

# Canopy precipitation interception in urban forests in relation to stand structure

Janez Kermavnar<sup>1</sup>  · Urša Vilhar<sup>1</sup>

Published online: 21 June 2017

© The Author(s) 2017. This article is an open access publication

**Abstract** Urban forests provide important ecosystem services. In terms of hydrological benefits, forest ecosystems in urban environments represent qualitative and quantitative filter for rainwater. We quantified the canopy interception in relation to urban forest stand structure and rainfall intensity in an urban transect of the mixed (upland) forest in the city centre, towards a riparian pine forest and a floodplain hardwood forest in the City of Ljubljana, Slovenia. Bulk precipitation in open areas and throughfall were measured with fixed rainfall collectors in each forest. Stemflow was estimated from a review of relevant literature. We found that canopy interception in selected urban forests was mainly affected by tree species composition and other stand structure variables, such as canopy cover and tree dimensions. Average annual canopy interception was highest in the mixed forest (18.0% of bulk precipitation), while the riparian pine forest had the lowest level (3.9% of bulk precipitation) and the floodplain hardwood forest had the intermediate level for interception (7.1% of bulk precipitation). The mixed forest exhibited the stand structure factors that contributed to the highest canopy interception among the studied forests: high assemblage of dominant coniferous trees, denser canopy cover and the highest growing stock. Furthermore, rainfall intensity has proven to be an important factor for the seasonal partitioning (comparing the leafed and leafless period) of canopy interception. A better understanding of precipitation interception processes in

urban forests is needed to assist urban forest managing and planning, aiming at maximizing canopy interception for the mitigation of stormwater runoff and flooding in urbanized watershed.

**Keywords** Throughfall · Stemflow · Tree species composition · Canopy cover · Tree dimensions · Rainfall intensity

## Introduction

Urban forests provide numerous important ecosystem services (Bolund and Hunhammar 1999; Tyrväinen et al. 2005; Sanesi et al. 2011). The most recognized benefits, stemming from urban forest ecological services (McPherson et al. 2005), are: rainwater retention (Chen and Jim 2008), flood regulation (Sanders 1986), water quality protection (Xiao et al. 1998), moderation of the urban climate (Laforteza et al. 2009; Hamada and Ohta 2010; Armson et al. 2012) and air pollution reduction (Brack 2002; Bealey et al. 2007; McDonald et al. 2007; Zupancic et al. 2015). In terms of hydrological role, forest ecosystems in urban environments represent qualitative and quantitative filter for rainwater (Bellot and Escarre 1998). With the interception and retention of precipitation in tree canopies, forests are capable of regulating throughfall – the proportion of precipitation that either passes through gaps in the canopy or drips from foliar and woody components of the canopy (Schooling and Carlyle-Moses 2015). Consequently, they mitigate soil erosion processes and the related negative effects of intense rainfall events, e.g., water accumulation, flooding (Chen and Jim 2008), stormwater runoff and the costs of controlling it (McPherson et al. 2005; Zabret and Šraj 2015).

The ability of urbanized watersheds to mitigate stormwater runoff and flooding (Beniston et al. 2007; Livesley et al. 2014)

---

✉ Janez Kermavnar  
janez.kermavnar@gozdis.si

Urša Vilhar  
ursa.vilhar@gozdis.si

<sup>1</sup> Slovenian Forestry Institute, Večna pot 2, 1000 Ljubljana, Slovenia

has decreased in many regions around the world due to increased rainfall intensities, increased urbanization (impervious surfaces), and aging and deficient urban infrastructure, since the existing drainage infrastructures (or the green infrastructure) were not designed for current rainfall intensities (Kirnbauer et al. 2013). Previous studies have shown that urban forests can contribute significantly in terms of precipitation redistribution, interception and evaporation. However, the spatial variability of forest canopy interception (interception, storage, and subsequent evaporation of precipitation by tree crowns; Livesley et al. 2014) is largely controlled by forest stand structure (e.g., tree species composition, canopy cover), seasonality (seasonal presence or absence of foliage), as well as rainfall spatial distribution and its intensity (Xiao et al. 2000b; Šraj et al. 2008b). In addition, Siegert et al. (2016) and Šraj et al. (2008a) suggest that hillslope position within a watershed must also be considered for its effects on microclimate growing conditions and species distribution. Knowledge of the optimal urban forest stand structure for maximizing canopy interception is useful for urban forest managers and planners when developing strategies for mitigating stormwater runoff and flooding.

Sufficient information on the hydrology of forests in urban areas is lacking (e.g., Fletcher et al. 2014). Stand-scale studies of natural urban forests (e.g., Xiao et al. 1998; Xiao and McPherson 2002; Asadian and Weiler 2009; Inkiläinen et al. 2013) throughfall, canopy interception and stemflow (the spatially localized fraction of precipitation that is intercepted by the tree cover and subsequently flows down the branches and stem to the base of the tree; Levia and Frost 2003) have been largely overlooked (Inkiläinen et al. 2013), even in temperate regions. Previous studies have generally focused on rural forests and isolated street trees. Hydrological processes in urban forests differ from those in plantations (Rutter et al. 1971; Stogsdill et al. 1989; Crockford and Richardson 1990; HouBao et al. 1999; Park and Cameron 2008; Saito et al. 2013), urban parks (Šraj et al. 2008b; Schooling 2014; Schooling and Carlyle-Moses 2015) and isolated urban/street trees (Xiao et al. 2000a; Guevara-Escobar et al. 2007; Asadian and Weiler 2009; Xiao and McPherson 2011; Livesley et al. 2014). Consequently, results from plantations (homogeneous structure), urban parks or street trees (individual level) cannot be generalized to natural urban forests (stand-scale). Therefore, it is of great importance to investigate canopy interception in specific forest types and climates over long time intervals.

The aim of this study was to evaluate optimal stand structure in different urban forests regarding tree species composition, canopy density and tree dimensions (height, diameter) on the seasonal and annual canopy interception. The study occurred over a six-year period in an urban transect from the mixed (upland) forest in the city centre towards the riparian pine forest and the floodplain hardwood forest, thereby

covering a range of forest types likely to be encountered in Slovenian urban forests. In addition, we tested whether seasonal rainfall intensity influenced the generation of throughfall and canopy interception in selected urban forests. The results could aid in the development of urban forest management measures for maximized canopy interception, aiming at mitigating stormwater runoff and flooding in urbanized watershed.

## Materials and methods

### Site and stand description

The studied forests are located near the city of Ljubljana, Slovenia (46°04' N, 14°31' E) with a population of 280,140 (Loose et al. 2010). The Slovenian capital is situated in the Ljubljana Basin, characterized by a continental climate (CfB according to the Köppen climate classification system), with well-defined seasons. Mean annual precipitation is 1393 mm and the mean annual air temperature is 9.8 °C. The inter-annual variability of precipitation is rather significant, with maximal precipitation in summer and fall (Zupančič 1995). The sites were established in a transect from an urban mixed (upland) forest in the city centre towards the riparian pine forest and the floodplain hardwood forest along the Sava River (Fig. 1). Stand characteristics of urban forests were collected according to the ICP Forests protocol (Dobbertin and Neumann 2010) and are given in Table 1.

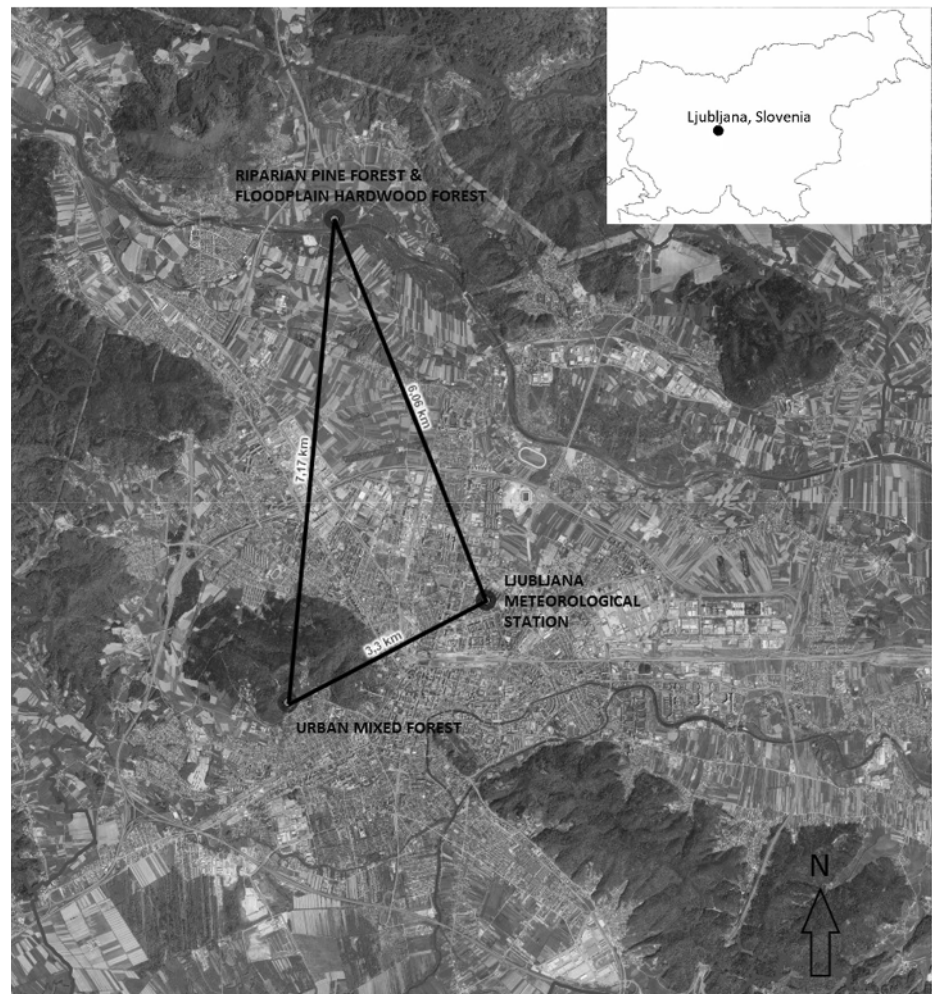
#### 1) Mixed forest

The natural, urban mixed forest is located in the landscape park of Tivoli, Rožnik and Šišenski Hrib in the very center of the city of Ljubljana (Fig. 1). Since 2010, most of the forest area has been protected due to its highly valued social and ecological forest ecosystem services (Verlič et al. 2014a). A study conducted in 2010 (Smrekar et al. 2011) estimated 1,750,000 visits to this park per year.

The site is 310 m above sea level, and consists of a 0.25 ha (50 × 50 m) plot. The forest canopy is comprised of sessile oak (*Quercus petraea* (Mattuschka) Liebl.), sweet chestnut (*Castanea sativa* (Mill.)) and Norway spruce (*Picea abies* (L.) Karst.). The canopy cover is very dense. Forest floor vegetation contains few species in the shrub and herb layer. Bedrock material consists of sedimentary rocks (slate, clay and quartz sandstones). The soil was classified as *Dystric cambisol* (WRB 2007). The thickness of the O horizon was 0 to 6 cm and the depth of the M horizon was between 0 and 130 cm, with a clay-loam texture (Verlič et al. 2014b).

#### 2) Riparian pine forest

**Fig. 1** Locations of investigated urban forest stands within the city of Ljubljana. The urban mixed forest is positioned closely to the city center, while the riparian pine forest and the floodplain hardwood forest (represented with one point due to their close proximity) are situated along the Sava river in the sub-urban part of the municipality. The position of Ljubljana Meteorological Station is also shown. The points are connected with solid line and air distances between them are added (online source: Geopedia, [http://www.geopedia.si/#T105\\_x465512\\_y104064\\_s13\\_b2](http://www.geopedia.si/#T105_x465512_y104064_s13_b2))



The riparian pine forest is located in the sub-urban part of the city of Ljubljana, along the Sava river (Fig. 1). It is positioned on a raised riverine terrace, outside of the direct influence of the river water (Verlič et al. 2014b). The site is located at 300 m above sea level, and consists of a 0.25 ha (50 × 50 m) plot of Scots pine (*Pinus sylvestris* L.) in the upper canopy layer, with 78% of total growing stock and a mixture of deciduous tree species in the mid-story and lower canopy layer, such as small-leaved lime (*Tilia cordata* Mill.), sessile oak (*Quercus petraea* (Mattuschka) Liebl.) and European hornbeam (*Carpinus betulus* L.). The canopy cover is very loose (fragmented), containing rather dense shrub and forest floor vegetation (Vilhar et al. 2013). The bedrock material is glaciofluvial gravel and the soil was classified as *Fluvisols* (WRB 2007). The thickness of the O horizon was 0 to 6 cm and the depth of the M horizon was 0 and 40 cm, with a sandy-loam texture (Verlič et al. 2014b).

### 3) Floodplain hardwood forest

The floodplain hardwood forest is located in the vicinity of the riparian pine forest (Fig. 1), approximately 2 m above the

Sava River terrace during the daily high flow (Vilhar et al. 2013). The site is located at 296 m above sea level, and consists of a 0.25 ha (50 × 50 m) plot of sycamore maple (*Acer pseudoplatanus* L.), gray alder (*Alnus incana* (L.) Moench.), small-leaved lime (*Tilia cordata* Mill.), European ash (*Fraxinus excelsior* L.), willows (*Salix* sp.), European black poplar (*Populus nigra* L.), etc. Canopy cover is loose, with rather dense shrub and forest floor vegetation. This site is especially exposed to spontaneous spreading of invasive alien plant species, e.g., *Fallopia japonica*, *Solidago canadensis*, *Rudbeckia laciniata* (Dakschobler et al. 2013; Verlič et al. 2014b) as a result of frequent flooding (Vilhar et al. 2013). Bedrock material is glaciofluvial gravel and the soil was classified as *Fluvisols* (WRB 2007). The thickness of the O horizon was 0 to 4 cm and the depth of the M horizon was between 0 and 90 cm, with a clay-loam texture (Verlič et al. 2014b).

### Collection of rainfall partitioning components

Bulk precipitation and throughfall were monitored from 1 January 2008 to 31 December 2013. Samples were manually

**Table 1** General characteristics of the study forest sites near Ljubljana, Slovenia

Site	Average tree height (m)	Average diameter at breast height – DBH (cm)	Growing stock (m <sup>3</sup> ha <sup>-1</sup> )	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	Canopy cover (%)	Deciduous / evergreen trees (% in the growing stock)	Ground vegetation cover (%)
Mixed forest	21.9	33.4	589.1	42.9	90–100*	54 / 46	100*
Riparian pine forest	11.7	13.5	151.1	20.8	50**	21 / 79	100**
Floodplain hardwood forest	15.8	17.6	246.9	25.0	30–50**	100 / 0	80–100**

\*(Verič et al. 2014b)

\*\*(Vilhar et al. 2013)

collected fortnightly (in the mixed forest) or monthly (in the riparian pine forest and in the floodplain hardwood forest).

Bulk precipitation was measured on an adjacent meadow (an open area), approximately 100 m outside each forest. Three fixed rainfall collectors (0.23 m in diameter) in the leafed period and three snow collectors (0.23 m in diameter) in the leafless period (solid state precipitation requires different collection methods; Siegert et al. 2016), were installed 140 cm above ground level (Clarke et al. 2010). Bulk precipitation data were combined to coincide with the throughfall sampling periods and were compared to precipitation at the Ljubljana Meteorological Station (299 m above sea level; 46°04' N, 14°31' E) (Slovenian Environment Agency archive 2015), for which the hourly precipitation intensity in the leafed and leafless period was also calculated. Rainfall intensity classes (mm h<sup>-1</sup>) were defined according to the Slovenian Environment Agency classification (Kermavnar 2015).

The mixed forest site was equipped with eight systematically distributed, fixed-funnel collectors (0.23 m in diameter), installed 140 cm above ground level. In addition, throughfall was collected using ten systematically distributed gutter collectors (3-m long tube, 4-cm in diameter, with three, 87-cm long and 0.9-cm wide slits in lines), with the upper portion installed 0.60 m above the forest floor, draining directly into polyethylene tanks, which were used as collection containers (Zlindra et al. 2011). The total sampling area in the 0.25 ha plot was 0.52 m<sup>2</sup> (the receiving area of each funnel collector was 415 cm<sup>2</sup> and of each gutter 185 cm<sup>2</sup>).

From 2008 to 2012, the riparian pine forest and the floodplain hardwood forest were equipped with three randomly placed funnel collectors (0.24 m in diameter), installed 130 cm above ground level. The total sampling area in the 0.25 ha plot was 0.14 m<sup>2</sup> (the receiving area of each funnel collector was 452 cm<sup>2</sup>). In winter 2012, ten funnel collectors (0.16 m in diameter) and three snow collectors (0.23 m in diameter) were installed 140 cm above ground level and distributed combining systematic and random approaches as recommended by Clarke et al. (2010). The total sampling area in the 0.25 ha plot was 0.20 m<sup>2</sup> (the receiving area of each funnel collector was 201 cm<sup>2</sup>). The volumes of bulk precipitation and throughfall were measured in the field with a graduated cylinder.

Results of the full study period were split up into two seasons for further investigation, according to phenology development of dominant tree species at each site: a. the leafed period, when deciduous trees fully develop their leaves (the mixed forest from May 1 to October 31, the riparian pine forest and the floodplain hardwood forest from April 15 to October 31); b. the leafless period, when deciduous trees do not have leaves in the crowns (the mixed forest from November 1 to April 30, the riparian pine forest and the floodplain hardwood forest from November 1 to April 14). This division was particularly applied due to deciduous trees not retaining their leaves year round (Asadian 2007), which

substantially influences the variability of rainfall partitioning (Herbst et al. 2008; Gerrits et al. 2010; Zabret et al. 2016). Phenological data were obtained from the observations of Slovenian Environment Agency, Bureau of Meteorology (Department of Agricultural Meteorology) for selected tree species (*Robinia pseudoacacia*, *Alnus glutinosa*, *Populus nigra*, *Quercus* sp., *Picea abies*, *Pinus sylvestris*, *Salix* sp., *Fraxinus excelsior*) and their phenophases (Archive of phenological data 2015). Data series were available for the years 1991–2013, except for the *Populus nigra* from 1998 to 2011. Additional information was also found on Slovenian Environment Agency website and in the dendrological literature dealing with tree species in Slovenia (e.g., Brus 2004). We focused on phenophase of the first leaves occurrence in spring (as the beginning of the leafed period) and on the leaves fall off in autumn (as the end of the leafed period). The average value (date) of each phenophase for all years of observations was calculated for each urban forest stand (Kermavnar 2015).

Stemflow at each site was estimated based on the relevant literature review for dominant tree species and their basal area, assuming that stemflow is proportional to the respective tree basal area. There is a clear correlation between stemflow production and tree size (i.e., stem diameter and basal area, respectively) (Bellot and Escarre 1998; Dietz et al. 2006; Vilhar 2010; Vilhar 2016). Several studies reported stemflows for each dominant tree species that were averaged and weighted with the share of species basal area in the total (stand) basal area at the site. Stemflow has been investigated as a function (among other influential variables) of seasonality (Dolman 1987; Livesley et al. 2014). Herbst et al. (2008) exposed that stemflow yield is much higher during the leafless period compared to the leafed period. Therefore, the upper range was used as estimated seasonal stemflow in the leafless period and the lower range for the leafed period. For the mixed forest, 23 studies reporting on stemflow for five dominant tree species were used; for the riparian pine forest, 23 studies for eight dominant tree species and in case of the floodplain hardwood forest, 11 studies reporting on stemflow for six dominant tree species were used (Table 3).

Canopy interception was calculated from a simple mass balance equation often used to describe precipitation partitioning (Crockford and Richardson 2000; Xiao and McPherson 2002; Toba and Ohta 2005; Herbst et al. 2008; Barbier et al. 2009; Gerrits et al. 2010; Inkiläinen et al. 2013; Zabret et al. 2016):

$$\text{Canopy interception} = \text{Bulk precipitation} - (\text{Throughfall} + \text{Stemflow}) \quad (1)$$

To allow better comparison with other studies, we report canopy interception, throughfall, and stemflow as % of bulk precipitation, calculated from cumulative seasonal or annual

data (i.e., the cumulative annual % throughfall is calculated by summing all monthly throughfall values (mm) for the respective year and dividing by cumulative bulk precipitation (mm)).

## Data analysis and statistical methods

Missing data values on bulk precipitation were gap-filled using linear regression between measured bulk precipitation and precipitation at Ljubljana Meteorological Station (Slovenian Environment Agency archive) (Kermavnar 2015). Missing data on throughfall in the mixed forest were gap-filled using linear regression between funnel and gutter collectors. Missing data on throughfall in the riparian pine forest and the floodplain hardwood forest were gap-filled using linear regression between bulk precipitation and measured throughfall.

Microsoft Excel was used for data verification and processing. Statistical data analyses were performed using the program IBM® SPSS® Statistics Version 20. The Spearman correlation coefficient ( $\rho$ ) was used to test the association among bulk precipitation measured at selected sites and Ljubljana Meteorological Station. To assess the potential differences between seasonal throughfall (presence of foliage vs. absence of foliage) at each site, a Mann-Whitney (Wilcoxon) test, a non-parametric alternative to the  $t$ -test, was used because precipitation and throughfall data followed a non-Gaussian distribution (Voss et al. 2016; Siegert et al. 2016). The standard significance level ( $\alpha$ ) was set to 0.05.

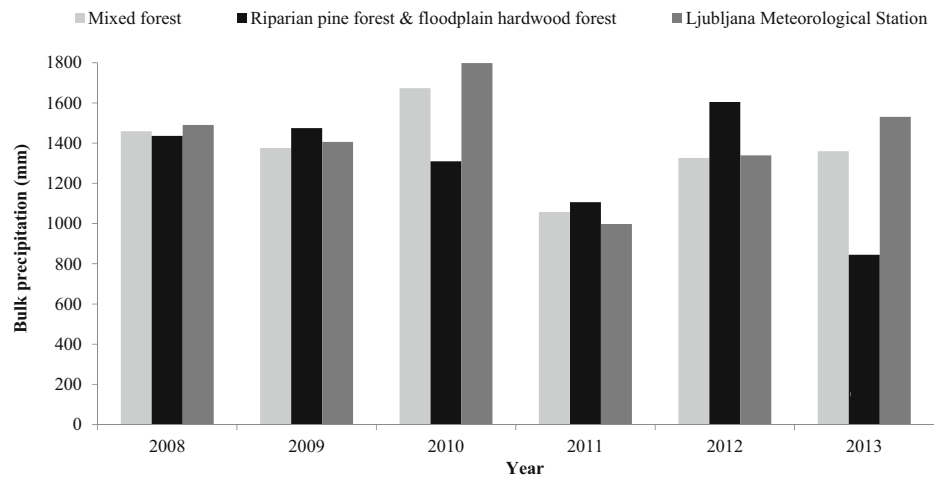
## Results

### Bulk precipitation and throughfall

In the mixed forest annual bulk precipitation ranged from 1057 to 1673 mm (Fig. 2). Compared to the long-term (1961–1991) annual precipitation average recorded at Ljubljana Meteorological Station (1394 mm), 2009, 2011, 2012 and 2013 were drier than average years and 2008 and 2010 were wetter compared to the average. In the riparian pine forest and the floodplain hardwood forest, the annual bulk precipitation ranged from 845 mm to 1605 mm (Fig. 2). The years 2010, 2011 and 2013 were drier and 2008, 2009 and 2012 were wetter than the reported long-term annual average.

Bulk precipitation at sites did not differ significantly from the precipitation measured at Ljubljana Meteorological Station ( $p > 0.05$ ). However, a higher correlation was observed in the mixed forest ( $\rho = 0.963$ ,  $p < 0.001$ ,  $n = 156$ ) compared to the riparian pine forest and the floodplain hardwood forest ( $\rho = 0.846$ ,  $p < 0.001$ ,  $n = 105$ ). This could be likely due to shorter air distance between the mixed forest and Ljubljana Meteorological Station compared to distance between the riparian pine forest (the floodplain hardwood forest) and Ljubljana Meteorological Station (Fig. 1).

**Fig. 2** Annual bulk precipitation amount (mm) in the mixed forest, the riparian pine forest, the floodplain hardwood forest and Ljubljana Meteorological Station from 2008 to 2013



The average rainfall intensity at Ljubljana Meteorological Station was significantly higher in the leafed period ( $1.86 \pm 3.08 \text{ mm h}^{-1}$ ) compared to the leafless period ( $1.05 \pm 1.31 \text{ mm h}^{-1}$ ) ( $p < 0.001$ ). The highest rainfall intensities recorded during the leafed period were  $52.4 \text{ mm h}^{-1}$  and  $10.4 \text{ mm h}^{-1}$  in the leafless period. In the leafless period, low rainfall intensity ( $< 4 \text{ mm h}^{-1}$ ) was most frequent (96%), with only 4% being classified as high intensity rainfall events ( $4.1\text{--}16.0 \text{ mm h}^{-1}$ ). However, in the leafed period, 87% of the rainfall events were low intensity and 13% were considered high intensity ( $4.1\text{--}50.0 \text{ mm h}^{-1}$ ) (Fig. 3).

The highest annual throughfall was in the riparian pine forest (1220 mm or 94.1% of bulk precipitation, standard deviation (SD) = 3.4%) and was lowest in the mixed forest (1077 mm or 78.3% of bulk precipitation, SD = 7.1%), followed by the floodplain hardwood forest with 1165 mm or 89.1% of bulk precipitation (SD = 5.4%). Seasonal differences in throughfall among the forests were not statistically significant ( $p > 0.05$ ). Nevertheless, the leafed period throughfall in the riparian pine forest and the floodplain hardwood forest were lower compared to the leafless period throughfall in each forest, whereas in the mixed forest, the leafed period throughfall was slightly higher compared to the leafless period throughfall (Table 2, Fig. 4). Moreover, in

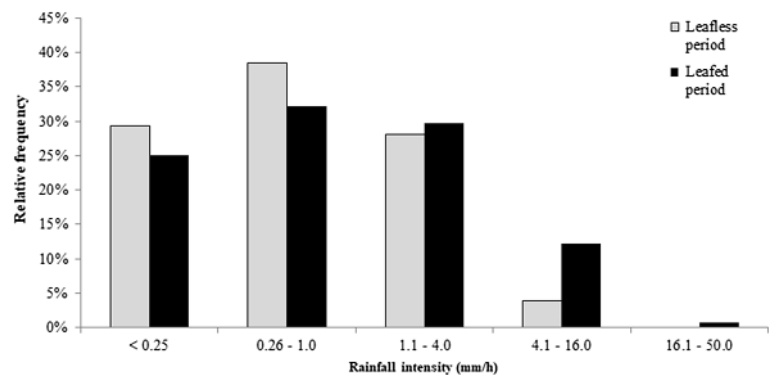
the leafed period of 2013, throughfall in the riparian pine forest and the floodplain hardwood forest (177 mm or 59.0% and 164 mm or 54.7% of bulk precipitation, respectively) was evidently lower compared to average throughfall for the overall study period (816 mm or 89.5% and 766 mm or 83.9%, respectively). However, in the mixed forest, throughfall in the leafed period 2013 was not exceptionally low (381 mm or 71.5%) compared to the average (606 mm or 78.7% of bulk precipitation).

The relationship between bulk precipitation and throughfall showed a positive and significant ( $R^2 > 0.95$ ) linear correlation at all sites for the leafed and the leafless period, thereby confirming that the amount of bulk precipitation is the main factor controlling throughfall (Bellot and Escarre 1998; Guevara-Escobar et al. 2007; Vilhar 2016; Vilhar et al. 2017). As expected, throughfall percentage increased while rainfall interception rate decreased with bulk precipitation amount (Sadeghi et al. 2016).

### Stemflow

The average estimated stemflow was 3.7% of bulk precipitation in the mixed forest, 2.0% in the riparian pine forest and 3.8% in the floodplain hardwood forest (Table 3). At all sites,

**Fig. 3** Frequency distribution of hourly rainfall intensity ( $\text{mm h}^{-1}$ ) in the leafless and the leafed period at Ljubljana Meteorological Station (Slovenian Environment Agency archive 2015). Rainfall intensity classes were defined according to the Slovenian Environment Agency classification (Kermavnar 2015)

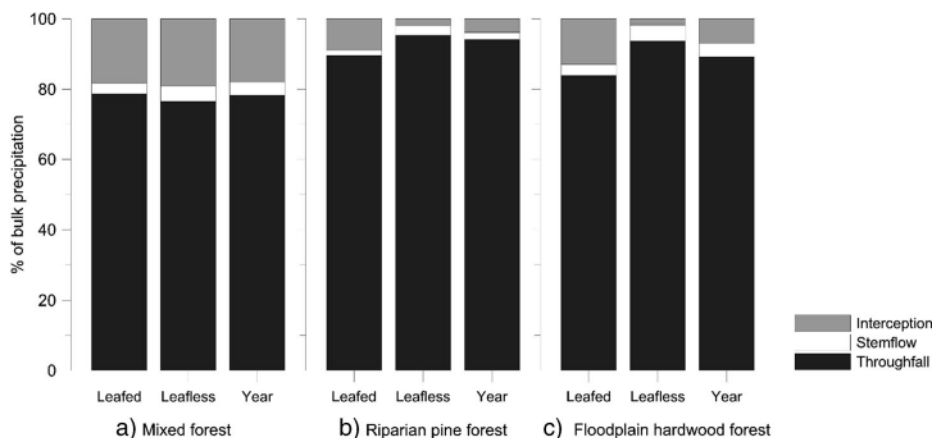


**Table 2** Throughfall (Tf) in mm and percentage of bulk precipitation (%) for selected urban forests for the period from 2008 to 2013 (n = number of sampling periods)

Year	Season	Mixed (upland) forest		Riparian pine forest		Floodplain hardwood forest	
		Tf (mm)	Tf (% bulk precipitation)	Tf (mm)	Tf (% bulk precipitation)	Tf (mm)	Tf (% bulk precipitation)
2008	Leafed period	633	80.2	881	93.7	849	90.3
	Leafless period	499	74.6	470	94.6	460	92.6
	Year	1132	77.6	1351	94.1	1309	91.2
2009	Leafed period	547	82.8	870	98.0	863	97.2
	Leafless period	592	80.3	590	100.7	571	97.4
	Year	1139	85.2	1460	99.0	1434	97.2
2010	Leafed period	765	82.9	1017	94.4	900	83.5
	Leafless period	690	91.9	214	92.2	236	101.7
	Year	1455	87.0	1231	94.0	1136	86.7
2011	Leafed period	583	75.6	843	96.2	738	84.2
	Leafless period	216	75.7	203	88.3	190	82.6
	Year	799	75.6	1046	94.6	928	83.9
2012	Leafed period	725	79.0	1106	95.5	1083	93.5
	Leafless period	293	71.8	409	91.5	397	88.8
	Year	1018	76.8	1515	94.4	1480	92.1
2013	Leafed period	381	71.5	177	59.0	164	54.7
	Leafless period	537	64.9	570	104.6	540	99.0
	Year	918	67.5	747	88.4	704	83.3
Average ± standard deviation		606 ± 138	78.7 ± 4.4	816 ± 329	89.5 ± 15.0	766 ± 316	83.9 ± 15.3
Leafless period		471 ± 181	76.5 ± 9.1	409 ± 169	95.3 ± 6.2	399 ± 157	93.7 ± 7.1
Year		1077 ± 226	78.3 ± 7.1	1225 ± 288	94.1 ± 3.4	1165 ± 304	89.1 ± 5.4

\* the sum of sampling periods

**Fig. 4** Average throughfall, stemflow and canopy interception (% of bulk precipitation) in a) the mixed forest b) the riparian pine forest and c) the floodplain hardwood forest for the leafed period, the leafless period, and year from 2008 to 2013



the estimated leafed period stemflow was lower than estimated leafless period stemflow. In the mixed forest, the leafed period stemflow ranged from 2.2% to 3.7% of bulk precipitation and stemflow in the leafless period was between 3.7% and 5.2%. In the riparian pine forest, the leafed period stemflow ranged from 0.7% to 2.0% of bulk precipitation and the leafless period stemflow was estimated between 2.0% and 3.3%. In the floodplain hardwood forest, the leafed period stemflow was estimated to represent 2.4% to 3.8% of bulk precipitation and stemflow values in the leafless period accounted between 3.8% and 5.2%.

### Canopy interception

Annual canopy interception was highest in the mixed forest (248 mm or 18.0% of bulk precipitation) and lowest in the riparian pine forest (51 mm or 3.9%), followed by the floodplain hardwood forest (92 mm or 7.1%) (Fig. 4). Seasonally, the floodplain hardwood forest exhibited the largest seasonal differences in canopy interception, followed by the riparian pine forest, which had considerably higher leafed period canopy interception compared to that in the leafless period. In the mixed forest, where the leafed period canopy interception was higher compared to that in the riparian pine forest and the floodplain hardwood forest, seasonal canopy interception partitioning was nearly identical. In addition, the leafed period canopy interception in the mixed forest was 2% lower compared to that during the leafless period.

### Discussion

Canopy interception of precipitation is one of the most important (Li et al. 2016) hydrological processes in forest ecosystems (Brauman et al. 2010). The results of this study suggest that canopy precipitation partitioning in selected urban forests is strongly influenced by tree species composition, canopy cover and growing stock (i.e., tree dimensions) as well as

rainfall spatial distribution and intensity. Optimal stand structure for maximized canopy interception regardless of the season was in the mixed forest, characterized by a substantial share of coniferous evergreen trees (especially dominant Norway spruce trees), dense canopy cover and the highest growing stock, compared to other forest types under the study.

### Canopy interception in relation to stand structure of urban forests

The variables responsible for throughfall and canopy interception partitioning are numerous and complex, stemming from individual canopy characteristics (Li et al. 2016), ecoregion (Zimmermann et al. 2007), rainfall intensity (Bryant et al. 2005; Šraj et al. 2008a; Moreno Perez et al. 2013), and seasonality (Deguchi et al. 2006; Siegert et al. 2016). Every forest ecosystem, defined by its tree species composition, structural traits, soil features and microsite conditions, is somehow unique. Hence, it is difficult to draw general conclusions about throughfall and canopy interception by investigating specific forest types and climates.

The mixed forest had consistently higher canopy interception than the other two forest types, i.e., the floodplain hardwood forest and the riparian pine forest. This can be attributed to denser canopy cover in the mixed forest, a substantial assemblage of coniferous evergreen trees (46% in the growing stock) with wider crowns, especially dominant Norway spruce trees, and the highest growing stock (Table 1). Those are all stand structure variables which contribute to higher canopy interception (Toba and Ohta 2005; Dietz et al. 2006; Vilhar 2016). Conifers tend to have greater interception capacity than deciduous trees (Inkiläinen et al. 2013) and large trees with considerable canopy surface area can decrease throughfall by intercepting a substantial fraction of bulk precipitation (Brauman et al. 2010). In an urban park in the city of Ljubljana, coniferous tree species (*Pinus sylvestris*) exhibited evidently higher canopy interception (51–65% of bulk precipitation) compared to deciduous tree (*Betula pendula*; 23–



**Table 3** Estimated stemflow (% of bulk precipitation) for dominant tree species (order reflects share of species basal area in the total stand basal area from the highest to the lowest) and used results from various studies for stemflow estimation at each forest site

Site	Tree species	Species stemflow (% of bulk precipitation)	Used references	
Mixed forest	Sessile oak ( <i>Quercus petraea</i> )	4.4	Bellot and Escarre (1998) Bryant et al. (2005)	
	Norway spruce ( <i>Picea abies</i> )	3.1	Cantú Silva and Okumura (1996) Carlyle-Moses and Price (1999)	
	Sweet chestnut ( <i>Castanea sativa</i> )	4.6	Dohnal et al. (2014) Dolman (1987)	
	Scots pine ( <i>Pinus sylvestris</i> )	1.9	Hosseini Ghaleh Bahmani et al. (2012) Leonardi et al. (1993)	
	Black locust ( <i>Robinia pseudoacacia</i> )	6.2	Liang (2014) Limousin et al. (2008) Loustau et al. (1992) McKee (2010) Mosello et al. (2002) Nihlgard (1970) Moreno Perez et al. (2013) Price and Carlyle-Moses (2003) Spittlehouse (1998) Šraj et al. (2008a) Šraj et al. (2008b) Tsiontsis et al. (2001) Valente et al. (1997) Wang et al. (2013) Williams (2004)	
Riparian pine forest	Scots pine ( <i>Pinus sylvestris</i> )	1.9	Bellot and Escarre (1998) Bryant et al. (2005)	
	Small-leaved lime ( <i>Tilia cordata</i> )	1.5	Cantú Silva and Okumura (1996) Carlyle-Moses and Price (1999)	
	Sessile oak ( <i>Quercus petraea</i> )	4.4	Dohnal et al. (2014) Dolman (1987)	
	Willows ( <i>Salix</i> sp.)	3.0	Hosseini Ghaleh Bahmani et al. (2012) Krämer and Hölscher (2010)	
	European hornbeam ( <i>Carpinus betulus</i> )	1.5	Limousin et al. (2008) Liang (2014)	
	Hop hornbeam ( <i>Ostrya carpinifolia</i> )	2.6	Liu et al. (2011) Loustau et al. (1992)	
	Sycamore maple ( <i>Acer pseudoplatanus</i> )	3.9	Mahendrappa (1990) McKee (2010)	
	Norway spruce ( <i>Picea abies</i> )	3.1	Mosello et al. (2002) Nihlgard (1970) Moreno Perez et al. (2013) Price and Carlyle-Moses (2003) Spittlehouse (1998) Šraj et al. (2008a) Šraj et al. (2008b) Valente et al. 1997 Williams (2004)	
Floodplain hardwood forest	Willows ( <i>Salix</i> sp.)	3.0	Carlyle-Moses and Price (1999) Clements (1971)	
	Black poplar ( <i>Populus nigra</i> )	5.2	Clements (1972) Dalsgaard (2007)	
	European ash ( <i>Fraxinus excelsior</i> )	3.1	Mahendrappa (1990) Herwitz and Levia (1997)	
	Sycamore maple ( <i>Acer pseudoplatanus</i> )	3.9	Krämer and Hölscher (2010) Liu et al. (2011)	
	Grey alder ( <i>Alnus incana</i> )	5.3	Price and Carlyle-Moses (2003) Šraj et al. (2008a)	
	Small-leaved lime ( <i>Tilia cordata</i> )	1.5	Zhang (2009)	

40%) (Šraj et al. 2008b). In the mixed beech-spruce forests in the Pohorje Mountains (Slovenia), a higher share of Norway spruce (coniferous tree species) in the growing stock contributed to lower annual net precipitation – the sum of throughfall and stemflow (Vilhar 2016). High interception by forest canopies is frequently associated with high leaf area index (Sadeghi et al. 2016), which is closely related to canopy cover. The study from Livesley et al. (2014) illustrated that urban street tree with denser canopy (greater plant area index) intercepted more annual rainfall (44%) than street tree with a less dense canopy (29%). In streets, parks and natural forested areas interception accounted for on average 76.5% and 56.4% of bulk precipitation for coniferous and deciduous trees (Asadian 2007). For a broad-leaved deciduous urban forest, Inkiläinen et al. (2013) reported throughfall from 78.1% to 88.9% of bulk precipitation, indicating 9.1–24.1% rainfall interception.

Seasonally, the floodplain hardwood forest and the riparian pine forest exhibited considerably higher leafed period canopy interception compared to that in the leafless period (Fig. 4), potentially resulting from the seasonal variation of canopy cover (Bryant et al. 2005). Deciduous broadleaved trees shed leaves at wintertime, therefore contributing to reduced canopy interception (Deguchi et al. 2006; Xiao and McPherson 2011). In contrast, the presence of foliage (for deciduous trees) during the leafed period is expected to increase the amount of precipitation intercepted in the canopies (Siegert et al. 2016; Vilhar 2016). Zabret et al. (2016) showed clear variability in canopy interception, associated with the leafed and leafless period of two distinct tree species (*Betula pendula* and *Pinus nigra*). For instance, *Betula pendula* intercepted 60% of precipitation in the leafed period compared to 30% interception rate in the leafless period. Another study conducted in Ljubljana showed that throughfall under silver birch (*Betula pendula*, deciduous tree) during the leafless period was almost 23% higher than in the leafed period (Zabret and Šraj 2015). For the mixed beech-spruce forests, the net precipitation was on average 10% lower during the growing season (the leafed period) than during dormancy (the leafless period) (Vilhar 2016). Xiao et al. (1998) observed that the greatest interception occurred during the leaf-on season in an urban forest in Sacramento, USA. In a study of a municipal urban forest, Xiao and McPherson (2002) reported seasonal variation in rainfall interception for a large deciduous tree during the leafless period (14.8% of bulk precipitation) and during the leafed period (79.5%).

Riparian pine forest had the highest share of conifers (Scots pine) (79% in the growing stock, Table 1), but exhibited the lowest canopy interception among selected urban forest types. In general, a higher share of deciduous trees in mixed forests contributes to higher throughfall and stemflow and lower canopy interception (Vilhar 2016). However, during the time of our study, the riparian pine forest experienced more loose canopy cover where the upper canopy of Scotch pine was

open and spacious. This forest also contained many hardwood tree species with smaller dimensions (height, diameter) compared to the mixed forest (Table 1). Smaller crowns do not intercept as much precipitation as wider crowns. Leafed period interception for an urban forest stand with dense canopy cover, dominated by large, broadleaf evergreens and conifers, was 36% and for an urban forest with less dense canopy cover, dominated by medium-sized conifers and broadleaf deciduous trees, it was 18% (Xiao et al. 1998). This indicates that canopy interception in urban forests can be, among other parameters, influenced by tree dimensions within a forest stand.

In the leafed period of 2013, the riparian pine forest and the floodplain hardwood forest displayed significant decreases in throughfall (Table 2) compared to other years (leafed periods). This could be attributed to very low summer precipitation amount in 2013, causing drought throughout Slovenia (Sušnik and Valher 2014). Another important aspect could be rainfall characteristics (e.g., type of precipitation event, rainfall duration, rainfall rate, drop size distribution etc.) (Šraj et al., 2008a, b; Zabret et al. 2016), which were not assessed in this study, but could contribute to better explanation of comparable deviations in throughfall in selected forests. However, low throughfall amount in the leafed period 2013 could be attributed to other reasons, which were not related to rainfall characteristics. In particular, progressing shrub (in the riparian pine forest) and forest floor vegetative growth (an invasive alien species with great vigor in the floodplain hardwood forest) (Vilhar et al. 2013) in early spring may contribute to increased interception and reduced throughfall throughout the leafed period (Cantú Silva and Okumura 1996). The abundance of ground vegetation, dominated by early successional species, is often attributed to greater canopy light transmittance (Canham et al. 1994; Barbier et al. 2009). This is an effect of the particular canopy multilayer structure (Bellot and Escarre 1998), where secondary interception occurs – water drips from the overstory (canopy layer) and is intercepted by lower plants (understory vegetation) – which makes a denser environment for rainwater to penetrate and results in a lower throughfall amount (Asadian 2007). Shrubs and grasses also contributed to total interception in the urban forest of Sacramento (Xiao et al. 1998). Therefore, further investigations into the development of understory vegetation and its impact on precipitation partitioning are necessary.

### Canopy interception in relation to rainfall characteristics

Weather conditions vary at small and large scales (Brauman et al. 2010). The precipitation amount can change significantly over short distances due to complex topography (Diodato 2005; Vilhar 2010; Vilhar et al. 2017), contributing to considerably different microclimate conditions (Crockford and Richardson 2000; Tetzlaff and Uhlenbrook 2005). When

comparing the annual amount of bulk precipitation at sites with that at Ljubljana Meteorological Station (Fig. 2), the differences could be attributed to greater air distance between the riparian pine forest, the floodplain hardwood forest and Ljubljana Meteorological Station (6.06 km), compared to air distance between the mixed forest and Ljubljana Meteorological Station (3.3 km) (Fig. 1). The differences across small topographic gradients are also evident in throughfall hydrology (Siegert et al. 2016; Vilhar 2016). The amount of bulk precipitation is the main influential factor for throughfall and consequently for canopy interception partitioning (Bellot and Escarre 1998; Guevara-Escobar et al. 2007).

In the riparian pine forest and the floodplain hardwood forest, the canopy interception in the leafed period was higher compared to the leafless period (Fig. 4), which was expected and in an agreement with other studies from temperate forests (e.g., Dolman 1987; Barbier et al. 2009; Vilhar 2016). This can be mainly recognized as a consequence of the reduced interception storage capacity of the leafless canopy (Herbst et al. 2008; Gerrits et al. 2010). Deciduous tree species were quite abundant in the riparian pine forest and the floodplain hardwood forest, especially in the latter (Table 1). In addition, those two forest stands exhibited different forest structure properties (i.e., canopy cover, tree dimensions) compared to the mixed forest. This most likely counterbalanced the impact of rainfall characteristics (intensity) on canopy interception.

In the mixed forest, the seasonal canopy interception partitioning was nearly similar year round, but with slightly lower (2%) leafed period canopy interception compared to that in the leafless period. Several studies have reported higher leafless period canopy interception in the mixed forests due to the seasonal variation in rainfall intensity (Bryant et al. 2005; Šraj et al. 2008b; Moreno Perez et al. 2013), which may obscure changes caused by the decreasing leaf area (Inkiläinen et al. 2013). Šraj et al. (2008b) demonstrated clear differences in rainfall intensities among seasons. The highest rainfall intensity was recorded for summer and autumn (the leafed period), while in winter (the leafless period) rainfall intensity was significantly lower. Rainfall of high intensity and short duration presents lower interception values than low intensity, long duration events (Scatena 1990; Veneklaas and Van Ek 1990; Xiao et al. 1998; Wang et al. 2008; Asadian and Weiler 2009), as shown in the leafless period at Ljubljana Meteorological Station (Fig. 3). In low intensity rainfall events, which are generally associated with small drop size, the flow paths do not become overloaded (Crockford and Richardson 2000). During the leafed period (spring and summer), characterized by convective precipitation events (thunderstorms), canopy interception and storage capacity (which varies considerably among tree species; Livesley et al. 2014) saturate much faster, which in turn leads to dripping rainwater

on the forest ground and consequently, a larger amount of throughfall (Barbier et al. 2009; Siegert et al. 2016).

Differences in canopy interception partitioning between the riparian pine forest and the floodplain hardwood forest on one side (higher overall canopy interception in the leafed period) and the mixed forest on the other side (higher overall canopy interception in the leafless period), could be explained by the possible differences in rainfall intensity between those two locations (Fig. 1). It seems that rainfall intensity did not have evident impact on canopy interception in the riparian pine forest and in the floodplain hardwood forest. In the mixed forest, higher rainfall intensity in the leafed period resulted in lower canopy interception compared to the leafless period. Measurements of rainfall characteristics (e.g., type of precipitation event, rainfall duration, rainfall rate, drop size distribution etc.) for each forest stand separately could contribute to better understanding of canopy interception partitioning in selected forests.

In the leafless periods of 2009, 2010 and 2013 measured throughfall in the riparian pine forest and the floodplain hardwood forest exceeded bulk precipitation (underlined values in Table 2), resulting in negative interception values. Several studies report throughfall values greater than bulk precipitation due to drip points from the canopy where throughfall is preferentially deposited to the forest floor, leading to quantities greater than those of observed bulk precipitation (Bellot and Escarre 1998; Dietz et al. 2006; Vilhar 2006; Šraj et al. 2008a; Gerrits et al. 2010; Siegert et al. 2016). Zimmermann et al. (2010) mentioned that throughfall data may include extreme (upper tail) values from a few isolated spots where throughfall is concentrated, i.e., sampling locations beneath drip points, which contribute to an overestimation of the mean throughfall (Brauman et al. 2010; Llyod and Marques 1988). A likely source of bulk precipitation error, leading to its underestimation (Valente et al. 1997), is the less reliable measurement of bulk precipitation, which is a problem in many studies (Crockford and Richardson 2000).

The results of this and other comparable studies clearly demonstrate that canopy interception by forests is extremely variable and difficult to measure (Asadian and Weiler 2009). To achieve a higher spatial representativeness of the throughfall measurements and to improve canopy interception estimates in forests with a large canopy heterogeneity, a higher number of throughfall collectors should be used (Zlindra et al. 2011). In addition, the rainfall pattern must be considered when selecting the type and number of collecting devices, since the coefficient of variation increases with decreasing throughfall depth (Zimmermann et al. 2010). However, it is important to note that precipitation partitioning in our study was considered across a longer time scale (six years), in which differences in canopy interception induced by urban forest stand structure became more apparent compared to short-term sampling campaigns.

## Potential forest management implications

Urban forest management and planning requires knowledge on optimal stand structure for maximizing canopy interception when developing strategies for mitigating stormwater runoff and flooding. Forest stand structure has a direct impact on rainfall partitioning in forest ecosystems (Brauman et al. 2010). In order to maximize canopy interception, appropriate forest stand structure should be established and then maintained with silvicultural measures. Urban forest management activities alter the structure of forest stands, which can be expected to influence rainfall partitioning in canopies. The impacts of managing the forest structure were evident and the effects of logging on rainfall partitioning have been observed in many studies (Dietz et al. 2006). Typically, interception in an unlogged forest would be greater than in a selectively logged (or naturally disturbed) forest stand (Asdak et al. 1998). Dietz et al. (2006) reported lower canopy interception in forest plots under management than in natural or unmanaged forest (18–20% versus 30% of bulk precipitation, respectively).

When canopy interception by urban forest is a priority in forest management goals, several general aspects ought to be considered. Firstly, species composition should contain deciduous and coniferous trees, forming mixed forest stands. Forests containing species that are adapted to particular site are also more biologically resilient and prone to sudden environmental (climate) changes (Beniston et al. 2007). Secondly, continuous canopy cover should be maintained and larger canopy gaps need to be avoided. And finally, evergreen tree species with larger dimensions (wider crowns) are desired due to their ability to intercept precipitation in the leafless period. In our study, the mixed forest exhibited many of these features, while the riparian pine forest and the floodplain hardwood forest fulfilled them to a lesser degree.

Key findings of this study indicate that for the maximized canopy interception, urban forest structure should have mixed tree species composition and canopy cover must be maintained at sufficient level. This may be useful for urban forest management and planning and could contribute to the implementation of hydrology-oriented silvicultural measures in urban forests, aiming at mitigating stormwater runoff and flooding (Kimbauer et al. 2013; Livesley et al. 2014).

## Conclusions

In this study, selected urban forests differed considerably in terms of tree species composition, canopy cover and tree dimensions. Gerrits et al. (2010) reported that interception is considered to be about 15–50% of total incoming precipitation on forests in temperate humid latitudes. In the mixed forest, average canopy intercepted accounted for 18% of bulk precipitation, which is within this interval. Hence, optimal stand

structure for maximized canopy interception regardless of the season was in the mixed forest, characterized by high share of coniferous evergreen trees, highest canopy cover and highest growing stock. However, the riparian pine forest (experiencing loose canopy cover and smaller tree dimensions) and the floodplain hardwood forest (in which deciduous tree species prevailed) exhibited evidently lower canopy interception (3.9% and 7.1% of bulk precipitation, respectively).

Canopy interception was related to rainfall spatial distribution and rainfall intensity as well. Seasonal variation in canopy interception was explained by different rainfall intensity. In the mixed forest, canopy interception was higher during the leafed period due to higher rainfall intensity. However, canopy interception in the riparian pine forest and the floodplain hardwood forest was higher during the leafless period. This could indicate different rainfall characteristic patterns between two locations of selected urban forest stands and the need for further investigations.

With the precipitation interception, vegetation cover (especially forests) importantly influence quantity and quality of water resources in urbanized watersheds. Thus, urban forest management and planning requires knowledge on optimal stand structure for maximizing canopy interception when developing strategies for mitigating stormwater runoff and flooding. In addition, future research, including a larger number of sites and in situ measurements of stemflow and rainfall characteristics, might contribute to a better understanding of the effect of stand structure on canopy interception in urban forests.

**Acknowledgements** The study was part of a Master of Science thesis at the Department of Forestry and Renewable Forest Resources, Biotechnical Faculty, University of Ljubljana, and partially funded by the Pahernik Foundation, Life + project EMonFur - Establishing a monitoring network to assess lowland forest and urban plantation in Lombardy and urban forests in Slovenia (LIFE+ 10 ENV/IT/000399), COST Action FP1204 ‘Green Infrastructure approach: linking environmental with social aspects in studying and managing urban forests’ and the Slovenian Research Agency core funding for the Programme Group ‘Forest biology, ecology and technology’ P4-0107. We would like to acknowledge our gratitude to prof. Janez Pirnat for reading previous versions of the manuscript. We thank Jean McCollister for proofreading our manuscript.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

## References

- Archive of phenological data (2015) Slovenian environment Agency. Bureau of Meteorology, Department of Agrometeorology
- Armson D, Stringer P, Ennos AR (2012) The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban For Urban Gree* 11:245–255

- Asadian Y (2007) Rainfall interception in an urban environment. Master's thesis, the Faculty of Graduate Studies (Forestry), the University of British Columbia, 84 p
- Asadian Y, Weiler M (2009) A new approach in measuring rainfall interception by urban trees in coastal British Columbia. *Water Qual Res J Can* 44:16–25
- Asdak C, Jarvis PG, Gardingen PV (1998) Modelling rainfall interception in unlogged and logged forest areas of Central Kalimantan, Indonesia. *Hydrol Earth Syst Sc* 2:211–220
- Barbier S, Balandier P, Gosselin F (2009) Influence of several tree traits on rainfall partitioning in temperate and boreal forests: a review. *Ann Forest Sci* 66:602–613
- Bealey WJ, McDonald AG, Nemitz E, Donovan R, Dragosits U, Duffy TR, Fowler D (2007) Estimating the reduction of urban PM10 concentrations by trees within an environmental information system for planners. *J Environ Manag* 85:44–58
- Bellet J, Escarre A (1998) Stemflow and throughfall determination in a resprouted Mediterranean holm-oak forest. *Ann Forest Sci* 55:847–865
- Beniston M, Stephenson DB, Christensen OB, Ferro CAT, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B, Palutikof J, Schöll R, Semmler T, Woth K (2007) Future extreme events in European climate: an exploration of regional climate model projections. *Clim Chang* 81:71–95
- Bolund P, Hunhammar S (1999) Ecosystem services in urban areas. *Ecol Econ* 29:293–301
- Brack CL (2002) Pollution mitigation and carbon sequestration by an urban forest. *Environ Pollut* 116:195–200
- Brauman KA, Freyberg DL, Daily GC (2010) Forest structure influences on rainfall partitioning and cloud interception: a comparison of native forest sites in Kona, Hawai'i. *Agric For Meteorol* 150:265–275
- Brus R (2004) Drevesne vrste na Slovenskem. Ljubljana, Mladinska knjiga 399 p
- Bryant ML, Bhat S, Jacobs JM (2005) Measurement and modeling of throughfall variability for five forest communities in the southeastern US. *J Hydrol* 312:95–108
- Canham CD, Finzi AC, Pacala SW, Burbank DH (1994) Causes and consequences of resource heterogeneity in forests: interspecific variation in light transmission by canopy trees. *Can J For Res* 24:337–349
- Cantú Silva I, Okumura T (1996) Throughfall, stemflow and interception loss in a mixed white oak forest (*Quercus serrata* Thunb.) *J Forest Res* 1:123–129
- Carlyle-Moses DE, Price AG (1999) An evaluation of the gash interception model in a northern hardwood stand. *J Hydrol* 214:103–110
- Chen WY, Jim CY (2008) Assessment and Valuation of the Ecosystem Services Provided by Urban Forests. In: Carreiro MM, Song YC, Wu J (eds) *Ecology, planning, and Management of Urban Forests. International Perspectives*, Springer-Verlag, New York, pp 53–83
- Clarke N, Zlindra D, Ulrich E, Mosello R, Derome J, Derome K, König N, Lövblad G, Draaijers GPJ, Hansen K, Thimonier A, Waldner P (2010) Sampling and analysis of deposition. Manual part XIV. In: *Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. United Nations economic Commission for Europe Convention on long-range Transboundary air pollution, ICP forests, Hamburg, part XIV*, 66 p
- Clements JR (1971) Evaluating summer rainfall through a multilayered Largetooth aspen community. *Can J For Res* 1:20–31
- Clements JR (1972) Stemflow in a multi-storied aspen community. *Can J For Res* 2:160–165
- Crockford RH, Richardson DP (1990) Partitioning of rainfall in a eucalypt forest and pine plantation in southeastern Australia: I throughfall measurement in a eucalypt forest: effect of method and species composition. *Hydrol Process* 4:131–144
- Crockford RH, Richardson DP (2000) Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrol Process* 14:2903–2920
- Dakskobler I, Kutnar L, Šilc U (2013) Poplavni, močvirni in obrežni gozdovi v Sloveniji: gozdovi vrb, jelš, dolgopecljatega bresta, velikega in ozkolistnega jesena, doba in rdečega bora ob rekah in potokih. Ljubljana, Silva Slovenica, Gozdarski inštitut Slovenije, Zveza gozdarskih društev Slovenije, Gozdarska založba:128 p
- Dalsgaard L (2007) Above and below ground gaps – the effects of a small canopy opening on throughfall, soil moisture and tree transpiration in Suserup Skov, Denmark. *Ecol Bull* 52:81–102
- Deguchi A, Hattori S, Park HT (2006) The influence of seasonal changes in canopy structure on interception loss: application of the revised gash model. *J Hydrol* 318:80–102
- Dietz J, Hölscher D, Leuschner C, Hendrayanto (2006) Rainfall partitioning in relation to forest structure in differently managed montane forest stands in Central Sulawesi, Indonesia. *Forest Ecol Manag* 237:170–178
- Diodato N (2005) The influence of topographic variables on the spatial variability of precipitation over small regions of complex terrain. *Int J Climatol* 25:351–363
- Dobbertin M, Neumann M (2010) Tree growth. Manual part V. In: *Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. United Nations economic Commission for Europe Convention on long-range Transboundary air pollution, ICP forests, Hamburg, part V*, 29 p
- Dohnal M, Čemý T, Votrubová J, Tesař M (2014) Rainfall interception and spatial variability of throughfall in spruce stand. *J Hydrol Hydromech* 62:277–284
- Dolman AJ (1987) Summer and winter rainfall interception in an oak forest. Predictions with an analytical and a numerical simulation model. *J Hydrol* 90:1–9
- Fletcher TD, Vietz G, Walsh CJ (2014) Protection of stream ecosystem from urban stormwater runoff: the multiple benefits of an ecohydrological approach. *Prog Phys Geogr* 38:543–555
- Gerrits AMJ, Pfister L, Savenije HHG (2010) Spatial and temporal variability of canopy and forest floor interception in a beech forest. *Hydrol Process* 24:3011–3025
- Guevara-Escobar A, González-Sosa E, Véliz-Chávez C, Ventura-Ramos E, Ramos-Salinas M (2007) Rainfall interception and distribution patterns of gross precipitation around an isolated *Ficus Benjaminia* tree in an urban area. *J Hydrol* 333:532–541
- Hamada S, Ohta T (2010) Seasonal variations in the colling effect of urban green areas on surrounding urban areas. *Urban For Urban Gree* 9:15–24
- Herbst M, Rosier PTW, McNeil DD, Harding RJ, Gowing DJ (2008) Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest. *Agric For Meteorol* 148:1655–1667
- Herwitz SR, Levia DF (1997) Mid-winter stemflow drainage from bigtooth aspen (*Populus grandidentata* Michx.) in central Massachusetts. *Hydrol Process* 11:169–175
- Hosseini Ghaleh Bahmani SM, Attarod P, Bayramzadeh V, Ahmadi MT, Radmehr A (2012) Throughfall, stemflow, and rainfall interception in a natural pure forest of chestnut-leaved oak (*Quercus castaneifolia* C. A. Mey.) in the Caspian Forest of Iran. *Ann For Res* 55:197–206
- HouBao F, Wei H, Zhuang M, Kosuke W (1999) Acidity and chemistry of bulk precipitation, throughfall and stemflow in a Chinese fir plantation in Fujian, China. *Forest Ecol Manag* 122:243–248
- Inkiläinen ENM, McHale MR, Blank GB, James AL, Nikinmaa E (2013) The role of the residential urban forest in regulating throughfall: a case study in Raleigh, North Carolina, USA. *Landscape Urban Plan* 119:91–103
- Kermavnar J (2015) Sestojne padavine v izbranih urbanih gozdovih Ljubljane. Stand precipitation in selected urban forests in the City of Ljubljana. MSc thesis, University of Ljubljana, Biotechnical faculty, Department of Forestry and Renewable Forest Resources, Slovenia, 102 p

- Kirnbauer MC, Baetz BW, Kenney WA (2013) Estimating the stormwater attenuation benefits derived from planting four monoculture species of deciduous trees in vacant and underutilized urban land parcels. *Urban For Urban Gree* 12:401–407
- Krämer I, Hölscher D (2010) Chapter 2: rainfall partitioning along a tree diversity gradient in a deciduous old-growth forest in Central Germany. In: rainfall partitioning and soil water dynamics along a tree species diversity gradient in a deciduous old-growth forest in Central Germany (Krämer I.): dissertation, MSc environmental sciences, Göttingen Centre for Biodiversity and Ecology: 17–46
- Laforteza R, Carrus G, Sanesi G, Davies C (2009) Benefits and well-being perceived by people visiting green spaces in periods of heat stress. *Urban For Urban Gree* 8:97–108
- Leonardi S, Rapp M, Failla M, Guarnaccia D (1993) Interception of rainfall, input and leaching of nutrients within two *Castanea sativa* Mill stands at the Etna volcano. *Oecol Mont* 2:7–12
- Levia DF, Frost EE (2003) A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. *J Hydrol* 1–4:1–29
- Li X, Xiao Q, Niu J, Dymond S, van Doorn NS, Yu X, Xie B, Lv X, Zhang K, Li J (2016) Process-based rainfall interception by small trees in northern China: the effect of rainfall traits and crown structure characteristics. *Agric For Meteorol* 218–219:65–73
- Liang W (2014) Short communication: simulations of gash model to rainfall interception of *Pinus tabulaeformis*. *Forest Syst* 23:300–303
- Limousin JM, Rambal S, Ourcival JM, Joffre R (2008) Modelling rainfall interception in a mediterranean *Quercus ilex* ecosystem: lesson from a throughfall exclusion experiment. *J Hydrol* 357:57–66
- Liu ZW, Chen RS, Song YX (2011) Characteristics of stemflow for typical alpine shrubs in Qilian Mountain. *J Appl Ecol* 22:1975–1981
- Livesley SJ, Baudinette B, Glover D (2014) Rainfall interception and stemflow by eucalypt street trees – the impacts of canopy density and bark type. *Urban For Urban Gree* 13:192–197
- Llyod CR, Marques ADO (1988) Spatial variability of throughfall and stemflow measurements in Amazonian rainforest. *Agric For Meteorol* 42:63–73
- Loose A, Jazbinšek Sršen N, Jankovič M (2010) Ready for Tomorrow. The Ljubljana Environmental Protection Program to 2013. City of Ljubljana. Department of Environmental Protection, Ljubljana, 18 p
- Loustau D, Berbigier P, Granier A, El Hadj MF (1992) Interception loss, throughfall and stemflow in a maritime pine stand. Variability of throughfall and stemflow beneath the pine canopy *J Hydrol* 138: 449–467
- Mahendrappa MK (1990) Partitioning of rainwater and chemicals into throughfall and stemflow in different forest stands. *For Ecol Manag* 30:65–72
- McDonald AG, Bealey WJ, Fowler D, Dragosits U, Skiba U, Smith RI, Donovan RG, Brett HE, Hewitt CN, Nemitz E (2007) Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. *Atmos Environ* 41:8455–8467
- McKee AJ (2010) The quantitative importance of stemflow: an evaluation of past research and results from a study in lodgepole pine (*Pinus contorta* Var. *latifolia*) stands in southern British Columbia: thesis for the degree of Master of Science (environmental Science). Thompson rivers University, British Columbia 113 p
- McPherson G, Simpson JR, Peper PJ, Maco SE, Xiao Q (2005) Municipal Forest benefits and costs in five US cities. *J Forestry* 103:411–416
- Moreno Perez MF, Roldan Cañas J, Perez Arellano R, Cienfuegos I (2013) Distribution of incident rainfall through vegetation in a watershed located in southern Spain. EGU General Assembly Conference Abstracts 15:4234
- Mosello R, Brizzio MC, Kotzias D, Marchetto A, Rembges D, Tartari G (2002) The chemistry of atmospheric deposition in Italy in the framework of the National Programme for Forest ecosystems control (CONECOFOR). *J Limnol* 61:77–92
- Nihlgård B (1970) Precipitation, its chemical composition and effect on soil water in a beech and a spruce forest in south Sweden. *Oikos* 21: 208–217
- Park A, Cameron JL (2008) The influence of canopy traits on throughfall and stemflow in five tropical trees growing in a Panamanian plantation. *Forest Ecol Manag* 255:1915–1925
- Price AG, Carlyle-Moses DE (2003) Measurement and modelling of growing-season canopy water fluxes in a mature mixed deciduous forest stand, southern Ontario, Canada. *Agric For Meteorol* 119:69–85
- Rutter AJ, Kershaw KA, Robins PC, Morton AJ (1971) A predictive model of rainfall interception in forests, 1. Derivation of the model from observations in a plantation of Corsican pine. *Agr Meteorol* 9:367–384
- Sadeghi SMM, Attarod P, Van Stan JT, Pypker TG (2016) The importance of considering rainfall partitioning in afforestation initiatives in semiarid climates: a comparison of common planted tree species in Tehran, Iran. *Sci Total Environ* 568:845–855
- Saito T, Matsuda H, Komatsu M, Xiang Y, Takahashi A, Shinohara Y, Otsuki K (2013) Forest canopy interception loss exceeds wet canopy evaporation in Japanese cypress (Hinoki) and Japanese cedar (Sugi) plantations. *J Hydrol* 507:287–299
- Sanders RA (1986) Urban vegetation impacts on the hydrology of Dayton, Ohio. *Urban Ecol* 9:361–376
- Sanesi G, Gallis C, Kasperidus HD (2011) Chapter 2: urban forests and their ecosystem services in relation to human health. In: Nilsson K, Sangster M, Gallis C, Hartig T, de Vries S, Seeland K, Schipperijn J (eds) forests, trees and human health. Springer, pp 23–40
- Scatena FN (1990) Watershed scale rainfall interception on two forested watersheds in the Luquillo Mountains of Puerto Rico. *J Hydrol* 113: 89–102
- Schooling JT (2014) The influence of tree traits and storm event characteristics on stemflow production from isolated deciduous trees in an urban park. Ph.D Thesis, Thompson Rivers University, Kamloops, British Columbia, Canada, 103 p
- Schooling JT, Carlyle-Moses DE (2015) The influence of rainfall depth class and deciduous tree traits on stemflow production in an urban park. *Urban Ecosyst* 18:1261–1284
- Siegert CM, Levia DF, Hudson SA, Dowtin AL, Zhang F, Mitchell MJ (2016) Small-scale topographic variability influences trees species distribution and canopy throughfall partitioning in a temperate deciduous forest. *Forest Ecol Manag* 359:109–117
- Slovenian Environment Agency archive (2015) Archive of measurements - observed and measured meteorological data in Slovenia. <http://meteo.arso.gov.si/met/sl/archive/>. Accessed July/August 2015
- Smrekar A, Erhartič B, Hribar Šmid M (2011) Krajinski park Tivoli, Rožnik in Šišenski hrib (Landscape park Tivoli, Rožnik, Šišenski hrib). GEORITEM, Založba ZRC, Ljubljana, 134 p
- Spittlehouse DL (1998) Rainfall interception in young and mature conifer forest in British Columbia. In: proceedings. In: 23rd Conference on agricultural and Forest Meteorology, Albuquerque, Boston, N. M. American Meteorological Society, pp 171–174
- Šraj M, Brilly M, Mikoš M (2008a) Rainfall interception by two deciduous Mediterranean forests of contrasting stature in Slovenia. *Agric For Meteorol* 148:121–134
- Šraj M, Lah A, Brilly M (2008b) Meritve in analiza prestreženih padavin navadne breze (*Betula pendula* Roth.) in rdečega bora (*Pinus sylvestris* L.) v urbanem okolju. *Gozdarski vestnik (Professional Journal of Forstry)* 66: 406–416 and 433
- Stogsdill WR, Wittwer RF, Hennessey TC, Dougherty PM (1989) Relationship between throughfall and stand density in a *Pinus Taeda* plantation. *Forest Ecol Manag* 29:105–113
- Sušnik A, Valher A (2014) Od mokre pomladi do sušnega poletja 2013 (from wet spring to severe summer drought of 2013). *Ujma* 28:75–84
- Tetzlaff D, Uhlenbrook S (2005) Significance of spatial variability in precipitation for process-oriented modelling: results from two nested catchments using radar and ground station data. *Hydrol Earth Syst Sc* 9:29–41

- Toba T, Ohta T (2005) An observational study of the factors that influence interception loss in boreal and temperate forests. *J Hydrol* 313:208–220
- Tsiontsis AI, Dini-Papanastasi O, Gakis S (2001) Water cycling in black locust (*Robinia pseudoacacia* L.) plantations in northern Greece. In: proceedings international Conference Forest research: a challenge for an integrated European approach, volume II. Radoglou K (ed): 543–546
- Tyrväinen L, Pauleit S, Seeland K, de Vries S (2005) Chapter 4: Benefits and Uses of Urban Forests and Trees. In: Konijnendijk CC, Nilsson K, Randrup TB, Schipperijn J (eds) Urban forests and trees. Springer-Verlag, Berlin Heidelberg, pp 81–114
- Valente F, David JS, Gash JHC (1997) Modelling interception loss for two sparse eucalypt and pine forest in central Portugal using reformulated Rutter and gash analytical models. *J Hydrol* 190:141–162
- Veneklaas EJ, Van Ek R (1990) Rainfall interception in two tropical montane rain forests, Colombia. *Hydrol Process* 4:311–326
- Verlič A, Đurić N, Kokalj Ž, Marsetič A, Simončič P, Oštir K (2014a) Tree species classification using WorldView-2 satellite images and laser scanning data in a natural urban forest = Klasifikacija vrsta drveča u prirodnoj urbanoj šumi koristeći WorldView-2 satelitske snimke i lidar. *Šumarski list* 138:477–488
- Verlič A, Eler K, Ferlan M, Flajšman K, De Groot M, Hauptman T, Jurc D, Kopal M, Kutnar L, Levanič T, Marinšek A, Ogris N, Simončič P, Skudnik M, Vochl S, Žlindra D, Vilhar U (2014b) EMONFUR – Zasnova mreže za spremljanje stanja nižinskega gozda in pogozditev v urbanem prostoru v Lombardiji in urbanega gozda v Sloveniji: zaključno poročilo o projektu. EMONFUR – establishing a monitoring network to assess lowland forest and urban plantation in Lombardy and urban forest in Slovenia: final project report. Gozdarski inštitut Slovenije. Slovenian Forestry Institute, Ljubljana, 156 p
- Vilhar U (2010) Padavinski režim v izbranih vrzelih in sestojih dinarskega jelovo-bukovega gozda. Precipitation regime in gaps and mature stands of Dinaric silver fir-beech forests *Zbornik gozdarstva in lesarstva* 91:43–58
- Vilhar U (2016) Sestojne padavine v mešanih sestojih smreke in bukve na Pohorju. Throughfall in Mixed Beech-Spruce Forests in the Pohorje Mountains *Gozdarski vestnik (Professional Journal of Forestry)* 74: 28–45
- Vilhar U, Čarni A, Božič G (2013) Rastne in vegetacijske značilnosti evropskega črnega topola (*Populus nigra* L.) v poplavnem gozdu ob reki Savi in temperaturne razlike med izbranimi rastišči. Growth and vegetation characteristics of European black poplar (*Populus nigra* L.) in a floodplain forest along river Sava and temperature differences among selected sites. *Folia biologica et geologica* 45:193–214
- Vilhar U, Zupin R, Diaci J (2017) Primerjava padavin na ploskvah intenzivnega monitoringa gozdov v Sloveniji. Comparison of Precipitation on Forest Monitoring Plots in Slovenia *Gozdarski vestnik* 75:59–74
- Voss S, Zimmermann B, Zimmermann A (2016) Detecting spatial structures in throughfall data: the effect of extent, sample size, sampling design, and variogram estimation method. *J Hydrol* 540:527–537
- Wang J, Endreny TA, Nowak DJ (2008) Mechanistic simulation of tree effects in an urban water balance model. *J Am Water Resour As* 44:75–85
- Wang L, Zhang Q, Shao M, Wang Q (2013) Rainfall interception in a *Robinia pseudoacacia* Forest stand: estimates using Gash's analytical model. *J Hydrol Eng* 18:474–479
- Williams MB (2004) Investigating the contribution of stemflow to the hydrology of a forest catchment, Bachelor's degree in environmental Science. University of Southampton 52 p
- WRB (2007) World reference base for soil resources 2006, first update 2007. IUSS, ISRIC, FAO, Rome, World Soil Resources Reports No 103, 115 p
- Xiao Q, McPherson EG (2002) Rainfall interception by Santa Monica's municipal urban forest. *Urban Ecosyst* 6:291–302
- Xiao Q, McPherson EG (2011) Rainfall interception of three trees in Oakland, California. *Urban Ecosyst* 14:755–769
- Xiao Q, McPherson EG, Simpson JR, Ustin SL (1998) Rainfall interception by Sacramento's urban forest. *J Arboric* 24:235–244
- Xiao Q, McPherson EG, Ustin SL, Grismer ME, Simpson JR (2000a) Winter rainfall interception by two mature open-grown trees in Davis, California. *Hydrol Process* 14:763–784
- Xiao Q, McPherson EG, Ustin SL, Grismer ME (2000b) A new approach to modeling tree rainfall interception. *J Geophys Res* 105:173–188
- Zabret K, Šraj M (2015) Can urban trees reduce the impact of climate change on storm runoff? *Urbani izzivi* 26:165–178. doi:10.5379/urbani-izziv-en-2015-26-supplement-011
- Zabret K, Mikoš M, Rakovec J, Šraj M (2016) Proces prestrezanja padavin: vpliv fenološke faze, trajanja padavinskega dogodka ter mikrostrukture padavin. Conference Paper, Raziskave s področja geodezije in geofizike, Ljubljana, Slovenia, Zbornik referatov: 111–121
- Zhang J (2009) Water conservation function of *Alnus cremastogyne* Burk plantations in north of Hunan Province: Master's thesis. Central South University of Forestry Science and Technology 191 p
- Zimmermann A, Wilcke W, Elsenbeer H (2007) Spatial and temporal patterns of throughfall quantity and quality in a tropical montane forest in Ecuador. *J Hydrol* 343:80–96
- Zimmermann B, Zimmermann A, Lark MR, Elsenbeer H (2010) Sampling procedures for throughfall monitoring: a simulation study. *Water Resour Res* 46:W01503
- Zlindra D, Eler K, Clarke N, Simončič P (2011) Towards harmonization of forest deposition collectors – case study of comparing collector designs. *iForest* 4:218–225
- Zupančič B (1995) Klimatografija Slovenije. Količina padavin: obdobje 1961–1990. Hidrometeorološki zavod Republike Slovenije, Ljubljana 366 p
- Zupancic T, Westmacott C, Bulthuis M (2015) The impact of green space on heat and air pollution in urban communities: a meta-narrative systematic review. David Suzuki Foundation, Vancouver, 68 p