MUOGHALU; OKE, 2011; SÁ; CHAFFE; QUILLET, 2016). Therefore, meteorological characteristics of rainfall events drive the spatial and temporal variability of hydrological processes (LEVIA JUNIOR; FROST, 2006; ZIMMERMANN et al., 2008).

Throughfall is the fraction of rainfall that passes through the canopy and reaches the forest floor, either directly or dripping after interaction with the vegetation. Biotic factors affect this process by altering the distribution of plant surfaces with potential to intercept a given amount of rainfall (CHAPPELL; BIDIN; TYCH, 2001). Ahmadi, Attarod and Bayramzadeh (2013) emphasize that rainfall partitioning into other processes occurs similarly in different vegetation types. However, the combination of biotic and meteorological factors may further increase the spatial heterogeneity of throughfall, since forests are rarely homogeneous, especially in tropical regions (CHAZDON, 2014). In this sense, small-scale variations in forest structure can influence the amount of water that reaches the forest floor (SHACHNOVICH; BERLINER; BAR, 2008), as well as the concentration of deposited nutrients (KOWALSKA et al., 2016; SÁ; CHAFFE; QUILLET, 2016).

Meteorological factors influence rainfall partitioning into throughfall, stemflow or canopy interception (STAELENS et al., 2008), affecting the relative contribution of each process. The main meteorological factors influencing throughfall are rainfall depth, duration and intensity of rain events, temperature and air humidity, and wind speed and direction (CROCKFORD; RICHARDSON, 2000).

Several studies found a linear relationship between rainfall depth and throughfall depth (TF_{mm}) (Table 1), with a positive influence on throughfall variation. In contrast, when throughfall is considered in terms of percentage of rainfall ($TF_{\%}$), the relationship between the variables is not linear (ZOU et al., 2015). Fan et al. (2015) observed that the increase of rainfall depth positively affects $TF_{\%}$ until a threshold where no further increases are detected.

Similarly, the coefficient of variation of throughfall (CV_{TF}), which describes the degree of spatial variability of the process (FAN et al., 2015; HOLWERDA; SCATENA; BRUIJNZEEL, 2006; KOWALSKA et al., 2016; LEVIA JUNIOR; FROST, 2006; SIEGERT et al., 2016; STAELENS et al., 2006; ZIEGLER et al., 2009), presents an inverse relationship with rainfall depth. Recent studies (CARLYLE-MOSES; LAUREANO; PRICE, 2004; CARLYLE-MOSES; LISHMAN; MCKEE, 2014; SARI; PAIVA; PAIVA, 2015) suggest that CV_{TF} decreases asymptotically with the increase in rainfall depth, indicating a nonlinear relationship between these variables.

There are different methods for estimating hydrological processes, such as direct measurement, systems modelling, empirical modelling and geostatistical modelling (LEVIA JUNIOR; FROST, 2006; OLIVEIRA et al., 2008; STAELENS et al., 2008;

Table 1. Summary of fitted models for the relationship between rainfall (RF), throughfall depth (TF_{mm}), throughfall fraction ($TF_{\%}$) and its coefficient of variation (CV_{TF}).

Author(s)	Variables	Model	R^2
Arcova, Cicco and Rocha (2003)[a]	RF, TF_{mm}	Linear	0.913 – 0.993
Ávila et al. (2014)[a]	RF, TF_{mm}	Linear	0.849 – 0.895
Carlyle-Moses, Laureano and Price (2004)	RF, TF_{mm}	Linear	0.998
	RF, CV_{TF}	Exponential	0.860
Carlyle-Moses, Lishman and McKee (2014)	RF, TF_{mm}	Linear	0.910
Fan et al. (2015)	RF, TF_{mm}	Linear	0.996
Ferreira, Luizão and Dallarosa (2005)[a]	RF, TF_{mm}	Linear	0.819 – 0.989
Gasparoto et al. (2014)[a]	RF, TF_{mm}	Linear	0.740 – 0.900
Gênova, Honda and Durigan (2007)[a]	RF, TF_{mm}	Linear	0.985 – 0.993
Holwerda, Scatena and Bruijnzeel (2006)	RF, TF_{mm}	Linear	0.970 – 0.990
Lorenzon, Dias and Leite (2013)[a]	RF, TF_{mm}	Linear	0.988 – 0.992
Moura et al. (2009)[a]	RF, TF_{mm}	Linear	0.985
Oliveira et al. (2008)[a]	RF, TF_{mm}	Linear	0.956
Oliveira Júnior and Dias (2005)[a]	RF, TF_{mm}	Linear	0.988
Perez-Marin and Menezes (2008)[a]	RF, TF_{mm}	Linear	0.936
Pérez-Suárez et al. (2014)	RF, TF_{mm}	Linear	0.980
Sari, Paiva and Paiva (2015)[a]	RF, TF_{mm}	Linear	0.960 – 0.976
Shachnovich, Berliner and Bar (2008)	RF, TF_{mm}	Linear	0.996
Staelens et al. (2008)	RF, TF_{mm}	Linear	0.990
Teale et al. (2014)	RF, CV_{TF}	Linear	0.230
Thomaz (2005)[a]	RF, TF_{mm}	Linear	0.953 – 0.972
Togashi, Montezuma and Leite (2012)[a]	RF, TF_{mm}	Linear	0.945 – 0.992
Wullaert et al. (2009)	RF, TF_{mm}	Linear	0.800 – 0.840
Zou et al. (2015)	RF, $TF_{\%}$	Logarithmic	0.150 – 0.770

a: Studies conducted in Brazil.

ZIMMERMANN et al., 2010). It is difficult to directly measure some parameters, especially the canopy interception, due to the magnitude and temporal scale of variation of the factors that affect this process (CROCKFORD; RICHARDSON, 2000). Thus, empirical modelling provides simplified representations of the relationship between variables, allowing a better understanding of the functioning of these processes (JOHNSON; OMLAND, 2004). However, these models incorporate some degree of uncertainty in their inferences, due to the simplification of systems (i.e., non-incorporation of all influencing factors) (CARIBONI et al., 2007).

Despite its importance, few studies evaluating the adjustment of nonlinear models to describe the relationship between rainfall and throughfall estimates were carried out (CARLYLE-MOSES; LAUREANO; PRICE, 2004; ZOU et al., 2015). The identification of these patterns in empirical studies highlights the need for studies that address this gap, improving the understanding of how these variables interact with each other.

This is important to adequately manage watersheds, soil erosion, and nutrient cycling control in forest ecosystems (KEIM; SKAUGSET; WEILER, 2005; LEVIA JUNIOR; FROST, 2006; RODRIGO; ÀVILA, 2001). When the interactions between these variables are established, it is possible to model other associated hydrological processes (i.e. canopy interception) (PYPKER et al., 2005; ZOU et al., 2015) and to define strategies for sampling throughfall with smaller errors in the estimates (CARLYLE-MOSES; LAUREANO; PRICE, 2004; CARLYLE-MOSES; LISHMAN; MCKEE, 2014; HOLWERDA; SCATENA; BRUIJNZEEL, 2006; RITTER; REGALADO, 2014; RODRIGO; ÀVILA, 2001; SARI; PAIVA; PAIVA, 2015; ZIEGLER et al., 2009). Thus, knowledge of the characteristics and dynamics of hydrological processes in forest ecosystems can provide subsidies for more efficient watershed management, in order to guarantee the water supply in quantity and quality necessary for human activities.

Therefore, this study aims to evaluate the influence of rainfall on throughfall, and to describe the behavior of these variables in a secondary forest with predominance of *Pinus elliottii* Engelm. in southeastern Brazil. For this, the following questions were formulated:

1) What are the spatial and temporal patterns of rainfall in the study area during the rainy season?
2) Does the rainfall depth influence throughfall depth and its fraction?
3) Is the spatial variability of throughfall influenced by rainfall depth?
4) Which statistical model proposed by the literature provides a better description of the relationship between rainfall and throughfall variables?

MATERIAL AND METHODS

Study area

The study was carried out in an area located at the Federal University of São Carlos (UFSCar), campus São Carlos (21 ° 59’3.9 “S, 47 ° 53’37.5”) (Figure 1). The area of 9.5 ha is characterized by the predominance of *P. elliottii* in the tree stratum, and an understory in regeneration with native species of the region. It is located at elevations between 820 and 843 m, with average slope of 12.4%.

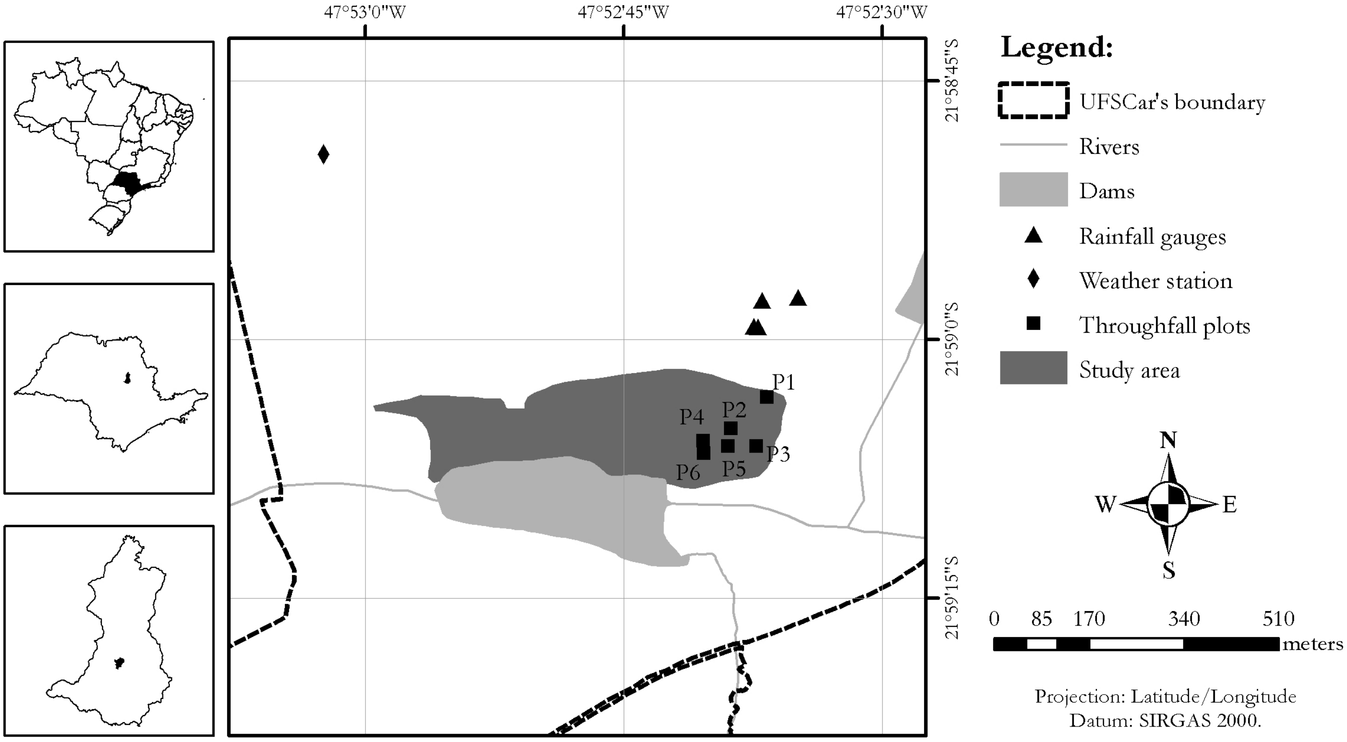

Figure 1. Location of the study area and distribution of throughfall plots and rainfall gauges.

The forest area was planted during the 1970s, to protect the banks around the dam of the campus. In the following decades, part of the vegetation was removed for the expansion of university infrastructure, with compensations made in other locations of the institution (MELÃO et al., 2011).

From a preliminary characterization of the vegetation, considering only trees above 1.3 m height, it was verified that the average height of tree individuals is 5.98 m; the average depth of the canopy (i.e. difference between the maximum height and the height of the base of canopy) is 2.78 m; the average density of trees in the plots is 4,733 trees.ha^{-1}, where trees above 20 m height (mostly *P. elliottii*) represent 416.67 trees.ha^{-1}; the average basal area is 47.88 m^2.ha^{-1}, in which trees above 20 m height represent 82% of this value; and the average diameter at breast height (DBH) is 5.98 cm (trees above 20 m height have DBH of 34.74 cm; and trees below 20 m height, DBH is 2.98 cm).

The local climate is classified as humid subtropical, with rainy summers and dry winters (Cwa, according to Köppen's classification). The average temperature of the area is 21.2°C, with monthly averages varying between 18 and 23 °C (CEPAGRI, 2017). The average annual accumulated rainfall of the region was estimated at 1,423 mm by CEPAGRI (2017) and 1,538 mm by Sanches (2015). The rainy season is concentrated between October and March, with an average contribution of 82% for the annual accumulated precipitation (CEPAGRI, 2017). In the study conducted by Sanches (2015), who analyzed rainfall data from 1993 to 2014, it was verified that the largest rainy days of the region present an average depth of 79.8 mm.day^{-1}. The author observed that, at annual intervals, the largest recorded events were not smaller than 45.0 mm.day^{-1}.

Sampling

The data for the present study were collected between 13/10/15 and 26/2/16 (comprising most of the rainy season) in six plots of 10 x 10 m installed in the forest area (Figure 1), with distances varying between 15 and 130 m among them. The data were collected, whenever possible, soon after rainfall; a rainfall event was considered as the accumulated record in one or more rainy days (LORENZON; DIAS; LEITE, 2013; ZIEGLER et al., 2009). Due to volumetric limitation of the gauges, some rain events were discarded. So, 24 rainfall events were sampled during the period. Figure 2 shows the hyetograph of the studied period, highlighting the intervals where rainfall depth was collected in relation to the total rainfall events.

To quantify rainfall depth, four polyethylene terephthalate gauges (catch area of 93.7 ± 13.9 cm^2) were used, distant up to 238 m from the throughfall (TF) plots. They were installed on supports at 1.3 m above ground to avoid the splattering from the soil. These data were compared with those obtained by INMET's automatic weather station, named "São Carlos-A711", located at 830 m of the rainfall gauges (Figure 1), to test for data correlation.

In order to estimate TF, 30 gauges were installed in each plot, with material similar to those described previously and with a catch area of 80.2 ± 8.0 cm^2. The throughfall gauges were systematically distributed in the plots (Figure 3) and remained in fixed positions during data collection.

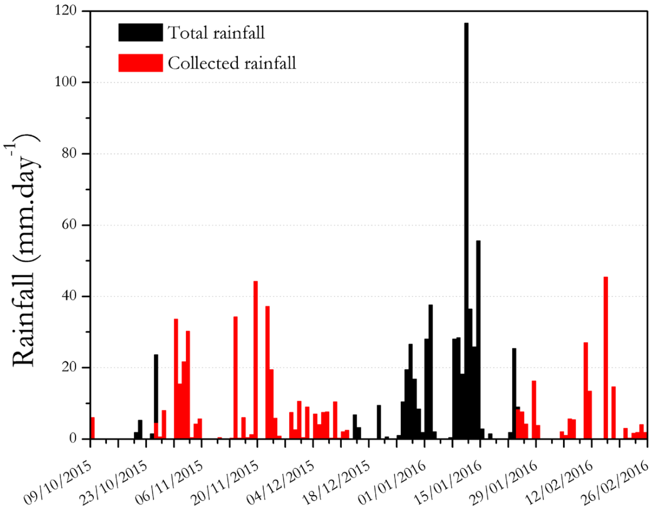

Figure 2. Hyetograph of daily precipitation data recorded by the INMET's weather station during the study period, highlighting the sampled events. Source: INMET Network Data.

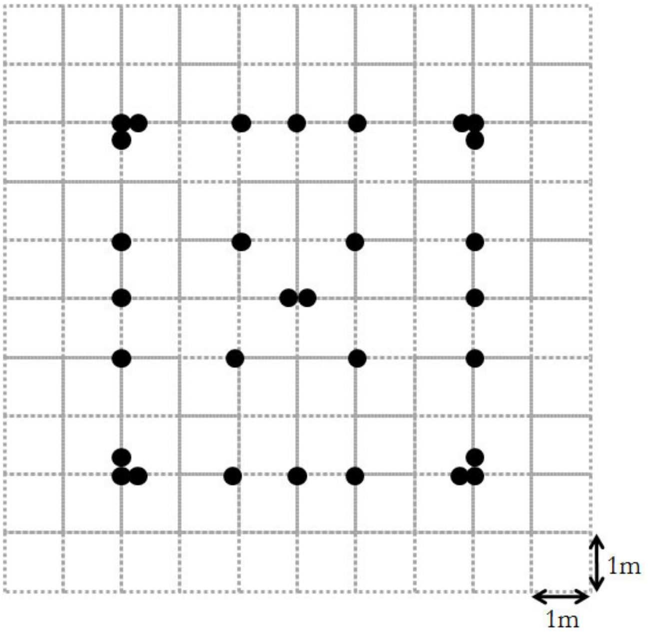

Figure 3. Schematic representation of gauge distribution used to evaluate the influence of rainfall on throughfall estimates.

Data analysis

To evaluate the spatial pattern of RF (Question 1), a correlation analysis was performed between RF data recorded by the rainfall gauges and the weather station, using Pearson's correlation coefficient (r). Both data sets were previously transformed using logarithmic functions [ln(x)], since Shapiro-Wilk tests indicated that the original distributions differed from a normal distribution.

To assess whether RF influenced the TF estimates and its spatial variability (Questions 2 and 3, respectively), ordinary least-squares linear regression models were used (GOTELLI;

ELLISON, 2011; QUINN; KEOUGH, 2002). Thus, RF was set as the explanatory variable, and TF_{mm}, $TF_{\%}$ and CV_{TF} were set as response variables. The data were previously transformed when necessary, as described early.

Finally, to evaluate which model provides the best description of the relationship between RF and TF estimates (Question 4), statistical models proposed in the literature, representing the relations between response and explanatory variables, were fitted. The following models were tested: linear (Equation 1); power (Equation 2) (STAELENS et al., 2006, 2008); logarithmic (Equation 3) (ZOU et al., 2015); and exponential (Equation 4) (CARLYLE-MOSES; LAUREANO; PRICE, 2004).

$$y = a + bx \tag{1}$$

$$y = ax^{b} \tag{2}$$

$$y = a \ln x + b \tag{3}$$

$$y = a + \left[b / \left(c + x \right) \right] \tag{4}$$

The models were fitted using the least squares method, performing up to 300 iterations to obtain the parameters of each model. This method considers the vertical deviation of each value of the response variable in relation to the value estimated by the model, defining the one with the smallest sum of squares of the deviations as the best fit for a given model (JOHNSON; OMLAND, 2004).

The models were evaluated based on the adjusted coefficient of determination (R^2), which enables to quantify how much of the total variation of the response variable is explained by the linear relationship with the explanatory variable. Hence, it allows to observe how much of the variation of the response variable remains unexplained (GOTELLI; ELLISON, 2011; JOHNSON; OMLAND, 2004; QUINN; KEOUGH, 2002). In addition to this metric, the Akaike Information Criterion (AIC) was applied for the selection of models based on the compensation between the quality of fit and the complexity of the model (JOHNSON; OMLAND, 2004). The AIC was calculated from Equation 5 (QUINN; KEOUGH, 2002):

$$AIC = n * \ln\left(RSS\right) + 2 * \left(P + 1\right) - n \ln\left(n\right) \tag{5}$$

Where: *AIC* is the Akaike Information Criterion; *n* is the sample size; *RSS* is the residual sum of squares of the model; and *P* is the number of parameters in the model.

RESULTS

During the study period, 24 rain events were sampled. It is noteworthy that in the first sampled event, three gauges were used to measure the rainfall. In the subsequent events, all rainfall data consisted of the average obtained by four rain gauges; the exception was one event (12/02/16), when two of the rain gauges presented values much higher than those recorded by the other gauges and weather station, and they were thus excluded from calculations, in a procedure analogous to Carlyle-Moses, Laureano and Price (2004).

Based on the recorded data, the average RF depth was 20.5 mm (median 10.44 mm), ranging from 0.7 to 107.7 mm. The accumulated RF depth during the 24 events was 492.1 mm. However, according to INMET data (Figure 2), it is estimated that 513.6 mm of precipitation were accumulated during the not sampled period between 12/14/2015 and 01/25/2016, including a single event of 312.2 mm.

Based on the histogram of recorded events (Figure 4), it was observed that a large portion of the rainfall events (45.8%) in the area consisted of depths lower than 10 mm. In contrast, two rain events (8.3%) exceeding the 50 mm volume were observed; these events contributed with 41% of the accumulated depth for the study period. The events with depths lower than 10 mm contributed with only 9% in the cumulative value.

The coefficient of variation of RF (CV_{RF}) per rain event ranged from 0.85 to 24.7%. CV_{RF} was greater than 10% in only three of the recorded events (all lower than 4.3 mm). In events with depths greater than 10 mm, the average value of CV_{RF} was 3.7%, ranging from 0.85 to 6.63%. Considering the data accumulated in the events in which the four gauges were installed in the field, the CV_{RF} was 2.52%.

For the correlation analysis of RF data, the events of 13/10/2015 and 26/01/2016 were not considered, due to uncertainties in the recording time of these specific events. From this analysis, a strong positive correlation ($r = 0.952$) was verified between the data obtained by the gauges in the field and the weather station (Figure 5).

Considering the measured TF data, it was found that the average TF per event is approximately 75% of the total RF. A cumulative depth of 430 mm was recorded, corresponding to 87% of the RF in the studied period, varying between 379.9 and 465.7 mm per plot.

From the linear regression analysis, it was verified that RF influenced TF_{mm} ($P < 0.001$), with a high proportion of TF_{mm} variation explained by RF ($R^2 = 0.944$). In addition, it was observed that increases in RF depth led to increases in TF_{mm} (Figure 6).

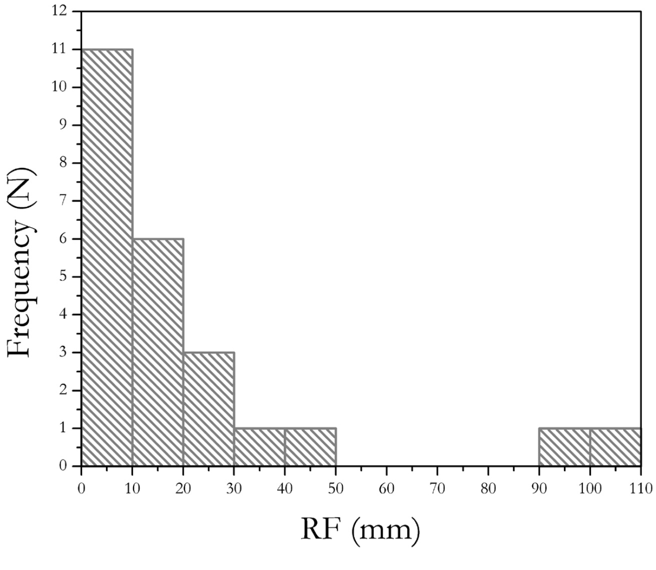

Figure 4. Histogram of rainfall (RF) recorded by the four gauges.

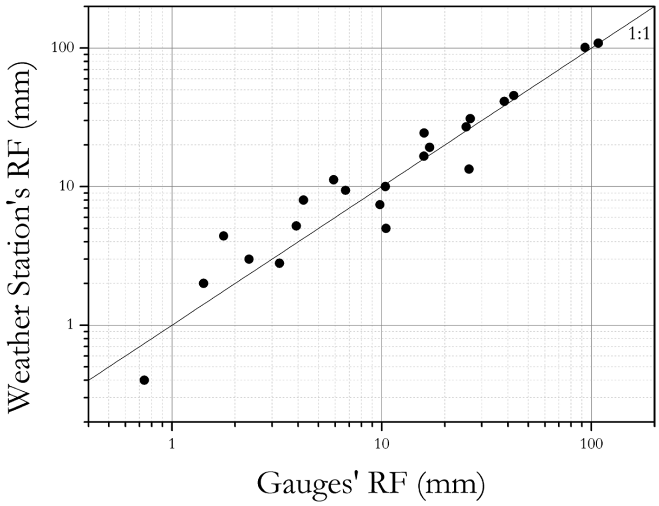

Figure 5. Relationship between RF estimated by the average of gauges in the field and by the weather station of São Carlos (INMET).

Regarding the influence of RF on $TF_{\%}$, a significant relationship was also verified, but with a lower value of R^2 (0.546) in relation to the analysis for TF_{mm} (0.944), indicating that one or more complementary variables may be exerting control over the response variable. As for TF_{mm}, a positive influence of RF on $TF_{\%}$ was observed (Figure 7).

In relation to CV_{TF}, the minimum value of 12.8% was verified in the event of 27/11/15, in plot 2. In the event of 12/11/15, which accumulated 0.7 mm of RF, the highest CV_{TF} value of the study (167.2%) was observed in plot 4. Considering the accumulated depth along the 24 rainfall events sampled, CV_{TF} had an average value of 16.6%, ranging from 13.2 to 20, 1%.

As for the other estimates, the regression analysis indicated a significant influence of RF on CV_{TF} ($P < 0.001$). Based on the relationship between the variables, it was observed that CV_{TF} decreases as a function of the increase in RF depth (Figure 8).

Different models performed better depending on the response variable (Table 2). The linear model presented the best values of R^2 and AIC in comparison to the other models to describe the influence of RF on TF_{mm}, but the power model presented values close to the linear model for these variables. For $TF_{\%}$, despite the low R^2 values in all models evaluated, the exponential model presented the best result; the logarithmic model presented the best AIC, indicating that the relationship between these variables follows a non-linear trend. Finally, the exponential model presented the best fit to describe the relationship between RF and CV_{TF}, both in terms of R^2 and AIC. For this variable, the fit of the linear model was significantly lower than the others.

DISCUSSION

The average RF value estimated by the four gauges installed in the field was strongly correlated to those of the weather station. Thus, the results indicate that the distance between the gauges and the weather station in the present study (about 830 m) is not enough to cause considerable differences in the depth registered

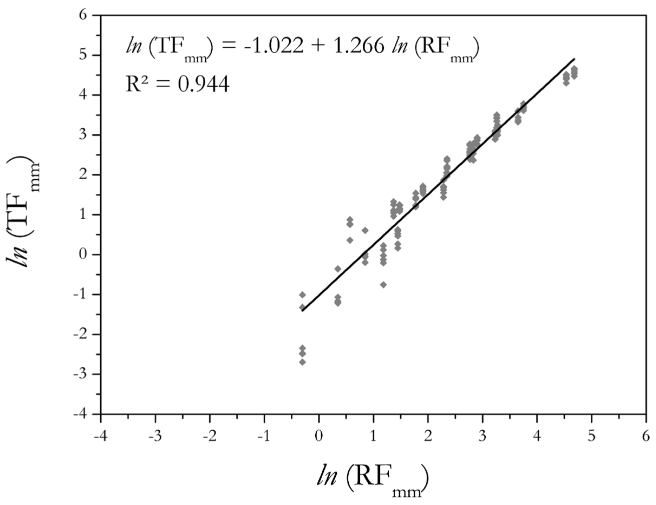

Figure 6. Linear regression of TF_{mm} recorded in each plot as a function of average RF.

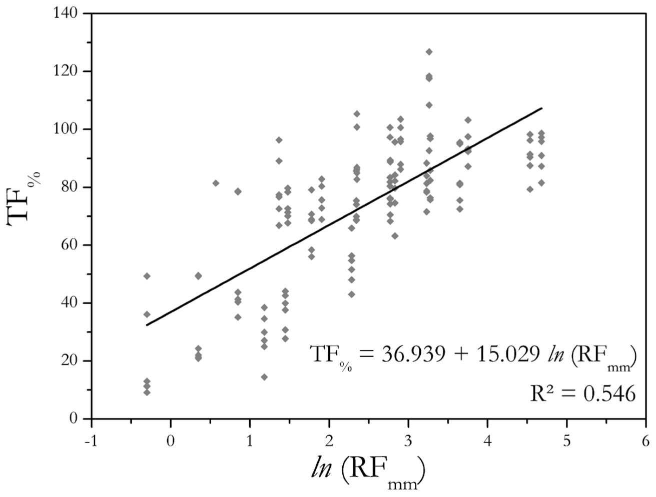

Figure 7. Linear regression of $TF_{\%}$ recorded in each plot as a function of average RF.

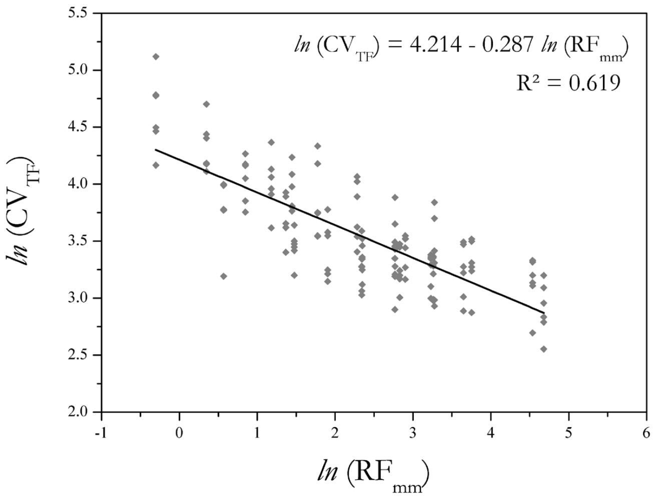

Figure 8. Linear regression of CV_{TF} recorded in each plot as a function of average RF.

Table 2. Results of the fit of models and estimated parameters for the relationship between RF and the TF estimates.

Variable	Model	Parameters			R²	AIC
		a	b	c		
TF_{mm}	Linear	-1.1	0.9	-	0.99	309.1
	Power	0.8	1.0	-	0.99	314.0
	Logarithmic	15.8	-18.5	-	0.65	782.2
	Exponential	19.3	-3.1	-1.3	0.04	928.5
$TF_{\%}$	Linear	68.1	0.3	-	0.10	965.4
	Power	54.2	0.1	-	0.21	946.9
	Logarithmic	11.0	50.0	-	0.22	944.5
	Exponential	96.5	-278.6	4.7	0.22	946.1
CV_{TF}	Linear	46.8	-0.4	-	0.19	871.7
	Power	82.2	-0.4	-	0.65	752.7
	Logarithmic	-13.0	69.1	-	0.53	792.9
	Exponential	24.4	80.3	0.3	0.68	738.3

at the two locations. Despite the large variability of RF data at small spatial scales, Krajewski, Ciach and Habib (2003) obtained correlation coefficients of at least 0.8 for distances up to 1 km with RF data in the Amazon. Sanches (2015) observed that the São Carlos' weather station presented data similar to those of the EMBRAPA's (Southeast Livestock) weather station, located in the same region, but farther than the gauges used in this study, suggesting low spatial heterogeneity of rainfall in the region, at the studied scale.

Therefore, these results suggest that, within this radius (about 800 m), RF data are correlated, and it is possible to use them to obtain TF estimates in the study area. However, it should be noted that, according to Krajewski, Ciach and Habib (2003), the small-scale variation of RF data is influenced by the climate regime, and further assessments are necessary to guarantee the validity of this relationship.

In this perspective, Teale et al. (2014) also observed low spatial variability of RF in a tropical forest (CV_{RF} = 1%). In addition, Fan et al. (2015) found that, in events with RF depths above 5 mm, CV_{RF} was approximately 3.5%. Thus, it can be inferred that the spatial pattern of RF in tropical regions is characterized by low heterogeneity and has an inverse relationship with the RF depth.

From the RF data in the study region, it was verified that, during the rainy season, a substantial portion of the rainfall events was constituted by depths lower than 10 mm. This pattern was also verified by Mair and Fares (2010) in a tropical system. Pérez-Suárez et al. (2014) and Fan et al. (2015) also found that many events with small rainfall depths contribute with small proportions to the annually accumulated rainfall in subtropical and semi-arid regions, respectively. For example, Fan et al. (2015) found that events with depths smaller than 5 mm (46.9% of total events) contributed with about 8% of the accumulated depth. Similarly to the results obtained in the present study, the mentioned authors observed a comparable value for RF events over 50 mm (41% of accumulated depth), indicating that, although less frequent, these events have great influence on the water balance in forest ecosystems, regardless of the region where they are located.

Albuquerque and Costa (2012) highlight that events with small RF depths are also important for the forest water balance, mainly for the plant-soil system, since they regulate the water flow to the soil and to the root system, with different volumes and compositions among the hydrological processes (PEREZ-MARIN; MENEZES, 2008). Considering that rainfall events in the region are characterized by small depths, it is expected that TF in the studied region presents high spatial variability due to the incomplete saturation of the forest canopy in this type of event.

As in the present study, Sanches (2015) also verified that rainfall events with depths greater than 60 mm are uncommon in the region. This type of event is important for the supply of water in the soil, generation of surface runoff and, hence, flow generation in watersheds (MAIR; FARES, 2010; PÉREZ-SUÁREZ et al., 2014). Moreover, these events are strongly related to the occurrence of stemflow, an hydrological process with low representativeness for the water balance in forest ecosystems, but with significant importance for nutrient cycling and water supply for the roots (MOURA et al., 2009; OLIVEIRA et al., 2008; OZIEGBE; MUOGHALU; OKE, 2011; SOUZA et al., 2007).

In locations with high frequency of events with small rainfall depths, Rodrigo and Àvila (2001) verified that more gauges are needed to sample TF than areas under the influence of events with large depths. According to the authors, this is due to the high spatial variability of this process in smaller events, corroborating the results obtained in the present study. Thus, it may be necessary to use a greater number of gauges to obtain TF estimates in our study area, considering that this type of rainfall event is more frequent, especially during the rainy season.

However, it is worth noting that, considering the accumulated depth in a given period, events with large RF depths can reduce the variability of TF data, since these events represent a larger portion of the accumulated data (HOLWERDA; SCATENA; BRUIJNZEEL, 2006). Hence, the inclusion of events with large depths, in addition to representing more accurately the rainfall pattern of a given locality, contributes with more accurate estimates for calculating the water balance at longer intervals (i.e. monthly, seasonally, annually, etc.), requiring a smaller number of gauges to obtain estimates with the same level of accuracy.

Therefore, it was possible to verify that RF in the studied region presents low spatial heterogeneity at scales up to 800 m, making it possible to use data obtained within this distance to estimate TF. It was also verified that the temporal distribution of RF in the rainy season is mainly composed of events with small RF depths, although the scarce events with large depths contribute with large portions of water input via TF in forest ecosystems. Moreover, the results suggest that the estimates provided by the two types of gauges are similar, and that the use of polyethylene terephthalate for the construction of gauges does not undermine the RF estimates. This finding corroborates Thomaz (2005), who also obtained a strong correlation between gauges with this material and standard ones.

Regarding TF data, the estimate obtained in this study (87% of the RF) is within the range recorded in other studies within tropical and subtropical regions (41 - 94%; see Table 3). This wide range of variation in TF data in tropical ecosystems was also presented in Levia Junior and Frost (2006). These authors attribute this high variability to differences in species composition,

Table 3. Summary of average $TF_{\%}$ and CV_{TF} estimates obtained in studies conducted in tropical and subtropical regions.

Author(s)	Region	Physiognomy	$TF_{\%}$	CV_{TF}
Present Study[a]	Tropical	*Pinus elliottii* forest and native understory in regeneration	87	17
Arcova, Cicco and Rocha (2003)[a]	Tropical	Evergreen forest (secondary)	81	-
Ávila et al. (2014)[a]	Tropical	Atlantic rainforest	79	-
Carlyle-Moses, Laureano and Price (2004)	Tropical	Open matorral and matorral-chaparral	84	3
Fan et al. (2015)	Subtropical	Pine plantation (exotic)	78	-
Ferreira, Luizão and Dallarosa (2005)[a]	Tropical	Upland forest (undisturbed)	74 – 87	-
		Upland forest (under selective logging)	86 – 92	-
Gasparoto et al. (2014)[a]	Tropical	Seasonal semideciduous forest	76	-
		Pinus spp. Plantation	84	-
		Eucalyptus cloeziana plantation	85	-
Gênova, Honda and Durigan (2007)[a]	Tropical	*Pinus elliottii* plantiation	73	-
		Tapirira guianensis plantiation	69	-
		Anadenanthera falcata plantiation	88	-
		Mixed plantation with Cerrado species	87	-
Holwerda, Scatena and Bruijnzeel (2006)	Tropical	Tabonuco-type forest	73 – 77	23 – 48
Lorenzon, Dias and Leite (2013)[a]	Tropical	Seasonal semideciduous forest (initial succession)	84	-
		Seasonal semideciduous forest (advanced succession)	73	-
Manfroi et al. (2006)	Tropical	Lowland evergreen forest	85 – 88	11 – 30
Moura et al. (2009)[a]	Tropical	Atlantic forest (primary)	85	-
Oliveira Júnior and Dias (2005)[a]	Tropical	Atlantic forest (secondary)	80	-
Ritter and Regalado (2014)	Tropical	Semideciduous moist forest	41	41
Sá, Chaffe and Quillet (2016)[a]	Tropical	Atlantic forest	90	-
Sari, Paiva and Paiva (2015)[a]	Tropical	Atlantic forest	71 – 78	22
Teale et al. (2014)	Tropical	Pre-montane transitional cloud forest	88	21 – 36
Thomaz (2005)[a]	Subtropical	Shrubbery vegetation(secondary)	48	-
		Araucaria pine forest (secondary)	77	-
Togashi, Montezuma and Leite (2012)[a]	Tropical	Atlantic forest(initial secondary succession)	94	15
		Atlantic forest (advanced secondary succession)	75	9
		Atlantic forest (edge)	89	15
Van Stan, Gay and Lewis (2016)	Subtropical	*Quercus virginiana* Mill. forest	73	-
Wullaert et al. (2009)	Tropical	Lower montane forest (undisturbed)	55 – 58	12 – 17
		Lower montane forest (managed)	66 – 74	12 – 15
Ziegler et al. (2009)	Tropical	Evergreen-dominated forest	82	5 – 10

a: Studies conducted in Brazil.

diversity of vegetation cover in these regions, tree density, past land use and canopy structure (factors that can control TF).

When compared to studies developed in forest physiognomies in Brazil, the records obtained are also within the range observed for TF% (69 - 94%, Table 3). The Brazilian studies with physiognomies more similar to the present study are Gasparoto et al. (2014) and Gênova, Honda and Durigan (2007), in which the studied areas are formed by pine plantations. Although there was no understory in Gasparoto et al. (2014), the TF estimate is close to that verified here, indicating that there are similarities in rainfall partitioning in areas with predominance of *Pinus* spp. In contrast, Gênova, Honda and Durigan (2007) obtained lower TF estimates (73%) than that observed in this study, although it was also a *P. elliottii* forest. This difference between estimates can be attributed to the tree density in both areas, since Gênova, Honda and Durigan (2007) verified a correlation between the canopy interception and tree density. Thus, the development of hydrological processes in equivalent physiognomies has variations that can be attributed to differences in vegetation structure.

However, some events in which TF was greater than RF may have overestimated the average value for the studied period. The influence of extreme values is determined mainly by the presence of drip points, which concentrates higher amounts of TF, making the data distribution scattered and asymmetric. An alternative to reduce the influence of these points is the use of a roving arrangement for TF sampling, which consists of the random repositioning of the gauges after specific time intervals (RITTER; REGALADO, 2014). The relocation of the gauges makes it possible to reduce the errors associated to the estimates, producing more accurate values than a fixed arrangement (CARLYLE-MOSES; LISHMAN; MCKEE, 2014; HOLWERDA; SCATENA; BRUIJNZEEL, 2006; RITTER; REGALADO, 2014; ZIEGLER et al., 2009). Since the spatial distribution of these points persists throughout the events (KEIM; SKAUGSET; WEILER, 2005), the repositioning of gauges seems to be an efficient method to reduce the influence of these values and provide more accurate estimates.

Linear regression for the relationship between RF and TF estimates is consistent with the results obtained in other studies (Table 1); RF has a significant positive effect on TF_{mm} (see Figure 6). Accordingly, the results obtained for R^2 of regression models are in agreement with other studies (Table 1), in which values varied between 0.740 and 0.998.

Regarding the comparison of models (Table 2), the high R^2 values in both linear (which presented the best fitting metrics) and power model indicate that the relationship of these variables presents a high degree of linearity (CARIBONI et al., 2007), as shown in Figure 9. In addition, it is also possible to obtain parameters for the modelling of other hydrological processes from linear models (PYPKER et al., 2005; ZOU et al., 2015), such as canopy water storage capacity, the fraction of direct TF, amongst others. For example, the inverse value of the parameter *a* obtained by the linear model in the present study (Table 2) represents the canopy water storage capacity, indicating the RF depth needed to saturate the canopy and promote TF (LORENZON; DIAS; LEITE, 2013; STAELENS et al., 2008; TONELLO et al., 2014). Although the linear and power models have similar capabilities to explain the variation of TF_{mm}, the use of linear models is recommended, since the parameters of these models can be used in more detailed analyzes of hydrological modelling, and allow comparison among the results obtained at different locations.

Regarding $TF_{\%}$, the results of the regression analysis indicate that there is a positive influence of RF on this variable (Figure 7). Considering only forested areas, Zou et al. (2015) obtained an equivalent result, but analyzing the logarithmic relationship between the variables; they obtained a R^2 value (0.66) similar to the present study (0.55), in which RF data was log-transformed.

Without transforming the data, R^2 values of the fitted models in the present study were much lower than those found by Zou et al. (2015), reaching a maximum value of 0.22 with the exponential model (Table 2). The logarithmic model showed similar ability to explain the variance of $TF_{\%}$ as a function of RF ($R^2 = 0.22$). The observed difference between the coefficients (with and without data transformation) suggests that other variables (e.g. species composition, vegetation structure, intensity and duration of events, canopy humidity conditions) may be determining the variability of $TF_{\%}$. For example, canopies with different densities are capable of storing different amounts of RF, thus influencing the fraction that reaches the forest floor as TF (CARLYLE-MOSES; LISHMAN, 2015; HSUEH; ALLEN; KEIM, 2016; PARK; CAMERON, 2008).

In relation to the AIC, the logarithmic model showed the best results, indicating that the increase in complexity promoted by the inclusion of another parameter in the exponential model does not compensate the gain in the fit of model. Thus, the logarithmic model seems to be the most adequate to describe the relationship between RF and $TF_{\%}$.

However, the exponential model allows a better visualization of the stabilization of $TF_{\%}$ with the increase of RF, which occurs in depths of approximately 25 mm, becoming stable in 96.5% (Figure 10). Teale et al. (2014) observed a similar pattern, verifying that $TF_{\%}$ stabilized in 90% in events with large rainfall depths. Thus, it is possible to measure the maximum TF rate in this location, which may constitute a parameter for hydrological models after more detailed studies on its validation are performed. From this perspective, this parameter may also indicate that losses of at least 3.5% of the RF depth on average always occur in the rain events.

Nevertheless, none of the models presented metrics with satisfactory values in relation to the capacity of explanation of the relationship among these variables. Thus, it is necessary to apply and evaluate a wider set of models that can represent the relationship between these variables, and, later, to use the parameters obtained to explain and understand this process.

Regarding the spatial variability of TF (Table 3), our estimates (13.2 to 20.1%) are within the range of variation of the estimates for tropical and subtropical regions (3-48%). Levia Junior and Frost (2006) associate the wide range of the CV_{TF} in tropical regions to the greater complexity of the structure and geometry of canopies in these areas, providing a greater number of potential drip points. According to Carlyle-Moses, Lishman and McKee (2014), the presence of these points may be a factor controlling the spatial variability of TF in events where the canopy storage capacity is saturated.

In addition, other factors such as rainfall intensity and wind conditions may also affect the spatial variability of TF (LEVIA JUNIOR; FROST, 2006). Given that most of the accumulated TF depth during the study period is composed by few events with large RF depths, there is a reduction in the spatial variability of

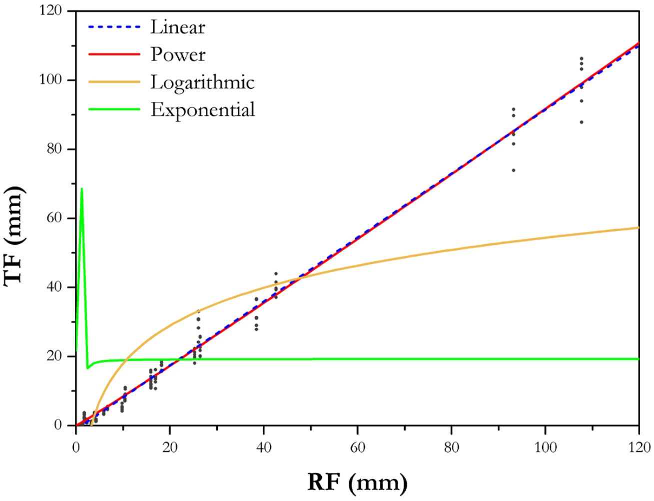

Figure 9. Fitted models for the relationship between RF and throughfall depth [TF (mm)].

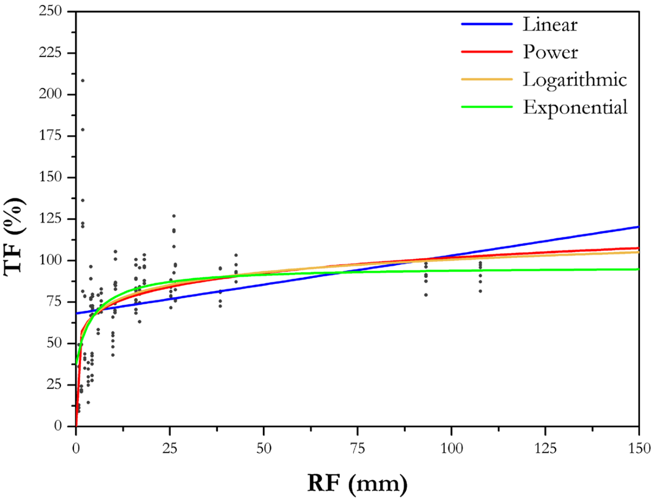

Figure 10. Fitted models for the relationship between RF and throughfall fraction [TF (%)].

this process when considering the accumulated data. However, analysis at the scale of individual rainfall events must be interpreted cautiously, as they are characterized by high spatial variability, and, hence, require methods that increase the accuracy of the estimates.

Regarding the influence of RF on CV_{TF}, evaluated from regression analysis, it was verified a negative influence on the latter (Figure 8). Carlyle-Moses, Laureano and Price (2004), Sari, Paiva and Paiva (2015) and Teale et al. (2014) also found similar patterns for the relationship between these variables.

Carlyle-Moses, Laureano and Price (2004) found a better fit using the exponential model for the relationship between the variables (0.860), in which CV_{TF} decreased as a function of the increase in RF for events up to 15 mm. Above this value, CV_{TF} stabilizes, resulting in a non-linear relationship between RF and CV_{TF}. Moreover, Teale et al. (2014), using linear regression analysis, also verified that CV_{TF} decreased as RF increases, but the linear model presented low values of R^2 (0.230), indicating that there are other variables controlling spatial variability of TF.

The results of the model fits for this relationship (Table 2) corroborate Carlyle-Moses, Laureano and Price (2004), who also verified a moderate fit of the exponential model. Graphically, it is possible to observe the pattern described by these authors and also found in this study, in which the stabilization of CV_{TF} occurs in events with large RF depths (Figure 11). According to the authors, this is due to the filling of the storage capacity of the entire canopy and complete formation of drip points, which become stable in events with large depths.

Based on these relationships, Carlyle-Moses, Laureano and Price (2004), Staelens et al. (2006) and Teale et al. (2014) verified that the change in the behavior of TF variability occurred at RF depths between 10 and 16 mm. Above these values, the CV_{TF} became stable, even with the increase in RF. Our results indicate that this stabilization occurs in RF depths close to 12.5 mm (Figure 11), based on the exponential model, which comprises the interval obtained by the authors. In events of this extent, CV_{TF} remains close to 24.4%, according to the analyzed model.

However, other studies observed very different values from those of the present study. For example, Carlyle-Moses, Lishman and McKee (2014) have found that this change in TF variability occurs at RF depths from 3.5 mm; Ziegler et al. (2009) verified the pattern only for events greater than 30 mm. The difference between the results can be attributed to the different storage capacities in the studied forests, as highlighted by Carlyle-Moses, Lishman and McKee (2014).

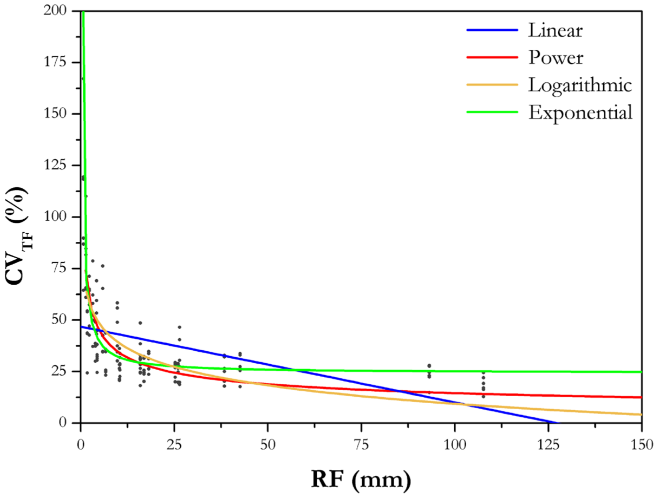

Figure 11. Fitted models for the relationship between RF and CV_{TF}.

Some authors (CARLYLE-MOSES; LAUREANO; PRICE, 2004; CARLYLE-MOSES; LISHMAN; MCKEE, 2014; FAN et al., 2015; MANFROI et al., 2006; STAELENS et al., 2006; TEALE et al., 2014), applying different criteria (i.e. spatial variation, correlation of accumulated depth), used these RF thresholds, where the stabilization of CV_{TF} occurs, for the classification of small or large RF events, in which each hydrological process occur at different rates. Thus, it is possible to understand in more detail how these processes occur during events of different magnitudes. From the categorization of events, it can be verified that, in events with small RF depth, a large portion of RF is intercepted by the forest canopy. As the canopy storage capacity is saturated, a larger portion of RF is converted into TF (SIEGERT et al., 2016). Although the RF depth explains considerably the variation of TF data, future studies must also consider the duration and intensity of the events, which are related to the effect of evaporation on intercepted water (STAELENS et al., 2008).

Carlyle-Moses, Lishman and McKee (2014) suggest that the spatial variability of TF in events with large RF depths may be related to the coefficient of variation of canopy cover, since they obtained values of 49.5% and 48.3% for these variables, respectively. In this perspective, if the relationship between both variables is validated, the complexity of canopy structure is expected to be the main factor controlling the spatial variability of TF in this kind of events.

In addition, modelling the relationship between these variables may contribute to the estimation of other related variables. For example, based on the equation developed by Kimmins (1973), widely applied in forest hydrology studies (e.g. CARLYLE-MOSES; LISHMAN; MCKEE, 2014; FAN et al., 2015; SARI; PAIVA; PAIVA, 2015), the modelled CV_{TF} can be applied to estimate the required number of gauges for TF monitoring with a pre-established precision level. In this way, it would be possible to adjust the calculated sample size to the evaluated time scale (i.e. rainfall event, climatic season, annual), based on the modeled CV_{TF} for a given RF pattern.

Similarly, this relationship can contribute to the understanding and modelling of other components of forest ecosystems, such as percolation rate (KLOS et al., 2014) and soil microbial biodiversity (ROSIER et al., 2015), for which a direct relationship with the spatial heterogeneity of TF has already been verified. However, these applications would require prior knowledge of the relationship between RF and TF in the area, demanding complementary studies that establish the relationship between variables.

In general, it was possible to verify that RF is the main source of TF_{mm} variability and a major source of variation for CV_{TF} and TF%, mainly in events with depths up to 12.5 and 25 mm, respectively. Above these values, there is no more variation of CV_{TF} and $TF_{\%}$ following the increase of RF, resulting in non-linear relationships. Thus, the linear models allowed verifying the influence of RF on the variables, but presented poor fits in relation to the other models. Therefore, the results obtained highlight that RF is not the only source of TF variation in the study area. Wullaert et al. (2009), for example, concluded that canopy structure was the main factor of influence in a tropical ecosystem. On the other hand, Styger, Kirkpatrick and Unwin (2016) found no relation with any vegetation variables tested. Similarly, Shinohara et al. (2010) also verified no association between the canopy cover and the spatial variation of TF, but concluded that RF depth exerts a strong influence on the CV_{TF}, especially in rainfall depths lower than 10 mm. This divergence in the identification of the main sources of the spatial variability of TF is due to the great complexity in the interaction between factors that control TF, which, for example, varies according to the spatial scale being studied (LEVIA JUNIOR; FROST, 2006). However, the observed reduction of the spatial variability of TF as a function of the increase of RF in the present study, both within and between plots, shows that the relation remains even with changes at the spatial scale of the analysis, highlighting the importance of RF on the variability of CV_{TF}.

In addition, Gotelli and Ellison (2011) state that most of ecological relationships are not linear, being approximations of the real relation at a given cut-off (i.e. amplitude of the data collected) of the total variation of the analyzed factors. Therefore, the choice of a particular model to describe the relationship between these variables should be made with caution, taking into account the spatial scale of the study and the amplitude of the gathered data. Although some tested models have presented higher coefficients of determination than others, it should be noted that the chosen models do not usually comprise all the variables that determine the variation in TF and its coefficient of variation, nor the interactions that occur in the environment and affect it (QUINN; KEOUGH, 2002), being considered only the most relevant, within the scope of the study.

Finally, based on Carlyle-Moses, Lishman and McKee (2014), it is suggested the development of studies that attempt to relate the parameters of nonlinear models with meteorological variables and vegetation structure, to highlight other sources of variability in TF estimates. Thus, the parameters obtained by model fitting (Table 2) can be used to determine relationships with potential influence factors on TF, such as those that establish different levels of CV_{TF} stabilization.

CONCLUSION

The present study aimed to evaluate the influence of rainfall on throughfall and to describe the behavior of these variables in a secondary forest. According to the previously defined questions, it was found that: (1) in the rainy season, rainfall in the study area presented low spatial heterogeneity in the 800m-scale and its temporal distribution is mainly composed by events with small RF depths; (2) rainfall depth had positive influence on throughfall depth (TF_{mm}) and its fraction ($TF_{\%}$); (3) rainfall depth had a negative influence on the spatial variation of throughfall (CV_{TF}); and (4) the relationship between RF and TF_{mm} was better explained by the linear model, whereas nonlinear models presented better fitting for $TF_{\%}$ (logarithmic and exponential) and CV_{TF} (exponential), although they have limited ability to explain these relationships.

From the analysis of the fitted models, it was observed that, as in other studies, the relationship between RF and TF_{mm} can be reasonably described by linear models, allowing further analysis, as already discussed. However, the relationships of $TF_{\%}$ and CV_{TF} with RF can be better described by non-linear models, with caveats to the models limitations to explain a large part of the variation of the response variables, suggesting that other variables may be influencing these variables, which requires complementary analyzes to verify the origin of the unexplained variation.

In general, the results indicate that rainfall is a major source of variation of throughfall and its spatial variability. However, part of the variation of this process could not be explained by linear regression models for both $TF_{\%}$ and CV_{TF}.

It should be noted that this study analyzed only one meteorological factor that interacts with throughfall, so it is necessary to consider other variables related to the intensity and duration of rainfall events, as well as wind characteristics and evaporation in canopy. Therefore, further studies are needed to examine the influence of other variables on hydrological processes, especially the vegetation, identifying and quantifying the effect of these factors alone and in combination with the characteristics of rainfall events for a better comprehension of their interaction.

ACKNOWLEDGEMENTS

To the Coordination for the Improvement of Higher Education Personnel (CAPES) by the granting of scholarship for the first author. To the National Institute of Meteorology (INMET) for providing historical rainfall data from weather stations.

REFERENCES

AHMADI, M. T.; ATTAROD, P.; BAYRAMZADEH, V. The role of rainfall size in canopy interception loss: an observational study in a typical beech forest. *Middle East Journal of Scientific Research*, v. 13, n. 7, p. 876-882, 2013.

ALBUQUERQUE, F. N. B.; COSTA, J. S. Interceptação de chuva em diferentes fisionomias de caatinga (Coreaú, CE). *Geografia Ensino & Pesquisa*, v. 16, n. 3, p. 63-75, 2012.

ARCOVA, F. C. S.; CICCO, V.; ROCHA, P. A. B. Precipitação efetiva e interceptação das chuvas por floresta de Mata Atlântica em uma microbacia experimental em Cunha - São Paulo. *Revista Árvore*, v. 27, n. 2, p. 257-262, 2003. http://dx.doi.org/10.1590/S0100-67622003000200014.

ÁVILA, L. F.; MELLO, C. R.; PINTO, L. C.; SILVA, A. M. Partição da precipitação pluvial em uma microbacia hidrográfica ocupada por Mata Atlântica na Serra da Mantiqueira, MG. *Ciência Florestal*, v. 24, n. 3, p. 583-595, 2014. http://dx.doi.org/10.5902/1980509815739.

CARIBONI, J.; GATELLI, D.; LISKA, R.; SALTELLI, A. The role of sensitivity analysis in ecological modelling. *Ecological Modelling*, v. 203, n. 1-2, p. 167-182, 2007. http://dx.doi.org/10.1016/j.ecolmodel.2005.10.045.

CARLYLE-MOSES, D. E.; LAUREANO, J. S. F.; PRICE, A. G. Throughfall and throughfall spatial variability in Madrean oak forest communities of northeastern Mexico. *Journal of Hydrology (Amsterdam)*, v. 297, n. 1-4, p. 124-135, 2004. http://dx.doi.org/10.1016/j.jhydrol.2004.04.007.

CARLYLE-MOSES, D. E.; LISHMAN, C. E. Temporal persistence of throughfall heterogeneity below and between the canopies of juvenile lodgepole pine (*Pinus contorta*). *Hydrological Processes*, v. 29, n. 18, p. 4051-4067, 2015. http://dx.doi.org/10.1002/hyp.10494.

CARLYLE-MOSES, D. E.; LISHMAN, C. E.; MCKEE, A. J. A preliminary evaluation of throughfall sampling techniques in a mature coniferous forest. *Journal of Forestry Research*, v. 25, n. 2, p. 407-413, 2014. http://dx.doi.org/10.1007/s11676-014-0468-8.

CEPAGRI – Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura. *Clima dos municípios paulistas*. Campinas: CPA, UNICAMP, 2017. Available from: <http://www.cpa.unicamp.br/outras-informacoes/clima-dos-municipios-paulistas.html>. Access on: 28 ago. 2017.

CHAPPELL, N. A.; BIDIN, K.; TYCH, W. Modelling rainfall and canopy controls on net-precipitation beneath selectively-logged tropical forest. *Plant Ecology*, v. 153, n. 1/2, p. 215-229, 2001. http://dx.doi.org/10.1023/A:1017532411978.

CHAZDON, R. L. *Second growth*: the promise of tropical forest regeneration in an age of deforestation. Chicago: The University of Chicago Press, 2014. http://dx.doi.org/10.7208/chicago/9780226118109.001.0001.

CROCKFORD, R. H.; RICHARDSON, D. P. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes*, v. 14, n. 16-17, p. 2903-2920, 2000. http://dx.doi.org/10.1002/1099-1085(200011/12)14:16/17<2903::AID-HYP126>3.0.CO;2-6.

FAN, J.; OESTERGAARD, K. T.; GUYOT, A.; JENSEN, D. G.; LOCKINGTON, D. A. Spatial variability of throughfall and stemflow in an exotic pine plantation of subtropical coastal Australia. *Hydrological Processes*, v. 29, n. 5, p. 793-804, 2015. http://dx.doi.org/10.1002/hyp.10193.

FERREIRA, S. J. F.; LUIZÃO, F. J.; DALLAROSA, R. L. G. Precipitação interna e interceptação da chuva em floresta de terra firme submetida à extração seletiva de madeira na Amazônia Central. *Acta Amazonica*, v. 35, n. 1, p. 55-62, 2005. http://dx.doi.org/10.1590/S0044-59672005000100009.

GASPAROTO, E. A. G.; TONELLO, K. C.; SHINZATO, E. T.; VALENTE, R. O. A. Throughfall in different forest stands of Iperó, São Paulo. *Cerne*, v. 20, n. 2, p. 303-310, 2014. http://dx.doi.org/10.1590/01047760.201420021260.

GÊNOVA, K. B.; HONDA, E. A.; DURIGAN, G. Processos hidrológicos em diferentes modelos de plantio de restauração de mata ciliar em região de cerrado. *Revista do Instituto Florestal*, v. 19, n. 2, p. 189-200, 2007.

GOTELLI, N. J.; ELLISON, A. M. *Princípios de estatística em ecologia*. Porto Alegre: Artmed, 2011.

HOLWERDA, F.; SCATENA, F. N.; BRUIJNZEEL, L. A. Throughfall in a Puerto Rican lower montane rain forest: a comparison of sampling strategies. *Journal of Hydrology (Amsterdam)*, v. 327, n. 3-4, p. 592-602, 2006. http://dx.doi.org/10.1016/j.jhydrol.2005.12.014.

HSUEH, Y.-H.; ALLEN, S. T.; KEIM, R. F. Fine-scale spatial variability of throughfall amount and isotopic composition under a hardwood forest canopy. *Hydrological Processes*, v. 30, n. 11, p. 1796-1803, 2016. http://dx.doi.org/10.1002/hyp.10772.

JOHNSON, J. B.; OMLAND, K. S. Model selection in ecology and evolution. *Trends in Ecology & Evolution*, v. 19, n. 2, p. 101-108, 2004. http://dx.doi.org/10.1016/j.tree.2003.10.013. PMid:16701236.

KEIM, R. F.; SKAUGSET, A. E.; WEILER, M. Temporal persistence of spatial patterns in throughfall. *Journal of Hydrology (Amsterdam)*, v. 314, n. 1-4, p. 263-274, 2005. http://dx.doi.org/10.1016/j.jhydrol.2005.03.021.

KIMMINS, J. P. Some statistical aspects of sampling throughfall precipitation in nutrient cycling studies in British Columbian coastal forests. *Ecology*, v. 54, n. 5, p. 1008-1019, 1973. http://dx.doi.org/10.2307/1935567.

KLOS, P. Z.; CHAIN-GUADARRAMA, A.; LINK, T. E.; FINEGAN, B.; VIERLING, L. A.; CHAZDON, R. Throughfall heterogeneity in tropical forested landscapes as a focal mechanism for deep percolation. *Journal of Hydrology (Amsterdam)*, v. 519, p. 2180-2188, 2014. http://dx.doi.org/10.1016/j.jhydrol.2014.10.004.

KOWALSKA, A.; BOCZON, A.; HILDEBRAND, R.; POLKOWSKA, Z. Spatial variability of throughfall in a stand of Scots pine (*Pinus sylvestris* L.) with deciduous admixture as influenced by canopy cover and stem distance. *Journal of Hydrology (Amsterdam)*, v. 538, p. 231-242, 2016. http://dx.doi.org/10.1016/j.jhydrol.2016.04.023.

KRAJEWSKI, W. F.; CIACH, G. J.; HABIB, E. An analysis of small-scale rainfall variability in different climatic regimes. *Hydrological Sciences Journal*, v. 48, n. 2, p. 151-162, 2003. http://dx.doi.org/10.1623/hysj.48.2.151.44694.

LEVIA JUNIOR, D. F.; FROST, E. E. Variability of throughfall volume and solute inputs in wooded ecosystems. *Progress in Physical Geography*, v. 30, n. 5, p. 605-632, 2006. http://dx.doi.org/10.1177/0309133306071145.

LORENZON, A. S.; DIAS, H. C. T.; LEITE, H. G. Precipitação efetiva e interceptação da chuva em um fragmento florestal com diferentes estágios de regeneração. *Revista Árvore*, v. 37, n. 4, p. 619-627, 2013. http://dx.doi.org/10.1590/S0100-67622013000400005.

MAIR, A.; FARES, A. Throughfall characteristics in three non-native Hawaiian forest stands. *Agricultural and Forest Meteorology*, v. 150, n. 11, p. 1453-1466, 2010. http://dx.doi.org/10.1016/j.agrformet.2010.07.007.

MANFROI, O. J.; KURAJI, K.; SUZUKI, M.; TANAKA, N.; KUME, T.; NAKAGAWA, M.; KUMAGAI, T.; NAKASHIZUKA, T. Comparison of conventionally observed interception evaporation in a 100-m2 subplot with that estimated in a 4-ha area of the same Bornean lowland tropical forest. *Journal of Hydrology (Amsterdam)*, v. 329, n. 1-2, p. 329-349, 2006. http://dx.doi.org/10.1016/j.jhydrol.2006.02.020.

MELÃO, M. G. G.; MOSCHINI, L. E.; MILANO, C. B.; LOCATELLI, E. T. *Diagnóstico e caracterização ambiental da UFSCar, campus de São Carlos*: relatório apresentado ao Ministério Público Federal e CETESB. São Carlos, 2011.

MOURA, A. E. S. S.; CORREA, M. M.; SILVA, E. R.; FERREIRA, R. L. C.; FIGUEIREDO, A. C.; POSSAS, J. M. C. Interceptação das chuvas em um fragmento de floresta da Mata Atlântica na Bacia do Prata, Recife, PE. *Revista Árvore*, v. 33, n. 3, p. 461-469, 2009. http://dx.doi.org/10.1590/S0100-67622009000300008.

OLIVEIRA JÚNIOR, J. C.; DIAS, H. C. T. Precipitação efetiva em fragmento secundário da Mata Atlântica. *Revista Árvore*, v. 29, n. 1, p. 9-15, 2005. http://dx.doi.org/10.1590/S0100-67622005000100002.

OLIVEIRA, L. L.; COSTA, R. F.; COSTA, A. C. L.; SOUSA, F. A. S.; BRAGA, A. P. Modelagem da interceptação na Floresta Nacional de Caxiuanã, no leste da Amazônia. *Revista Brasileira de Meteorologia*, v. 23, n. 3, p. 318-326, 2008. http://dx.doi.org/10.1590/S0102-77862008000300006.

OZIEGBE, M. B.; MUOGHALU, J. I.; OKE, S. O. Litterfall, precipitation and nutrient fluxes in a secondary lowland rain forest in Ile-Ife, Nigeria. *Acta Botanica Brasílica*, v. 25, n. 3, p. 664-671, 2011. http://dx.doi.org/10.1590/S0102-33062011000300020.

PARK, A.; CAMERON, J. L. The influence of canopy traits on throughfall and stemflow in five tropical trees growing in a Panamanian plantation. *Forest Ecology and Management*, v. 255, n. 5-6, p. 1915-1925, 2008. http://dx.doi.org/10.1016/j.foreco.2007.12.025.

PEREZ-MARIN, A. M.; MENEZES, R. S. C. Ciclagem de nutrientes via precipitação pluvial total, interna e escoamento pelo tronco em sistema agroflorestal com *Gliricidia sepium*. *Revista Brasileira de Ciência do Solo*, v. 32, n. 6, p. 2573-2579, 2008. http://dx.doi.org/10.1590/S0100-06832008000600034.

PÉREZ-SUÁREZ, M.; ARREDONDO-MORENO, J. T.; HUBER-SANNWALD, E.; SERNA-PÉREZ, A. Forest structure, species traits and rain characteristics influences on horizontal and vertical rainfall partitioning in a semiarid pine-oak forest from Central Mexico. *Ecohydrology*, v. 7, n. 2, p. 532-543, 2014. http://dx.doi.org/10.1002/eco.1372.

PYPKER, T. G.; BOND, B. J.; LINK, T. E.; MARKS, D.; UNSWORTH, M. H. The importance of canopy structure in controlling the interception loss of rainfall: Examples from a young and an old-growth Douglas-fir forest. *Agricultural and Forest Meteorology*, v. 130, n. 1–2, p. 113-129, 2005. http://dx.doi.org/10.1016/j.agrformet.2005.03.003.

QUINN, G.; KEOUGH, M. *Experimental design and data analysis for biologists*. United Kingdom: Cambridge University Press, 2002. http://dx.doi.org/10.1017/CBO9780511806384.

RITTER, A.; REGALADO, C. M. Roving revisited, towards an optimum throughfall sampling design. *Hydrological Processes*, v. 28, n. 1, p. 123-133, 2014. http://dx.doi.org/10.1002/hyp.9561.

RODRIGO, A.; ÀVILA, A. Influence of sampling size in the estimation of mean throughfall in two Mediterranean holm oak forests. *Journal of Hydrology (Amsterdam)*, v. 243, n. 3-4, p. 216-227, 2001. http://dx.doi.org/10.1016/S0022-1694(00)00412-1.

ROSIER, C. L.; VAN STAN II, J. T.; MOORE, L. D.; SCHROM, J. O. S.; WU, T.; REICHARD, J. S.; KAN, J. Forest canopy structural controls over throughfall affect soil microbial community structure in an epiphyte-laden maritime oak stand. *Ecohydrology*, v. 8, n. 8, p. 1459-1470, 2015. http://dx.doi.org/10.1002/eco.1595.

SÁ, J. H. M.; CHAFFE, P. L. B.; QUILLET, M. J. J. The influence of the interception process on the precipitation quality in a catchment covered by subtropical Atlantic Forest. *Revista Brasileira de Recursos Hídricos*, v. 21, n. 4, p. 742-751, 2016. http://dx.doi.org/10.1590/2318-0331.011616045.

SANCHES, R. G. *As chuvas na região de São Carlos/SP*: estudo do comportamento pluviométrico a partir de dados de estações climáticas, 1993-2014. 2015. 184 f. Dissertação (Mestrado em Ciências da Engenharia Ambiental) - Universidade de São Paulo, São Carlos, 2015.

SARI, V.; PAIVA, E. M. C. D.; PAIVA, J. B. D. Precipitação interna em Floresta Atlântica: comparação entre os sistemas de monitoramento fixo e móvel. *Revista Brasileira de Recursos Hídricos*, v. 20, n. 4, p. 849-861, 2015. http://dx.doi.org/10.21168/rbrh.v20n4.p849-861.

SHACHNOVICH, Y.; BERLINER, P. R.; BAR, P. Rainfall interception and spatial distribution of throughfall in a pine forest planted in an arid. *Journal of Hydrology (Amsterdam)*, v. 349, n. 1-2, p. 168-177, 2008. http://dx.doi.org/10.1016/j.jhydrol.2007.10.051.

SHINOHARA, Y.; ONOZAWA, Y.; CHIWA, M.; KUME, T.; KOMATSU, H.; OTSUKI, K. Spatial variations in throughfall in a Moso bamboo forest: sampling design for the estimates of stand-scale throughfall. *Hydrological Processes*, v. 24, p. 253-259, 2010.

SIEGERT, C. M.; LEVIA, D. F.; HUDSON, S. A.; DOWTIN, A. L.; ZHANG, F.; MITCHELL, M. J. Small-scale topographic variability influences tree species distribution and canopy throughfall partitioning in a temperate deciduous forest. *Forest Ecology and*

Management, v. 359, p. 109-117, 2016. http://dx.doi.org/10.1016/j.foreco.2015.09.028.

SOUZA, V. V.; DIAS, H. C. T.; COSTA, A. A.; OLIVEIRA JÚNIOR, J. C. Análise da qualidade das águas das precipitações em aberto e efetiva em um fragmento secundário da Mata Atlântica, no município de Viçosa, MG. *Revista Árvore*, v. 31, n. 4, p. 737-743, 2007. http://dx.doi.org/10.1590/S0100-67622007000400019.

STAELENS, J.; DE SCHRIJVER, A.; VERHEYEN, K.; VERHOEST, N. E. C. Spatial variability and temporal stability of throughfall water under a dominant beech (*Fagus sylvatica* L.) tree in relationship to canopy cover. *Journal of Hydrology (Amsterdam)*, v. 330, n. 3-4, p. 651-662, 2006. http://dx.doi.org/10.1016/j.jhydrol.2006.04.032.

STAELENS, J.; DE SCHRIJVER, A.; VERHEYEN, K.; VERHOEST, N. E. C. Rainfall partitioning into throughfall, stemflow, and interception within a single beech (*Fagus sylvatica* L.) canopy: influence of foliation, rain event characteristics, and meteorology. *Hydrological Processes*, v. 22, n. 1, p. 33-45, 2008. http://dx.doi.org/10.1002/hyp.6610.

STYGER, J.; KIRKPATRICK, J. B.; UNWIN, G. Throughfall and its spatial variability in a temperate rainforest of simple structure. *Physical Geography*, v. 37, n. 3–4, p. 251-263, 2016. http://dx.doi.org/10.1080/02723646.2016.1169476.

TEALE, N. G.; MAHAN, H.; BLEAKNEY, S.; BERGER, A.; SHIBLEY, N.; FRAUENFELD, O. W.; QUIRING, S. M.; RAPP, A. D.; ROARK, E. B.; WASHINGTON-ALLEN, R. Impacts of vegetation and precipitation on throughfall heterogeneity in a tropical pre-montane transitional cloud forest. *Biotropica*, v. 46, n. 6, p. 667-676, 2014. http://dx.doi.org/10.1111/btp.12166.

THOMAZ, E. L. Avaliação de interceptação e precipitação interna em capoeira e floresta secundária em Guarapuava-PR. *Geografia*, v. 14, n. 1, p. 47-60, 2005.

TOGASHI, H. F.; MONTEZUMA, R.; LEITE, A. F. Precipitação incidente e fluxo de atravessamento das chuvas em três estágios sucessionais de floresta atlântica no maciço da Pedra Branca, Rio de Janeiro. *Revista Árvore*, v. 36, n. 5, p. 907-918, 2012. http://dx.doi.org/10.1590/S0100-67622012000500013.

TONELLO, K. C.; GASPAROTO, E. A. G.; SHINZATO, E. T.; VALENTE, R. O. A.; DIAS, H. C. T. Precipitação efetiva em diferentes formações florestais na Floresta Nacional de Ipanema. *Revista Árvore*, v. 38, n. 2, p. 383-390, 2014. http://dx.doi.org/10.1590/S0100-67622014000200020.

VAN STAN, J. T.; GAY, T. E.; LEWIS, E. S. Use of multiple correspondence analysis (MCA) to identify interactive meteorological conditions affecting relative throughfall. *Journal of Hydrology (Amsterdam)*, v. 533, p. 452-460, 2016. http://dx.doi.org/10.1016/j.jhydrol.2015.12.039.

WULLAERT, H.; POHLERT, T.; BOY, J.; VALAREZO, C.; WILCKE, W. Spatial throughfall heterogeneity in a montane rain forest in Ecuador: extent, temporal stability and drivers. *Journal of Hydrology (Amsterdam)*, v. 377, n. 1-2, p. 71-79, 2009. http://dx.doi.org/10.1016/j.jhydrol.2009.08.001.

ZIEGLER, A. D.; GIAMBELLUCA, T. W.; NULLET, M. A.; SUTHERLAND, R. A.; TANTASARIN, C.; VOGLER, J. B.; NEGISHI, J. N. Throughfall in an evergreen-dominated forest stand in northern Thailand: comparison of mobile and stationary methods. *Agricultural and Forest Meteorology*, v. 149, n. 2, p. 373-384, 2009. http://dx.doi.org/10.1016/j.agrformet.2008.09.002.

ZIMMERMANN, A.; GERMER, S.; NEILL, C.; KRUSCHE, A. V.; ELSENBEER, H. Spatio-temporal patterns of throughfall and solute deposition in an open tropical rain forest. *Journal of Hydrology (Amsterdam)*, v. 360, n. 1-4, p. 87-102, 2008. http://dx.doi.org/10.1016/j.jhydrol.2008.07.028.

ZIMMERMANN, B.; ZIMMERMANN, A.; LARK, R. M.; ELSENBEER, H. Sampling procedures for throughfall monitoring: A simulation study. *Water Resources Research*, v. 46, n. 1, p. 1-15, 2010. http://dx.doi.org/10.1029/2009WR007776.

ZOU, C. B.; CATERINA, G. L.; WILL, R. E.; STEBLER, E.; TURTON, D. Canopy interception for a tallgrass prairie under juniper encroachment. *PLoS One*, v. 10, n. 11, p. e0141422, 2015. http://dx.doi.org/10.1371/journal.pone.0141422. PMid:26544182.

Authors contributions

Raul Sampaio de Lima: designed research, participated in the field, methodology for the data analysis, data analysis, and in the interpretation of the results.

Vandoir Bourscheidt: participated in the data analysis and in the interpretation of the results.

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