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Investigating the reduction of rainfall intensity beneath an urban deciduous tree canopy

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A R T I C L E I N F O

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A B S T R A C T

Trees have an indispensable role to play in the hydrological cycle. The process of interception by tree canopies alters the magnitude, pathway, and intensity of rainfall reaching the ground. This study investigates the rainfall intensity-attenuating effects of canopy interception by open-grown birch trees (*Betula pendula Roth.*) in an urban environment and the influence of atmospheric variables. Rainfall partitioning was measured in a research plot in the city of Ljubljana, Slovenia, from August 2021 to August 2022. Simultaneously, optical disdrometers above and below the birch tree canopy measured microstructures of rainfall and throughfall, from which the intensities were calculated. During the measurement period, the birch tree intercepted on average 25.6 % of gross rainfall, with the interception being twice as high during the leafed season than in the leafless season. Consequently, the total number and volume of drops under the canopy were reduced on average by 16.4 % and 48.7 %, respectively, indicating the interception and fragmentation of raindrops by the canopy. Owing to these processes, the leafed and leafless states of the birch tree canopy attenuate the average intensities of rainfall by 50.2 % and 41.6 %, respectively. Canopy interception also moderates the maximum 10-minute rainfall intensities by 11.6–83.8 % and 13.1–74.2 % during the leafed and leafless periods, respectively. This percentage of reduction in the rainfall intensities below the canopy decreases with rainfall amount and in the absence of foliage. Aside from pheno-seasons, we also found that vapor pressure deficit and air temperature were among the atmospheric variables that exert the highest influence on the intensities of throughfall. Furthermore, the regression analysis between the maximum throughfall intensity and peak water level for each rainfall event indicates that the reduction of rainfall intensity by the canopy has a significant effect on runoff peak water level ($R^2 = 0.76$, $p < 0.001$).

1. Introduction

As an integral component of public spaces, trees provide multiple ecosystem services to the urban environment (Livesley et al., 2014; McPherson et al., 2005), making cities socio-economically and environmentally sustainable (FAO, 1993). They play a requisite role in the urban hydrological cycle by intercepting rainfall, facilitating evaporation and transpiration, and modifying the rate and quantity of water infiltrating into the soil (Berland et al., 2017; Livesley et al., 2014; Yang et al., 2019), which have a substantial impact on the quantity and flow mechanism of stormwater runoff (Deutscher et al., 2019; Zabret and Šraj, 2019a). More specifically, canopy interception alters the amount, movement, and spatiotemporal variability of precipitation reaching the ground (Swaffer et al., 2014; Zabret and Šraj, 2018) by routing the rainfall to various components of the hydrologic cycle. Owing to this process, trees modify the intensity and drop size distribution (DSD) of rainfall (e.g., Zabret et al., 2017; Zabret and Šraj, 2019b) as well as the time and manner in which the rainwater flows to the soil surface (Livesley et al., 2014; Yang et al., 2019), which is essential in understanding the sub-canopy hydrologic and erosional processes (e.g., Liu and Zhao, 2020; Zore et al., 2022).

The interception process begins at the onset of a storm event (Berland et al., 2017), where the rain is temporarily stored on tree surfaces (e.g., leaves, stems, branches) and subsequently, either evaporates into the atmosphere during and after the rainfall events (interception loss) or reaches the ground via throughfall or stemflow, which drains from the branches and then channeled downwards to the main stem or trunk of the trees (Dingman, 2002; Dunkerley, 2000; Park and Cameron, 2008; Swaffer et al., 2014; Zhang et al., 2016). This redistribution of rainfall through the canopies causes variability in the magnitude, intensity, and chemical composition of throughfall, influencing the surface water, soil moisture, and biogeochemical processes (Keim and Link, 2018; Rosier

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et al., 2015). Hence, previous studies have identified notable distinctions in the rainfall partitioning components between forest canopies and open-grown trees as they depend on many influencing factors such as rainfall characteristics (amount, duration, and intensity), climatic conditions, available growing space, canopy structure, and phenology (Asadian and Weiler, 2009; Berland et al., 2017; Livesley et al., 2014; Nanko et al., 2008; Zabret et al., 2018; Zabret and Šraj, 2019b, 2021a; Xiao et al., 2000). As indicated in the review conducted by Carlyle-Moses and Gash (2011), the interception rate of coniferous forests is generally between 16 and 45 % of annual rainfall and 19–40 % for hardwood forests. Mixed and tropical forests have interception rates of 14–19 % and 6–32 %, respectively. Meanwhile, a metadata analysis by Beidokhti and Moore (2021) suggests higher interception rates for urban tree canopies compared to forest canopies, ranging from 14.3 to 45 % for deciduous trees and 27–72 % for evergreen trees. Although rainfall partitioning components in urban tree canopies can be inferred from studies in natural forests, the measurements from forest settings cannot be directly applied in urban areas (Asadian and Weiler, 2009; Beidokhti and Moore, 2021; Guevara-Escobar et al., 2007). Trees in forest environments often grow in dense and densely packed groups, facing constraints in terms of access to sunlight due to shading from neighboring trees and the necessity to compete for this vital resource. As a result, they allocate more resources towards height growth rather than expanding their crown foliage (Kuehler et al., 2017; MacFarlane and Kane, 2017; Staelens et al., 2008). In contrast to the closed growth pattern of forest canopies (Beidokhti and Moore, 2021), most trees in the cities are often planted and/or grown in open conditions, either individually (e.g., street trees) or with ample spacing between them (e.g., urban parks). These growing conditions favor urban trees to have greater access to sunlight from various directions, allowing them to develop larger crown volumes or higher live crown ratios (Hasenauer, 1997; MacFarlane and Kane, 2017; Zhou et al., 2011, 2015). In addition to differences in tree characteristics, the climatic conditions in urban environments also differ from those in forests, mainly due to the presence of heat islands and wind corridors (Asadian and Weiler, 2009; Guevara-Escobar et al., 2007; Huang et al., 2017; Kuehler et al., 2017). Hence, this disparity may lead to differences in rainfall partitioning processes among trees at different locations.

One of the consequential outcomes of the dynamic interplay between rainfall and tree canopy is the attenuation of rainfall intensity before reaching the ground, which constitutes an integral facet of the interception process. The delay and fragmentation of raindrops within the tree canopy results in a more gradual and moderated intensity pattern of water as it falls to the ground. The study conducted by Trimble and Weitzman (1954) revealed that the rainfall intensity under the deciduous forest canopy was effectively reduced by up to 21 % during the leafed period in summer and 19 % during the leafless period in winter. They emphasized that these reductions depend on the season (i.e., canopy phenology) and intensity of gross rainfall. Furthermore, a greater reduction in peak rainfall intensity was reported by Keim and Skaugset (2003) for young coniferous forest stands in Oregon and Washington, USA with up to 2 min peak delays. Liu and Zhao (2020) also reported that the mean throughfall intensity under the two native plant species in China (*Spiraea pubescens Turcz* and *Artemisia sacrorum Ledeb*) is lower compared to gross rainfall intensity, especially during heavy rainfall events. These studies have shown that trees do not only decrease the amount of incident precipitation but also delay and moderate the peak intensities of throughfall. Despite this, there remains a paucity of work that quantifies the role and effect of trees on attenuating the rainfall intensities under the canopy (Brasil et al., 2020; Keim and Skaugset, 2003), particularly in urban areas, where the potential benefit for an increased reduction in rainfall intensity may be observed as open-grown trees often have larger crown volumes (Kuehler et al., 2017).

The benefits of rainfall intensity attenuation by tree canopies encourage more water to infiltrate into the soil as the delivery of rainfall to the ground surface is effectively slowed down (Berland et al., 2017). This will delay the stormwater runoff in addition to runoff volume reduction (Bedient et al., 2008) which allows existing drainage systems and other green infrastructure technologies to function more efficiently (Berland et al., 2017; Kuehler et al., 2017). More notably in urban areas, where a high percentage of impervious surfaces allows little to no infiltration into the ground, a considerable portion of the stormwater runoff is directly collected by a system of drainage infrastructures. Several studies have recognized that rainfall intensity is one of the key factors that influence the generation and characteristics of surface runoff (i.e., peak discharge, total runoff volume, water level, and the lag time in peak flow) (e.g., Amore et al., 2004; Beven, 2004; Boening, 2020; Dunkerley, 2012; Mustafa et al., 2017; Ries et al., 2017; Wang et al., 2022). High-intensity rainfall events produce higher runoff rates and volume compared to low-intensity events (Dunkerley, 2012; Guan et al., 2016; Mustafa et al., 2017; Suharyanto, 2021; Yao et al., 2021). In this case, the increasing frequency and intensity of extreme rainfall induced by climate change may compromise the capacity of existing urban drainage infrastructures (Burrel et al., 2007; Kirnbauer et al., 2013; Mailhot and Duchesne, 2010; Ranger et al., 2011) as they are not designed to cater larger volumes of stormwater that are beyond their capacity (Berland et al., 2017; Zhou, 2014). As a result, this will lead to more frequent urban flooding (Mailhot and Duchesne, 2010; Semadeni-Davies et al., 2008; Zhou et al., 2012) which is associated with cascading impacts on the economy, environment, society, and infrastructures (Chang et al., 2018; Zhou et al., 2012). The cumulative impacts of accelerated urbanization and non-stationary climate emphasize the necessity of deliberately embracing other vital facets of urban water management, including runoff quality, esthetic value, recreational amenities, ecological protection, and other water uses (Chocat et al., 2007; France, 2002; Zhou, 2014). In this context, green infrastructures, where trees have an important role to play, are seen to offer the most viable and innovative approach to bolster the function of urban drainage systems in managing stormwater runoff and further deal with the increasing flood risk in urban areas (Houston et al., 2011; IUCN, 2009).

As trees are becoming increasingly recognized as an element of urban green infrastructures, the present research aims to investigate the extent to which the presence of an open-grown (urban) deciduous tree canopy attenuates the intensity of rainfall before reaching the ground. It is particularly imperative to quantify this potential benefit as our understanding of this specific sub-canopy process in an urban environment is currently limited. This study contributes to the discipline by improving our understanding of how trees influence the dynamics of interception and throughfall processes in urban environments and the subsequent movement and distribution of rainwater in the soil. Specifically, we also attempt to link the rainfall intensity reduction by birch tree canopy to the maximum water level of runoff. With this information, we aimed to provide insight into how the rainfall intensity-attenuating effects of tree canopies may contribute to delaying and lowering the peak water level of runoff. It is because aside from the discharge data, water level is one of the commonly monitored variables which is widely used in setting a flood warning signal and establishing a rating curve (Chang et al., 2018). It is also an important prerequisite in urban drainage and stormwater management to understand the behavior of water flow inside the drainage system and the functioning and performance of such critical infrastructures during large storm events (Larrarte et al., 2021). In this sense, the findings from our study are practically valuable to urban planners and stormwater managers in strategically incorporating trees into the design and planning of urban green spaces that maximize their hydrologic functions in harmony with other stormwater control measures (SCMs). Furthermore, we also assess the influence of canopy phenoseasons and atmospheric conditions on the rainfall intensity reduction under the birch tree canopies. It contributes to furthering the body of knowledge on the response of throughfall generation process to changes in meteorological conditions and canopy foliation states.

2. Materials and methods

2.1. Study area

The city of Ljubljana, Slovenia lies inside the Ljubljana basin surrounded by hills and mountains which are covered with 46 % of natural forests (ICLEI, 2022). The location is characterized by a temperate continental climate and well-defined seasons (Ogrin, 1996). Long-term meteorological data (1960–2021) at Ljubljana-Bežigrad meteorological station showed that the annual average precipitation in the city is 1388 mm with most of the rain being delivered in autumn (around 30 % of the total yearly rainfall), while the mean annual air temperature is 11 °C, varying between −3 °C during winter and 24 °C during summer (Zabret and Šraj, 2021b).

The experimental plot for rainfall partitioning measurement is located in a small urban park in the city of Ljubljana, Slovenia (Fig. 1c), which is adjacent to the building of the Department of Environmental Engineering of the University of Ljubljana (46.04° N, 14.49° E, 292 m a. m.s.l.). The size of the research plot is approximately 600 m^2 covered with regularly mowed grass and surrounded by impervious surfaces (i. e., buildings, parking spaces, roads) in four cardinal directions. In its western part, two open-grown groups of native tree species are approximately 60 years old, namely, the north-western black pines (*Pinus nigra Arnold*) and south-western birches (*Betula pendula Roth.*). Thus, we selected the birch tree for this study due to its distinct canopy phenological seasons (phenoseasons), which satisfy our underlying objectives. The observed birch tree has an average height of 16.2 m, a diameter at breast height of 18.3 cm, and a total projected crown area of 20.3 m^2. Its leaf area index (LAI) measured with the LAI-2200c sensor (LAI-2200 plant canopy analyzer, Li-Cor Inc., Lincoln, NE, USA) was 2.6 and 0.8 during the leafed and leafless seasons, respectively (Zabret and Šraj, 2021b). It grows throughout Europe, except in Spain, Portugal, and Greece, and is naturally found in Slovenia (Kotar and Brus, 1999). The bark texture is smooth with an average measured thickness of 3 mm and a storage capacity of 0.7 mm (Zabret and Šraj, 2018, 2021b). Appreciated for its white bark and delicate canopy, it is a popular ornamental tree that is often found growing individually or in small groups (Kotar and Brus, 1999).

2.2. Measurements

Gross rainfall was measured at 10-minute intervals with a tipping bucket (0.2 mm/tip) rain gauge (Onset RG2-M) connected to an automatic data logger (Onset HOBO Event), which was installed in the open field area of the experimental plot. Precipitation data were divided into individual rainfall events separated by at least 4 h of dry periods, which were determined based on the observations from the field and previous measurements as the average length of time for the canopy to dry after the cessation of rainfall (Zabret and Šraj, 2018, 2021b). Additional meteorological data (referred to as atmospheric variables here), including air temperature (T), relative humidity (RH), mean wind speed (WS), wind direction (WD), and maximum wind gust (WG) were observed at the nearest weather station in Ljubljana–Bežigrad (Fig. 1a), which is 3 km away from the experimental plot. Vapor pressure deficit (VPD) was computed using the information about air temperature and relative humidity as employed by Nanko et al. (2016a). The meteorological data were archived at 10- and 30-minute intervals and are accessible for free on the Slovenian Environment Agency (ARSO) website (https://meteo.arso.gov.si/met/en/app/webmet). Based on the specific location of the meteorological station and of the city inside the Ljubljana basin, the measurements are regarded as representative of the entire city of Ljubljana and its outskirts (Nadbath, 2008; Zabret and

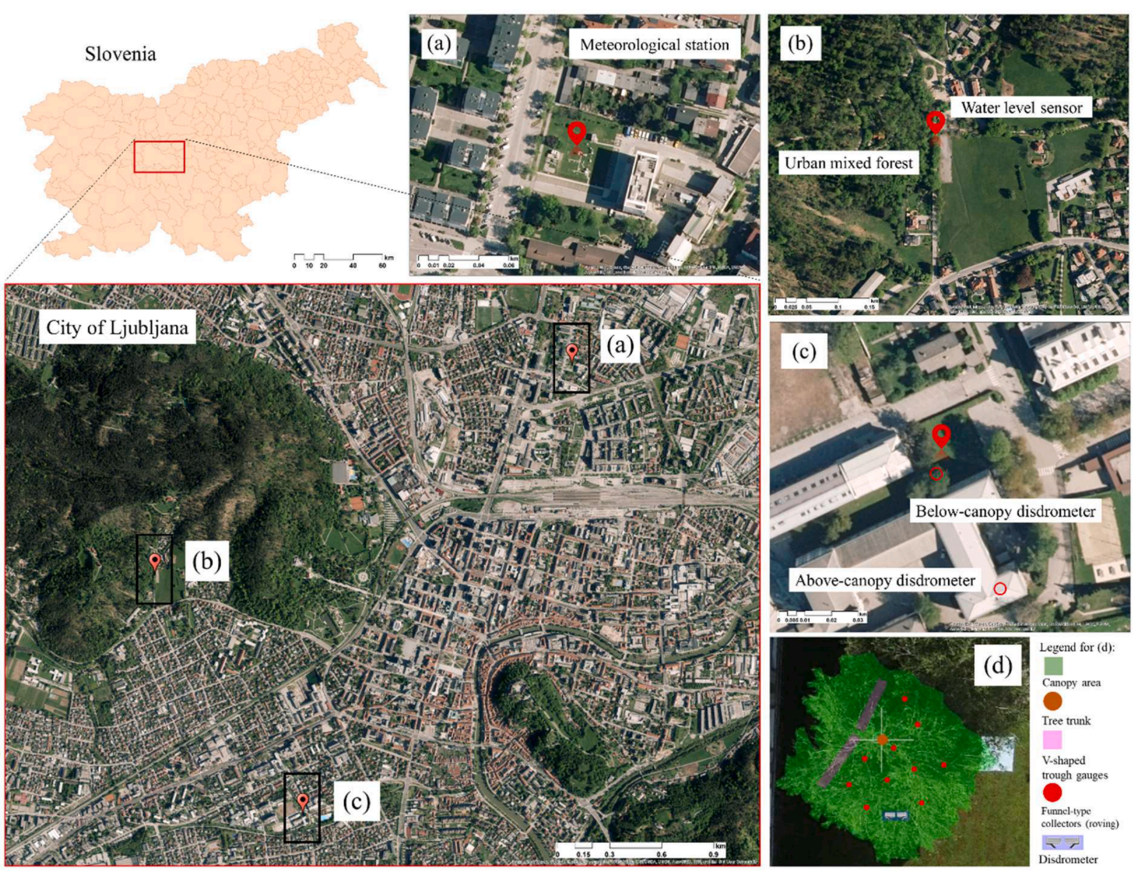

Fig. 1. Location of the study area: (a) Ljubljana-Bežigrad meteorological station, (b) water level sensor near the urban mixed forests, (c) experimental plot (for rainfall partitioning measurement and disdrometers above and below the birch tree canopy), and (d) schematic set-up of throughfall measurement.

Šraj, 2021a).

Throughfall measurements under the birch tree canopy were carried out both automatically and manually (Fig. 1d). The inherent spatial variability of throughfall is taken into consideration by combining fixed trough and roving funnel-type gauges for measurement (Bruijnzeel, 2000; Šraj et al., 2008; Carlyle-Moses et al., 2014; Zimmermann et al., 2014). A total of ten funnel-type throughfall collectors were positioned in a radial layout extending away from the tree trunk and randomly distributed after each rainfall event. We also placed two V-shaped steel trough gauges (0.75 m^2) below the canopy, where one of which was connected to a tipping bucket flow gauge (Unidata 6506G; 50 mL/tip) with an automatic data logger (Onset HOBO Event), while the other one was connected to polyethylene containers from which the data were collected manually after every rainfall event along with the roving gauges. On one hand, the stemflow from the birch tree was captured by a spiral-type gauge made of a halved rubber hose, which is attached to the tree trunk and draining into a tipping bucket gauge (Onset RG2-M, 0.2 mm/tip) connected to an automatic data logger (Onset HOBO Event). Moreover, water level was monitored at 10-minute interval using a pressure probe sensor (HOBO water level logger) deployed in a narrow creek of the landscape park of Tivoli, Rožnik, and Šišenski Hrib situated in the center of Ljubljana (Kermavnar and Vilhar, 2017), which is an urban mixed forest and approximately 1.7 km away from the study plot (Fig. 1). The creek is primarily receiving surface runoff from Rožnik hill which can be regarded as a natural catchment area (the closest to the research plot) with a large percentage of forest cover from different types of tree canopies. Its main outlet point joins one of the storm drainage systems of the city.

In addition to this, we installed a pair of OTT Parsivel disdrometers within the study plot, one on the rooftop of the nearby building to observe the rainfall characteristics above the canopy and another one below the birch tree canopy to sample throughfall drops, which enabled us to analyze the impact of the tree canopy on the characteristics and microstructure of rainfall. Hereafter, the above canopy measurements by Parsivel disdrometers are synonymously referred to as gross rainfall and the below canopy measurements are referred to as throughfall. Optical disdrometers measure the diameter, fall velocity, and the number of raindrops passing through a laser beam sensor of 54 cm^2. The measured particles at 1-min sampling resolution are stored in a 32 × 32 matrix of unequally spaced bins, ranging from 0.062 mm to 24.5 mm for drop diameter and 0.05 m/s to 20.8 m/s for fall velocity. Using these measured variables, we calculated the rainfall intensity above (gross rainfall) and below the birch tree canopy (throughfall). One should note that the first two diameter classes having a size smaller than 0.25 mm are always forced to zero by the manufacturer because they are outside the measurement range of the device due to the low signal-to-noise ratio (OTT, 2008). Aside from this, additional data filtering has been applied to the 1-minute disdrometer data by excluding the drop diameter greater than 7 mm from the analysis since the largest raindrop reported in the literature is around 8 mm (Beard et al., 1986). This filtering was employed to minimize the potential effect of measurement errors (Ma et al., 2019; Nanko et al., 2016b; Petan et al., 2010; Zhang et al., 2019) that can occur when two (or more) coincident drop particles would appear as one large raindrop when passing through the measuring area of the disdrometer (Bezak et al., 2021). This will cause overshooting in the peak intensities of rainfall as observed by Lanzinger et al. (2006).

2.3. Data analysis

A total of 92 rainfall events (excluding snow events) of varying magnitude and duration were observed in one year period of measurements from August 2021 to August 2022. For this study, rainfall events with an accumulated amount of less than 2 mm were eliminated because these events did not generate adequate throughfall amounts, leaving only 63 events for the analysis. The observation period was divided into two primary seasons according to the phenology of a deciduous tree canopy in Slovenia defined by Kermavnar and Vilhar (2017): (a) the leafed period, from May 1 to October 31; and (b) the leafless period, from November 1 to April 30. From these considered events, 39 of which occurred in the leafed season of birch tree and 24 events during its leafless period. For each rainfall event, the canopy interception (I_c) by birch tree was calculated as the difference between the gross rainfall (P_g) and the sum of throughfall (T_f) and stemflow (S_f) as shown in the following equation (Eq. (1)).

$$I_c = P_g - -(T_f + S_f) \tag{1}$$

The rainfall intensity, I (mm/h) for every 1-minute sampled data was calculated as the sum of raindrop volumes in all valid drop size classes i (<7 mm), assuming that these drops passing through the detection area ($A = 5400$ mm^2) are spherical in shape. Here, we used the formula (Eq. (2)) of Petan et al. (2010) to determine the 1-minute rainfall intensity above and below the tree canopy. Hereinafter, the term rainfall intensity under the tree canopy also refers to throughfall intensity and both terms are used interchangeably in the paper. While their respective DSD was characterized based on drop relative volume ratio (Eq. (3)) which is widely applied in throughfall studies (Levia et al., 2017).

$$I = \frac{\pi}{6A\Delta t}\sum_i n_i \frac{1}{D_{b,i} - D_{a,i}} \int_{D_{a,i}}^{D_{b,i}} D_i^3\, dD \tag{2}$$

$$V(D) = \frac{\sum_i^c n_i V_i}{V_{total}} \tag{3}$$

where n_i is the number of detected raindrops in the size class i, D_i (mm) is the drop class diameter ranging from $D_{a,i}$ to $D_{b,i}$, Δt is the sampling time (1/60 h), V_i is the raindrop class volume, and V_{total} is the cumulative volume of all drops. As for the water level data, we obtained the date and time from which there was a response in the behavior of the water level in the creek due to rainfall events and matched them to the observed rainfall data in the research plot. Using this information, the corresponding peak water level recorded for every rainfall event was extracted for the succeeding statistical analysis.

Linear regression analysis was employed to evaluate the degree of association between the considered variables with statistical significance assessed by one-way analysis of variance (ANOVA). While a two-sampled *t*-test was performed to determine if there is a statistically significant difference exists between leafed and leafless periods. Statistical significance was set at $p < 0.05$. For further analysis, five atmospheric parameters (T, VPD, WS, WD, WG) were selected as predictor variables for their probable functional relevance to the attenuation of rainfall intensities below the birch tree canopy, which is expressed as the ratio of throughfall intensity and gross rainfall intensity (response variable). The effect of gross rainfall intensity on throughfall intensity is muted by forming a ratio and from which the influence of the five atmospheric variables was investigated. Disdrometer-derived rainfall intensities were aggregated into a 30-minute interval to synchronize with the meteorological data from the Ljubljana-Bežigrad station. The analysis was carried out using a boosted regression tree (BRT) model approach. BRT is a non-parametric machine learning method that creates a large number of regression trees by bootstrapping subsamples of a given dataset (De'Ath, 2007; Elith et al., 2008). It combines the decision tree algorithms and boosting methods to improve the accuracy of the model (Elith et al., 2008). In this study, BRT analysis was performed in R software version 3.3.0+ (R Core Team 2021) using the "gbm" package version 2.1.8.1 (Greenwell et al., 2022), which is an implementation of extensions to Freund and Schapire's AdaBoost algorithm and Friedman's gradient boosting machine (Greenwell et al., 2022). Models were fitted using the gbm.step function and a Gaussian response type (aimed at minimizing squared error), with a learning rate of 0.0001, bag fraction of 0.5, tree complexity of 5, and a minimum number of trees of 1500. As part of the result, the expected sensitivity of our response variable to the changes in the predictors was quantified based on the relative influence (RI) of each predictor variable, which is specified by its importance value in the BRT models. The RI is scaled according to the number of independent variables so that the sum is equal to 100, with higher values indicating a greater influence on the response variable (Friedman, 2001). Additionally, partial dependence plots (PDP) were used to visualize how the response variable is affected by a certain value of the explanatory variable of interest (Friedman, 2001; Friedman and Meulman, 2003).

3. Results and discussion

The total amount of rainfall delivered during the measurement period encompassing the leafed and leafless conditions of the birch tree canopy was 986.4 mm representing 71.1 % of the average annual precipitation. This amount of rainfall is a consequence of severe precipitation deficit during the first two quarters of 2022 (ARSO, 2022), which continued to worsen during summer as the sequence of heatwaves aggravated the extreme drought conditions across Europe (Toreti et al., 2022). The Slovenian Environment Agency has also reported that the country was in grip of severe drought particularly in the greater Ljubljana area due to the lack of rainfall and extremely high temperatures (ARSO, 2022). After filtering the observed rainfall data (Section 2.3), the amount of rainfall was 922.8 mm from which 51.9 % was registered during the leafed season and the remaining 48.1 % during the leafless period. The average gross rainfall depth across all events within the investigated period was 14.4 mm, with individual events ranging from 2.0 to 87.6 mm. As reflected in the histogram of recorded events (Fig. 2), a large fraction of single rainfall events consisted of depths lower than 5 mm (31.7 %) and contributed to a total of 63.8 mm (6.9 % of the cumulative amount during the measurement period) whereas the frequency of larger events (> 20 mm) is less than 10 % but contributed a total of 525.4 mm (56.8 % of the cumulative amount). And for the succeeding analysis, we decided to further categorize them into four groups according to rainfall amount: G1 for ≥ 10 mm, G2 for > 10–20 mm, G3 for > 20–40 mm, and G4 for > 40 mm. As a result, we can see from Table 1 that more than half of the analyzed rainfall events fall in category G1, which consists of events with rainfall amounts of 2–10 mm, while extreme events (> 40 mm, G4) constitute less than 7 % of our data. Despite this, G4 contributed almost 25 % to the total rainfall amount because it consisted of events with an accumulated rainfall depth exceeding the 90th percentile event. Thus, the statistics over these four largest events are associated with large uncertainty, which may affect the results (e.g., regression) and more data would be needed in further studies. The highest rainfall amount of 87.6 mm within 7.6 h was recorded during the sudden storm event on September 29, 2021, which caused severe pluvial flooding in some parts of the city of Ljubljana. Average rainfall event intensities varied from 0.4 to 20.3 mm/h, with a single maximum instantaneous intensity of 49.9 mm/h that was reported on July 5, 2022 (40.6 mm in less than 1 hour).

3.1. Rainfall partitioning

The relationships of gross precipitation with the following rainfall partitioning components are presented in Figs. 3–5, showing that event throughfall, stemflow, and interception increased linearly with rainfall amount. The largest throughfall, stemflow, and interception values that we can observe from their respective regression plot occurred during the 7.6-hour storm event with 87.60 mm of accumulated gross rainfall amount, which influenced the regressions of the leafed period, particularly increasing the slope coefficient by a certain magnitude (1.3 % for Tf, 33 % for Sf, and 5.8 % for interception). Fig. 6 then describes the partition of total gross rainfall for predefined rainfall groups (G1, G2, G3, G4). Throughfall accounts for 74 % of the total gross precipitation observed within the study period, which is consistent with the measured values reported by other studies on the same tree species in urban areas (e.g., Livesley et al., 2014; Xiao and McPherson, 2011; Xiao et al., 2000; Zabret et al., 2018). Thus, throughfall exhibited a strong and statistically significant positive correlation with gross rainfall ($p < 0.001$, Fig. 3a), irrespective of the phenoseasons. This high degree of interdependence between gross rainfall and throughfall is a general consensus across all rainfall partitioning studies, both in the natural forest systems and urban areas (e.g., Carlyle-Moses et al., 2014; Kermavnar and Vilhar 2017; Livesley et al., 2014; Siegert and Levia, 2014; Šraj et al., 2008; Staelens et al., 2008; Xiao and McPherson, 2011; Zabret and Šraj, 2019a). Though there was a small difference in the throughfall values between phenoseasons, as also observed by some other researchers (e.g., Mużyło et al., 2012; Siegert and Levia, 2014; Staelens et al., 2008), it is still noticeable that leafless period generates more throughfall than the leafed period and a statistically significant difference exists ($p < 0.01$) between the two periods (Fig. 3b). Additionally, it can be observed from Fig. 6a that the amount of throughfall increases with rainfall amount, which is particularly emphasized for the events with more than 40 mm of rain.

Although stemflow only constitutes 0.4 % of the total gross rainfall, it yielded a moderate yet statistically significant ($p < 0.001$) linear correlation with rainfall in both phenoseasons. Our measured stemflow, like other studies conducted on deciduous and evergreen trees (e.g., Livesley et al., 2014), represents only a small proportion of the net precipitation reaching the ground. As depicted in Fig. 6b, the quantity of stemflow was much smaller across rainfall groups and occurred less frequently compared to throughfall. The stemflow delivered by group 1

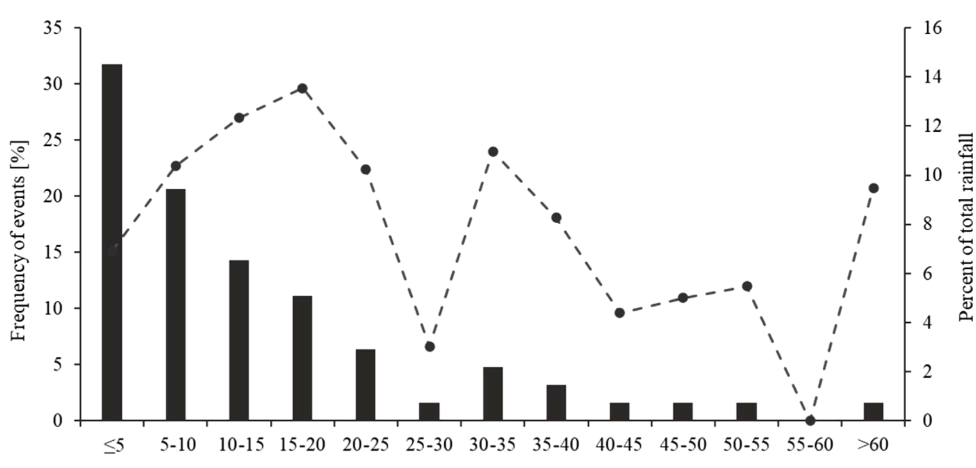

Fig. 2. Frequency distribution of rainfall events recorded during the measurement period.

Table 1
Statistical summary of the characteristics of different groups of rainfall events.

Rainfall Group	Number of events (total rainfall in mm)	Mean rainfall amount ± Std. dev. [mm]	Maximum rainfall amount [mm]	Coefficient of Variation	Duration ± Std. dev. [h]	Mean storm intensity ± Std. dev. [mm/h]
G1	33 (151.4)	4.6 ± 2.3	8.6	0.49	3.2 ± 2.6	3.5 ± 4.5
G2	16 (246)	15.4 ± 2.9	19.8	0.19	9.2 ± 5.9	3.3 ± 3.3
G3	10 (300.4)	29.9 ± 6.0	39.2	0.20	17.4 ± 6.5	2.0 ± 1.0
G4	4 (225)	56.3 ± 18.4	87.6	0.33	18.6 ± 15.2	16.1 ± 19.9

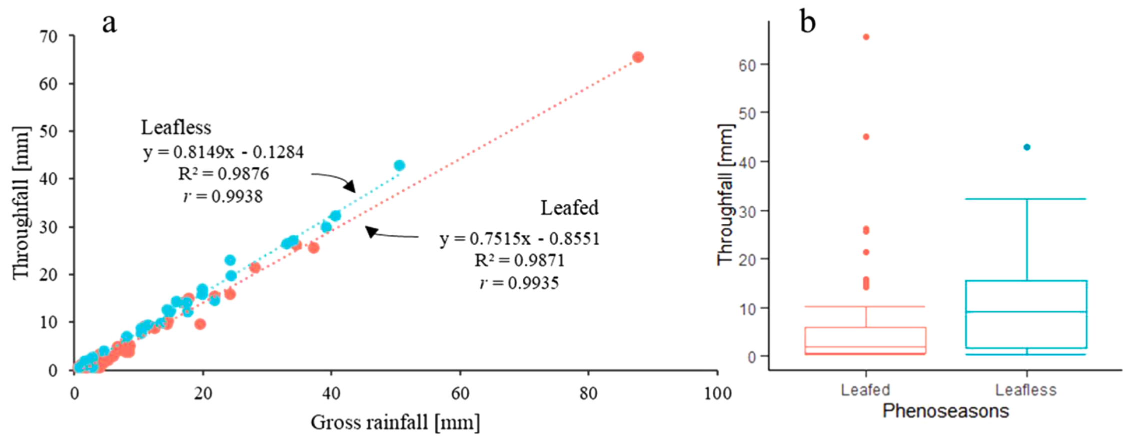

Fig. 3. (a) Relationship between gross rainfall and throughfall; (b) boxplot showing the amount of throughfall according to two distinct canopy phenoseasons. Boxplot: The horizontal line inside the box denotes the median value; the upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively; and whiskers represent values within 1.5 times the interquartile range. Filled dots plotted separately and outside the range of the upper whisker are outliers.

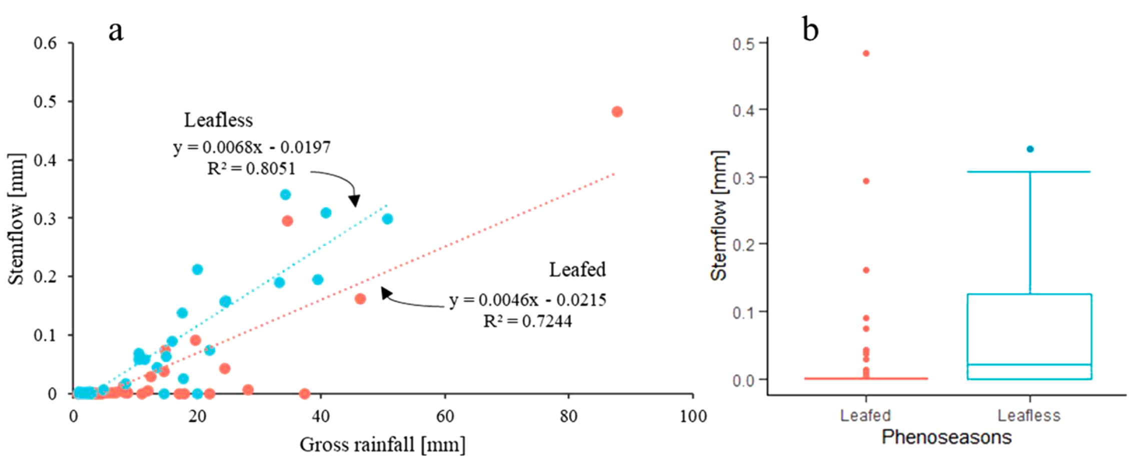

Fig. 4. (a) Relationship between gross rainfall and stemflow; (b) boxplot showing the amount of stemflow according to two distinct canopy phenoseasons. Boxplot: The horizontal line inside the box denotes the median value; the upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively; and whiskers represent values within 1.5 times the interquartile range. Filled dots plotted separately and outside the range of the upper whisker are outliers.

(G1) with a rainfall amount ranging from 2 to 10 mm was among the smallest (Fig. 4b) because the stemflow response of birch trees is primarily governed by the amount of rainfall per event, i.e., larger events generate more stemflow volume (Siegert and Levia, 2014; Staelens et al., 2008; Xiao et al., 2000; Zabret and Šraj, 2021a; Zhang et al., 2020). Some rainfall events smaller than 10 mm did not produce measurable values of stemflow, which explains the lower number of events reported. Zabret and Šraj (2019a) mentioned that at least 8 mm of rainfall is needed to initiate continuous stemflow of birch tree and in their following study, Zabret and Šraj (2021a) found that stemflow becomes negligible for shorter and more intense events with less than 5 mm of rainfall. Furthermore, the obtained correlation coefficient between stemflow and rainfall in this study is comparable to the values reported by other researchers for different deciduous trees. For instance, the correlation coefficient for an American beech (Fagus grandifolia Ehrh.) was 0.76 during the leafless season and 0.50 during the leafed season while for a common tulipwood (Liriodendron tulipifera L.), it was 0.85 and 0.80, respectively (Siegert and Levia, 2014). Staelens et al. (2008) reported a correlation of 0.90 and 0.88 for a European beech tree (Fagus sylvatica L.) in Belgium; 0.87 and 0.74 for a downy oak tree (Quercus pubescens Willd.) in Spain (Mużyło et al., 2012) during the leafless and leafed periods, respectively. Similarly, our study also showed that a significantly higher amount of stemflow is produced during the leafless period than in the leafed period which was also observed in previous studies (Šraj et al., 2008; Zabret et al., 2017, 2019a). This is because the presence of leaves favors more interception in the canopy and prevents branches from collecting rainwater and conducting stemflow through the trunk, as explained by Staelens et al. (2008).

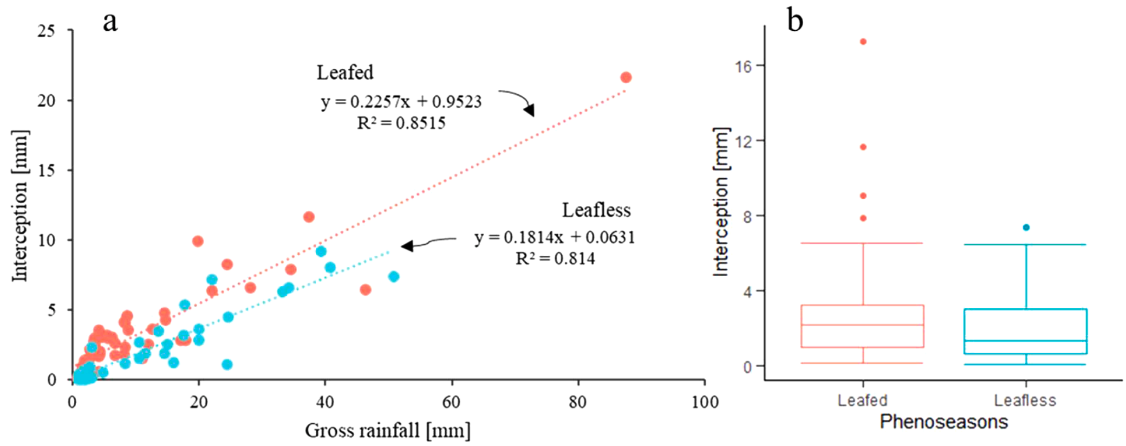

Fig. 5. (a) Relationship between gross rainfall and interception; (b) boxplot showing the amount of interception according to two distinct canopy phenoseasons. Boxplot: The horizontal line inside the box denotes the median value; the upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively; and whiskers represent values within 1.5 times the interquartile range. Filled dots plotted separately and outside the range of the upper whisker are outliers.

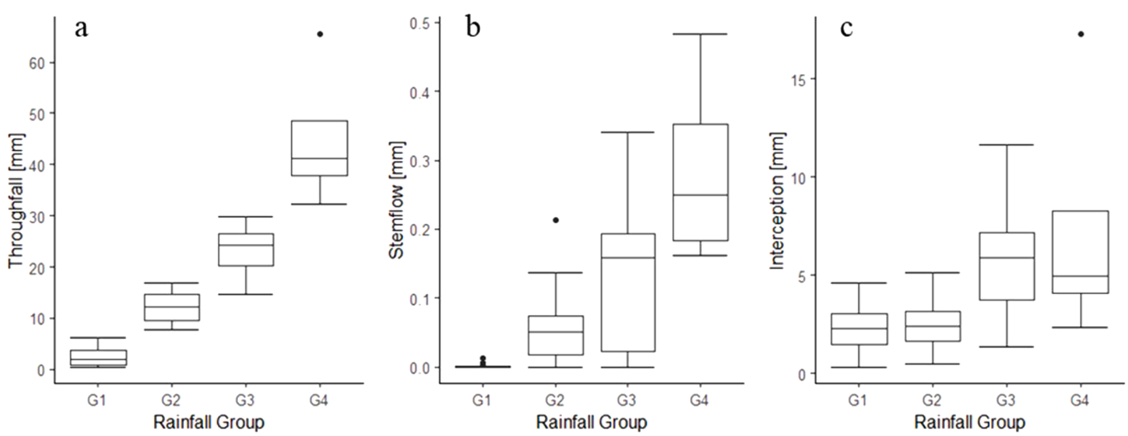

Fig. 6. Boxplot showing the amount of (a) throughfall, (b) stemflow, and (c) interception according to different predefined rainfall groups (G1, G2, G3, G4). Boxplot: The horizontal line inside the box denotes the median value; the upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively; and whiskers represent values within 1.5 times the interquartile range. Filled dots plotted separately and outside the range of the upper whisker are outliers.

The birch tree canopy intercepted 25.6 % of the total gross rainfall with a strong, statistically significant ($p < 0.001$) linear relationship with rainfall in both phenoseasons (R^2 is 0.81 for leafless and 0.85 for leafed). Notably, a seasonal pattern of interception can be observed when the retention capacity of the birch canopy was higher in the leafed period (46.9 % ± 23.0 %) and lower during the leafless period (20.4 % ± 16.1 %). These differences are also reflected in throughfall and stemflow values, which could be attributed to the presence and absence of leaves in the birch canopy. On average, the interception of the birch tree canopy was 35.4 % (± 25.0 %) of the gross rainfall per event. Our measured interception is slightly higher than the 3.5-year average interception of 23.7 % reported by Zabret and Šraj (2019b) for the same tree species and location. This could be explained by the differences in rainfall characteristics and meteorological conditions of the considered measurement periods, which are both included in the list of influential variables affecting the rainfall partitioning components (i.e., Tf, Sf, and interception) in trees (Livesley et al., 2014; Nanko et al., 2008; Xiao et al., 2000; Yu et al., 2022; Zabret et al., 2018; Zabret and Šraj, 2019b, 2021a; Zhang et al., 2023). Moreover, our reported proportion of intercepted precipitation by the birch tree is within the measured values reported for other deciduous trees in urban environments. An average interception of 21 % was observed in an open-grown beech tree (Fagus sylvatica L.) (Staelens et al., 2008), 25.2 % in ginkgo biloba (Ginkgo biloba L.) (Xiao and McPherson, 2011), 22.7 % in white siris tree (Albizia procera (Roxb.) Benth) (Nytch et al., 2019), and 29 % in Sydney blue gum (Eucalyptus saligna) street strees (Livesley et al., 2014). Looking closely at the interception of different rainfall groups (Fig. 5b), the average amount of interception was 51.1 % (± 25.4 %), 21.3 % (± 6.8 %), 20.3 % (± 7.6 %), and 18.3 % (± 5.0 %) for G1, G2, G3, and G4, respectively. The interception capacity of the birch canopy, as a percentage of gross rainfall, decreases gradually with rainfall amount until it reaches a minimum value of 13.9 % in case of events delivering more than 40 mm of rain. In this case, it would be crucial to investigate the interception of tree canopies and other relevant processes (e.g., infiltration) with more focus on large rainfall events (e.g., > 40 mm) in future studies.

3.2. *Drop size distribution of gross rainfall and throughfall*

The rainfall partitioning by tree canopies does not only modify the amount of rainfall reaching the ground but also the number, size, and velocity of raindrops passing through the canopy. Studies have shown that drop size distribution (DSD) of throughfall changes between and within the rainfall event due to several factors including the vibration on the leaves caused by the wind and the coalescence and/or splitting of drops on the canopy (Lüpke et al., 2019; Levia et al., 2019, 2017).

During the entire monitoring period, around 7.9 million drops were detected by the OTT Parsivel disdrometer installed above the birch tree canopy, while the disdrometer below the canopy registered approximately 6.6 million drops from the same rainfall events, predictably indicating that the foliage coverage reduces the total number of drops detected at the ground level by 16.4 % (Fig. 7a). This observation is slightly lower than the 20 % reduction obtained by Zore et al. (2022) over the period of 14 months for the same experimental area and tree species, but for a different experimental time period. Some studies also reported a reduction in the number of raindrops owing to the effect of canopy interception. Compared with gross rainfall, the number of throughfall drops was 16.3 % lower beneath a masson pine (Li et al., 2019), more than 50 % lower under the maize (*Zea mays* L.) canopy (de Moraes Frasson and Krajewski, 2011), and 5.5 times lower below the Japanese cypress tree (*Chamaecyparis obtusa*) (Nanko et al., 2004). However, it is worth noting that the differences in the architectural characteristics of vegetation canopies exist, and such further information may offer additional explanations in the comparison of values. Thus, as reported by Lüpke et al. (2019), some individual events that registered a higher number of throughfall drops may indicate significant variability in the drop size distribution of throughfall during the individual events. Moreover, the highest concentration of throughfall drops in our study occurred in the first classes of drop diameter for all predefined rainfall groups, as also observed in other studies (e.g., Brasil et al., 2022; de Moraes Frasson and Krajewski, 2011), which can be explained by the influence of the canopy in splitting the raindrops into smaller drop sizes (Levia et al., 2017; Lüpke et al., 2019). Nearly 90 % of the overall number of throughfall drops from the considered rainfall events have a diameter of less than 1 mm and 85 % in the case of raindrops above the canopy. It is hypothesized from this observation that drop splitting overcompensates the merging of smaller drops and the genesis of larger drops.

Fig. 7b depicts the DSDs of gross rainfall and throughfall based on the relative drop volume ratio. It shows that drops with diameters between 1 and 2 mm were more abundant than any other diameter classes. Specifically, the DSD plots reveal that the peaks corresponding to the relative volume ratio of drops smaller than 2 mm were higher for throughfall than for gross rainfall. And the relative volume of drops smaller than 2 mm accounted for 61.5 % of the cumulative raindrop volume and 80 % of the throughfall drops' relative volume. Conversely, drops larger than 2 mm represented less than 1 % of the drop counts for both gross rainfall and throughfall, but constituted 38.5 % and 19.9 % of the volume of rainfall and throughfall drops, respectively. Furthermore, the DSD of gross rainfall indicates that the relative volume of drops exceeding 2.75 mm in diameter increased continuously until 6.5 mm, with a corresponding increase in relative volume ratio from 3.7 % to 8.0 %. This specific observation could be attributed to high rainfall intensity events as described by Levia et al. (2017). In contrast, some researchers have argued that the decrease in throughfall drop counts results in larger drop sizes and DSD metrics due to coalescence in the canopy (e.g., Li et al., 2019; Lüpke et al., 2019; Nanko et al., 2006).

Consistent with the findings of Brasil et al. (2022) and Li et al. (2019), our study also demonstrated that the drop size diameter has more influence in determining the drop volume of gross rainfall and throughfall than the recorded number of drops. Even though the presence of the canopy facilitates the bifurcation process occurring during the rainfall event, which leads to a high frequency of smaller throughfall drops, the cumulative volume of raindrops is greater than that of the throughfall drops. Brasil et al. (2022) have a similar observation under the deciduous *Mimosa caesalpiniifolia, and Aspidosperma pyrifolium* trees, especially for events with a rainfall amount of less than 5 mm and explained that this was mainly due to the smaller drop diameter composition of throughfall. We have additionally observed that the number of drops per event is strongly correlated to the total amount of gross rainfall per event, regardless of the phenoseasons. These observations demonstrate that not only does the amount of throughfall increase with the total rainfall but also the number of throughfall drops.

3.3. The influence of tree canopy on throughfall intensity in an urban environment

The interception process of tree canopies has been shown to reduce the intensity of gross rainfall which has a particular effect on the stormwater flow mechanisms and in minimizing the erosive power of raindrops. Despite this, the research comparing and investigating the rainfall intensity below an urban tree canopy cover with gross rainfall intensity is still limited (e.g., Kuehler et al., 2017). In this study, the differences in the intensities of rainfall above and beneath the birch tree canopy were analyzed using the 1-minute disdrometer data for 63 rainfall events, grouped into 4 categories as described in Table 1. The aggregated mean of 1-min rainfall intensities per event above and below the birch tree (Fig. 8a) showed a statistically significant difference during the leafed and leafless periods ($p < 0.01$). It is evident that the birch tree attenuates the intensity of rainfall as it traverses the canopy, which is also observed in some other studies (Brasil et al., 2020; Liu and Zhao, 2020; Keim and Skaugset, 2003; Trimble and Weitzman, 1954); however, the amount of reduction varies depending on the phenoseason, rainfall amount, and duration. Across all rainfall events, the mean throughfall intensity is 57.3 % and 49.2 % lower than the gross rainfall intensity during the leafed and leafless periods, respectively (Fig. 8b). Similar to the findings reported by Brasil et al. (2020), the Caatinga deciduous vegetation reduced the rainfall intensity by 30–40 %. They

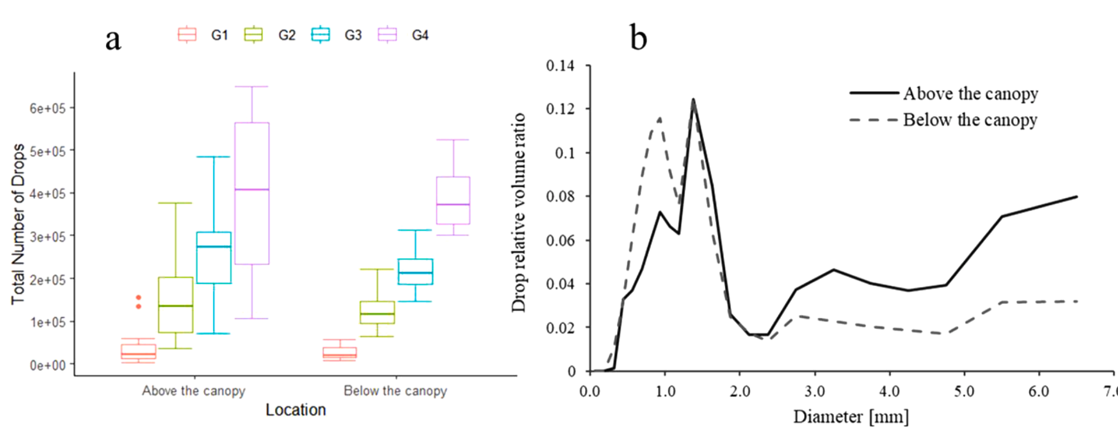

Fig. 7. (a) Boxplot showing the total number of drops for gross rainfall and throughfall for different rainfall groups (G1, G2, G3, G4); (b) their DSD based on drop relative volume ratio. Boxplot: The horizontal line inside the box denotes the median value; the upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively; and whiskers represent values within 1.5 times the interquartile range. Filled dots plotted separately and outside the range of the upper whisker are outliers.

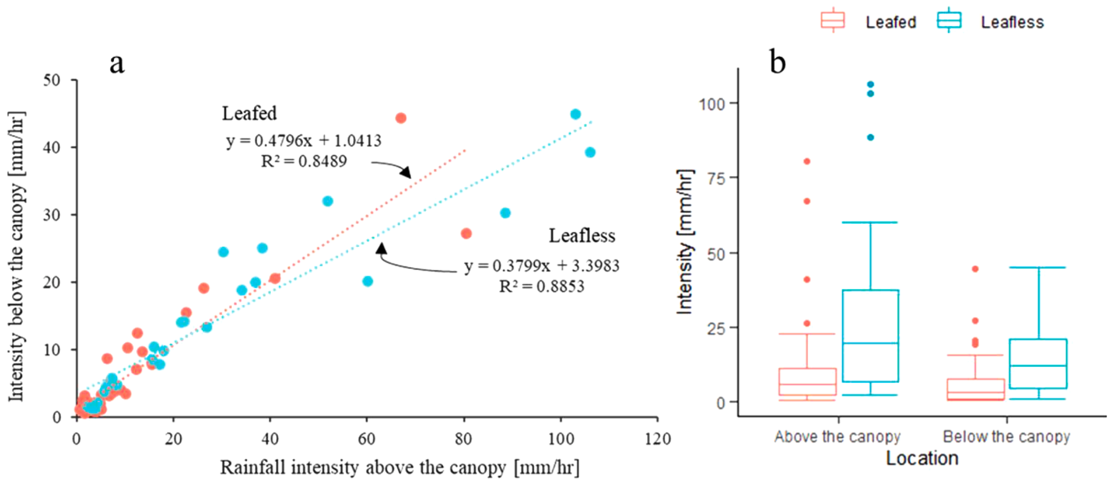

Fig. 8. (a) Relationship between; (b) boxplot of the aggregated mean of 1-min rainfall intensities (mm/h) above and below the birch tree canopy for two pheno-seasons. Boxplot: The horizontal line inside the box denotes the median value; the upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively; and whiskers represent values within 1.5 times the interquartile range. Filled dots plotted separately and outside the range of the upper whisker are outliers.

observed that for an average rainfall intensity of 1.0–31.2 mm/h, the corresponding mean throughfall intensity recorded under the canopy was 0.6–19.5 mm/h (Brasil et al., 2020). Furthermore, the linear regression plot in Fig. 8a shows that the 1-min intensity of throughfall is positively correlated with the intensity of rainfall above the canopy for both foliation periods ($p < 0.001$). This relationship demonstrates that we can reasonably estimate the below-canopy rainfall intensity for open-grown birch trees using the disdrometer-derived rainfall rate above the canopy.

The deciduous pattern of the birch tree also dampened the average maximum 10-minute intensities of rainfall after passing through the canopy by 11.6–83.8 % (43.6 % ± 19.5 %) during the leafed period and 13.1–74.2 % (40.2 % ± 14.8 %) in the leafless period. This difference is due to the presence and absence of foliage in the birch tree canopy. It indicates that the reducing effect is related to the rainfall interception process since a birch canopy in the leafed season can store and retain more rainfall than a bare canopy. This is substantiated by the linear dependence of throughfall intensity with the amount of throughfall and interception ($p < 0.001$, Fig. 9b), expressing the significant effect of tree canopy on temporarily storing rain, thus reducing throughfall amount and its intensity. Also, the percentage of reduction in the rainfall intensity below the canopy decreases with rainfall amount (Fig. 10). An

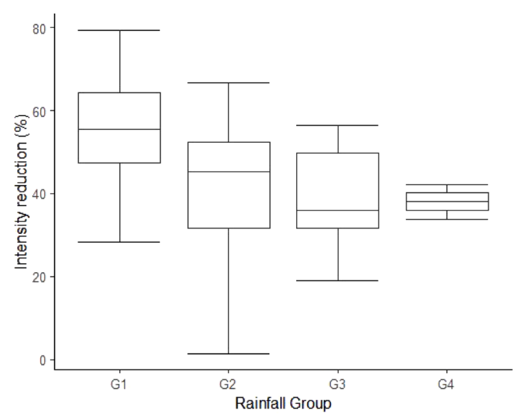

Fig. 10. Boxplot showing the percentage reduction in rainfall intensity due to the canopy for different rainfall groups (G1, G2, G3, G4). Boxplot: The horizontal line inside the box denotes the median value; the upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively; and whiskers represent values within 1.5 times the interquartile range. Filled dots plotted separately and outside the range of the upper whisker are outliers.

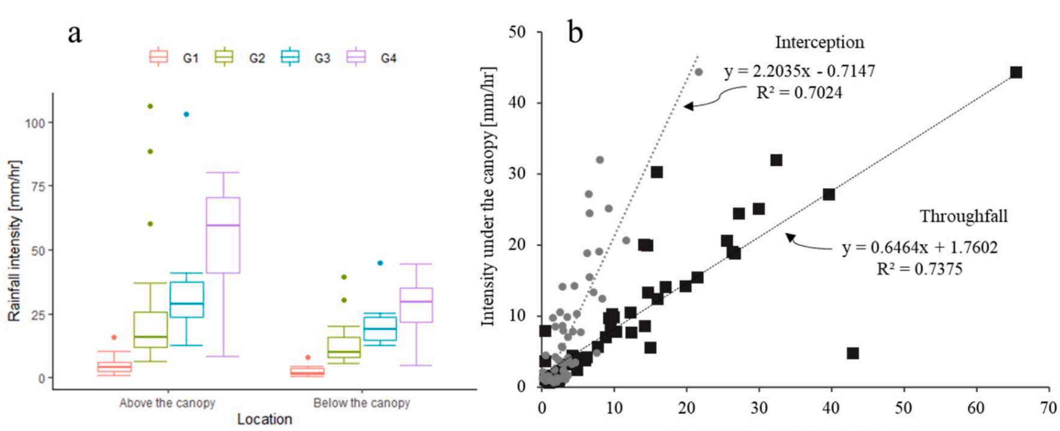

Fig. 9. (a) Boxplot of the aggregated mean of 1-min rainfall intensities (mm/h) above and below the birch tree canopy for different rainfall groups (G1, G2, G3, G4); (b) relationship of throughfall intensity with throughfall and interception amount. Boxplot: The horizontal line inside the box denotes the median value; the upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively; and whiskers represent values within 1.5 times the interquartile range. Filled dots plotted separately and outside the range of the upper whisker are outliers.

average reduction of 54.7 % (± 13.9 %), 41.4 % (± 17.7 %), 38.9 % (± 11.6 %), and 38.0 % (± 3.3 %) was observed in the rainfall intensity of G1, G2, G3, and G4, respectively. Similarly, the peak 10-minute intensity of events with less than 40 mm of rain was reduced, on average, by 40 %, and 31 % for extreme events larger than 40 mm. The highest reduction of 83.81 % in the maximum 10-minute intensity was observed during the storm event on July 5, 2022, with an accumulated rainfall of 46.2 mm in less than an hour. These results are in accordance with the findings presented by other researchers for specific forest canopies. The study of Trimble and Weitzman (1954) confirmed that under the hardwood forest canopy, the average maximum 15-minute rainfall intensity of between 2.5–19.0 mm/h was reduced to 0.9–16.5 mm/h during summer and 2.2–15.5 mm/h during winter. Their study also revealed that for high-intensity rainfall events (25.4–76.2 mm/h), the maximum reduction is lower than 20 %. Seconded by the findings of Keim and Skaugset (2003), the peak instantaneous intensities of a late-summer rainfall event in Oregon, USA were damped by 21–52 % and delayed by up to 2 min under a young forest stand with a homogenous closed canopy. Brasil et al. (2020) also found out that the average maximum 5-, 30-, and 60-minute throughfall intensities were considerably lower than those of gross rainfall for both phenoseasons. Additionally, the ratio of throughfall intensities to gross rainfall intensities reaches the lowest value at 0.3 (i.e., for the 5-minute maximum intensity) during the leafed period and nearly 0.9 during the leafless period. This demonstrates a greater influence of the vegetation in moderating the intensities of throughfall when the canopy presented a full leaf density, as discussed by Brasil et al. (2020). Another point worth noting is that we observed a delay in the peak intensities, but the lag time still needs to be explored and verified in more detail. However, observing the intensity of throughfall indicated that the birch tree effectively reduced the rainfall intensity, particularly in the presence of foliage.

Furthermore, the result of the BRT analysis revealed that among the examined atmospheric parameters, vapor pressure deficit (40.0 %) exerted the highest relative influence (RI) on the ratio of throughfall intensity to gross rainfall intensity, followed by air temperature (23.0 %) and wind direction (20.3 %). According to some studies, vapor pressure deficit (VPD) and air temperature are among the recognized variables that affect throughfall and canopy interception, next to rainfall characteristics (Nanko et al., 2016a; Mateos and Schnabel, 2001; Staelens et al., 2008; Zabret et al., 2018; Zabret & Šraj, 2021b). Since there is an existing interdependence of the intensities below the canopy with the amount of throughfall and as part of the interception process (Fig. 9b), it is more understandable to associate the influence of such atmospheric parameters with the rainfall partitioning processes rather than focusing on the intensity of throughfall alone. Additionally, for a geographical location with observed seasonal changes, these two parameters are closely linked with each other and to the season of the year, which also corresponds to the phenoseasons of deciduous species (Levia and Herwitz, 2000).

In order to assess the relevance of our predictor variables to the response variable, we used the partial dependence plots (PDPs) generated from the BRT model, as shown in Fig. 11b. These plots allow us to visualize the individual effect of each atmospheric variable (predictor) on the ratio of throughfall intensity to gross rainfall intensity (response), as well as their dependence pattern. From the plots, it is evident that our response varies significantly for any given value of the predictor. This suggests that the relationship between the atmospheric variables and the ratio of throughfall intensity to gross rainfall intensity is rather non-linear, non-monotonic, and more complex. Nevertheless, the first two profiles in Fig. 11b indicate that rainfall events occurring in low VPD and very low air temperatures (~0–1 °C) generate higher throughfall intensities, resulting in a higher ratio as seen in the plots. The partial dependence profile of VPD demonstrates that there is an inverse relationship between VPD and throughfall intensity as a fraction of gross rainfall intensity, at least within a certain range of VPD. After a gradual increase in VPD, the response subsequently reaches a plateau (VPD is ~3.5 kPa), suggesting that a further increase in VPD would not necessarily lead to a significant change in the ratio between the intensities of throughfall and gross rainfall. Similarly, the PDP of temperature exhibits two general responses that vary slightly with increasing temperature. First, the ratio of intensities is high at temperatures below or close to the freezing point (0 °C) and beyond this point, the response starts to decline gradually. In the second response, this ratio rapidly increases to a maximum when the temperature is around 9–11 °C, which is followed by a relatively stable relationship when temperature variations above ~14 °C do not significantly affect the ratio.

Weather conditions characterized by low VPD and low air temperature are generally observed during the leafless state of the canopy (winter season) with low interception capacity, resulting in a higher throughfall occurrence (Brasil et al., 2020; Mużyło et al., 2012; Staelens et al., 2008; Zabret et al., 2018; Zabret and Šraj, 2021b) with an intensity that may be higher than the gross rainfall. Moreover, such meteorological conditions weaken the driving forces of the evaporation process, resulting in a lower evaporative demand of the tree canopy. In addition, the occurrence of air frost, due to atmospheric temperature plunging to or below 0 °C, and temperature inversion, which is prevalent in the city of Ljubljana (study area) during winter due to its location within the basin (Kikaj et al., 2019; Rakovec et al., 2002), can lead to freezing of the outermost layer of tree skeletons (stems, branches, and twigs) (Sakai and Larcher, 2012), affecting their ability to capture and intercept rainfall.

Whereas, according to the PDP of wind direction, it thus appears that

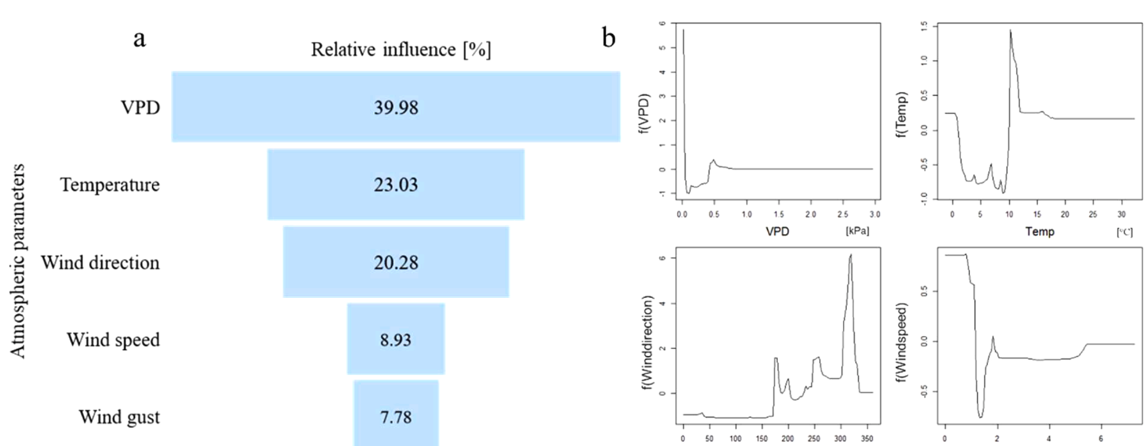

Fig. 11. (a) Relative influence of atmospheric parameters on the ratio of throughfall intensity and gross rainfall intensity; (b) partial dependence plots of the top four predictor variables according to their relative influence on the response.

winds originating from the north to south-southeast (0°−165°) do not have a significant effect on the ratio of throughfall intensity to rainfall intensity, as reflected by the relatively stable plot within this range. However, the ratio seems to exhibit dependence on the changes in wind direction from 180° (south) onwards. Winds blowing from the south, south-southwest (between 180°−225°), west (270°), and northwest (315°) have a stronger positive effect on the ratio and such wind directions may induce throughfall to have higher intensity than the gross rainfall. As there is limited research and field observations investigating the impacts of wind direction on rainfall partitioning, it is possible that specific wind directions with higher wind speeds may alter the interception and throughfall generation processes (Levia et al., 2017). On the other hand, the relationship between wind speed and throughfall intensity-to-rainfall intensity ratio is quite similar to what is observed in VPD. Initially, variations in the wind speed (~0.1–0.7 m/s) only have minimal effect on the throughfall intensity-to-rainfall intensity ratio. However, as wind speed gradually increases, this ratio declines until it reaches a minimum point. Afterward, the ratio begins to steadily increase with wind speed (~1.5–2 m/s) until it levels off at wind speed beyond ~2.5 m/s. It indicates that the relationship of wind speed with the ratio becomes less significant. Hence, the general effect of wind speed causes foliage motion from sudden vibration and deflection of leaves and branches, which can disturb the intercepted water and behavior of throughfall, as described by Levia et al. (2017). Mean wind speed was found to reduce the throughfall drops (Nanko et al., 2006) and affect the median drop volume diameter of throughfall (Nanko et al., 2016a). It should be noted that the wind characteristics measured at the meteorological station may differ from the conditions at the research plot due to the micro-location differences in the city. However, Zabret and Šraj (2019a) reported that for wind speeds higher than 1.3 m/s, the wind corridor seems to appear from the south and southwest towards the northeast. While for lower wind speeds, the corridor arises in a different direction, from the south and southeast towards the northwest. Both directions are created on the edges of the nearby buildings and not in between them. Hence, the influence of the corridors seems to be minor, as the test observations of the rainfall in two locations at the experimental site (in the open and near the building) were performed. The Pearson correlation coefficient between the measured values from both gauges was 0.99 and no statistically significant differences in the measured rainfall amount at the two locations were found (Zabret et al., 2019b). Nonetheless, an in-situ measurement of wind characteristics would substantiate our findings and further this area of research. While we observed that there exists a relationship between meteorological variables and the ratio of throughfall intensity to rainfall intensity as indicated by the BRT model, it is important to note that this does not necessarily indicate direct causality. An additional experiment is needed to determine the final causal effects of the meteorological variables on throughfall intensity as capturing the influence of micro-meteorological conditions in event-based rainfall interception processes is rather complex.

3.4. The implication of rainfall intensity reduction under the canopy on the maximum water level

The corresponding maximum water level for every rainfall event was extracted from the water level data acquired in the narrow creek of Rožnik hill (see Fig. 1, Section 2.2). In this study, a linear regression equation was fitted to the observed maximum throughfall intensity and peak water level (Fig. 12). Their correlation indicates a statistically highly significant positive correlation ($R^2 = 0.76$, $p < 0.001$). Though this is rather a straightforward approach, their statistical relationship confirms that the rainfall intensity attenuation due to tree canopies has a significant effect on the peak water level of runoff, but further validation would be needed in this respect using hydrological modeling. The ability of tree canopies to retain and temporarily detain rainfall has moderated the intensity of throughfall as shown above, which could benefit the

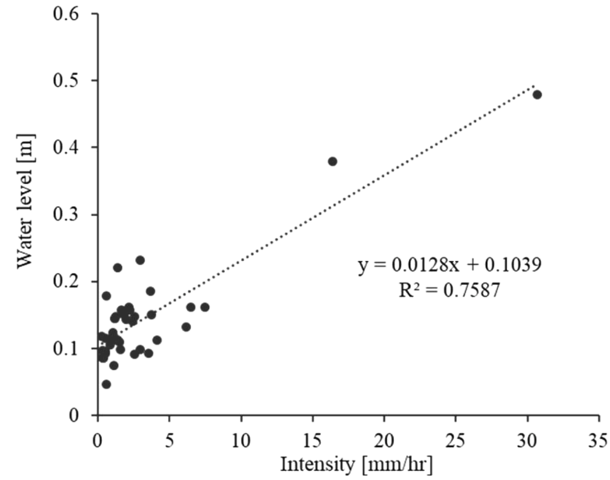

Fig. 12. Relationship of maximum 30-min throughfall intensity and peak water level of runoff per event.

drainage systems and other stormwater control measures by regulating the runoff volume, velocity, and peak water level (Berland et al., 2017; Kuehler et al., 2017; USEPA, 2017). The study of Zabret and Šraj (2019a) used a tree-planting scenario of 10 % of the parking lot area in Ljubljana, Slovenia, and hypothetically demonstrated that pine and birch trees could reduce the annual runoff by 7.3 % and 4.8 %, respectively. On the other hand, Bean et al. (2021) found that when impervious areas are covered with deciduous oak tree canopies, the runoff reduction per year is equal to 39 % while the annual reduction benefit provided by pine trees is only 4 %. As notably explained by Bean et al. (2021), urban areas can fully harness the hydrologic benefits of trees by increasing their canopy coverage (or planting them) in directly connected impervious areas (DCIAs) areas such as parking spaces, walkways, and streets. In this way, rainfall interception may greatly affect the outfall runoff quantities and promote soil infiltration, as discussed previously.

4. Conclusions

In this study, we investigated the potential reduction in rainfall intensity under an open-grown birch tree canopy by analyzing the simultaneous disdrometer data of gross rainfall and throughfall. Our rainfall partitioning measurements revealed that the average interception capacity of the canopy was twice as high during the leafed season, resulting in a 16.4 % reduction in the total number of drops and a 48.7 % reduction in cumulative drop volume. The higher frequency of smaller drops (< 2 mm) was due to the retention of some drops in the canopy and splitting of larger raindrops during the storm event. Notably, our study found a remarkable reduction in average event rainfall intensities under the canopy, with a higher reduction observed in the leafed period (50.2 %) than in the leafless period (41.6 %). The attenuation of the maximum 10-minute rainfall intensities was on average 43.6 % under a leafed birch tree and 40.2 % under a leafless state. The percentage of reduction differed significantly between phenoseasons and on average, followed a decreasing trend with the increasing amount of rainfall events. Our analysis also suggests that the ratio of throughfall intensity and gross rainfall intensity are mostly influenced by vapor pressure deficit and air temperature. However, the analysis of wind influence should be improved by considering micro-location differences within the city and with in-situ measurements.

Moreover, the correlation between the maximum throughfall intensity and the corresponding peak water level of runoff suggests that the reduction in rainfall intensity by the canopy may have a significant effect on the peak water level of runoff from every storm event. This finding may indicate that the combined effects of rainfall intensity attenuation and rainfall interception by deciduous trees in urban areas lead to a more controlled and gradual movement of water as it reaches the ground, allowing gradual infiltration rather than rapid runoff. Hence, the findings from this study could serve as an impulse to further investigate the interception process of different open-grown tree species in different urban landscapes, geographic settings, and climatic conditions. This will enhance our understanding of the dynamic interplay of urban tree canopies with rainfall and how to maximize their hydrological function in terms of controlling the stormwater runoff mechanisms such as volume reduction, delay in peak discharge, and other relevant processes.

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CRediT authorship contribution statement

Mark Bryan Alivio: Conceptualization, Formal analysis, Visualization, Writing – original draft. **Mojca Šraj:** Conceptualization, Writing – review & editing, Supervision. **Nejc Bezak:** Conceptualization, Writing – review & editing, Supervision, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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