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Comparative analysis of rainfall event characteristics and rainfall erosivity between two experimental plots in Austria and Slovenia

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ABSTRACT

Study region: This study investigated rainfall at two locations in the Danube Basin, the Hydrological Open Air Laboratory (HOAL) agricultural catchment in Petzenkirchen, Austria and an urban experimental plot in Ljubljana, Slovenia.

Study focus: The variability of rainfall characteristics and rainfall erosivity were explored using measurements of precipitation and drop size distributions in the period 2014–2018. Annual and seasonal rainfall event characteristics were analyzed for each site and comparatively assessed using hierarchical clustering. Annual and seasonal variability of rainfall erosivity was compared between the plots.

New hydrological insights for the region: Despite having the same Köppen-Geiger climate classification, differences were found between the sites. The long-term average annual precipitation in Ljubljana was almost twice as high as in the HOAL. According to the clustering analysis, larger and more intense rainfall events occurred in Ljubljana than in the HOAL. The average drop sizes and velocities tended to be lower in Ljubljana but the range of drop size distributions was larger in Ljubljana than in the HOAL. The seasonalities of rainfall event characteristics and rainfall erosivity were similar at the sites. Rainfall intensities tended to peak in summer when rainfall durations were shorter, and larger and faster drops were observed. Rainfall erosivity was between 2 and 7 times larger in Ljubljana than in the HOAL because of the more intense rainfall and single faster and larger drops during events.

1. Introduction

The temporal and spatial variability of rainfall events can be quantified by the rainfall amount, intensity, frequency, and duration based on rainfall measurements. The most direct measure of precipitation is provided by gauge networks. The spatial distribution of precipitation can be acquired by weather radars at the regional scale, and by satellites at the global scale (Kidd and Huffman, 2011).

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Detailed information on precipitation microstructure can be obtained by disdrometers (Uijlenhoet and Sempere Torres, 2006).

Rainfall variability influences several key processes, including soil erosion. Soil erosion has a significant impact on the environment as it affects sedimentation and pollution in water bodies or threatens agricultural production due to soil degradation (Bezak et al., 2020; Pidoto et al., 2022; Schmaltz et al., 2023). Soil erosion is most often estimated using the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE) models (Renard et al., 1991, 1997a, 1997b). The RUSLE model includes six factors to describe soil erosion, and among them is the 30-minute maximum intensity *EI30*. It includes the effects of rainfall amount, intensity and duration and as such considers the erosive power of raindrops as well as the potential transport of the detached soil particles with surface runoff (Vásquez et al., 2024).

Rainfall erosivity has been studied previously in various cases with different techniques (Wang et al., 2024). Rainfall erosivity estimates are available on the global (e.g., Panagos et al., 2017, 2023) and regional scales (e.g., Ballabio et al., 2017; Borrelli et al., 2016). Climate simulations can also provide larger scale rainfall erosivity estimates (Uber et al., 2024). Such large-scale studies and databases are efficient tools to assess differences between climatic and geographic conditions. Still, more local and more detailed studies are necessary to be able to determine the accuracy of regional rainfall erosivity. Vásquez et al. (2024) performed spatiotemporal assessment of rainfall event characteristics that induced rainfall erosivity over the main agricultural production zones of Austria. They found three dominant erosive types of events that were linked with the seasonality and topography of Austria (Vásquez et al., 2024). The largest rainfall erosivities affect the eastern regions of Austria that are also the agriculturally crucial regions of the country (Johannsen et al., 2022). Rainfall erosivity is still significantly smaller compared to the Mediterranean region including Slovenia (Panagos et al., 2023). On the other hand, the erosive power of rainfall can be considerably modulated by the vegetation. Zore et al. (2022) and Radulović et al. (2023) studied the influence of interception on soil erosion for an urban study plot in Slovenia and they found that rainfall erosivity decreased below the canopy.

Studies based on measurements are often limited to a single location (e.g., Evans, 2017; Majewski and Szpikowski, 2024; Porto et al., 2023), whereas studies that provide results for a larger area are usually based on spatial data (e.g., Bezak, et al., 2022; Thapa, 2020). However, spatial analyses are often supported by numerous on-site observations distributed across the study area (Fenta et al., 2023; Kebede et al., 2021; Panagos et al., 2015). On the other hand, due to the limited availability of disdrometer data, the majority of previous studies were based on only rainfall data, without information on the drop size distributions. Furthermore, these measurements may have different characteristics, such as using different measurement equipment, methods and time steps for data recording, or positions on a site with different characteristics such as land use. Many of these differences can be resolved by appropriate data pre-processing. There are only a few studies on exploring the regional variability of rainfall characteristics, along a transect, that are supported by ground-based observations of both rainfall and drop size distribution measurements. Therefore, the main objective of this study is to assess the similarities and differences of rainfall characteristics and estimated rainfall erosivity between two distinct study sites in the Danube River Basin, located in the same climate region. The study utilizes 5-year-long continuous measurements from not only rain gauges but also from optical disdrometers. The findings of this study are useful for assessing the accuracy of large-scale rainfall erosivity estimates.

Fig. 1. Location of the two study sites showing the Köppen-Geiger climate classification in the background superimposed on terrain (based on Beck et al., 2023).

2. Material and methods

2.1. Study area

Two study sites were included in the comparison, namely the Hydrological Open Air Laboratory (HOAL) in Petzenkirchen, Austria and a research plot in a small urban park in the city of Ljubljana, Slovenia (Fig. 1). Both locations are characterized by temperate oceanic climate type (Cfb) according to Köppen-Geiger climate classification and have a long-term established measurement network of various hydrological variables (Fig. 1).

2.1.1. Hydrological Open Air Laboratory (HOAL), Austria

One of the study plots was located at a small (66 ha) experimental catchment, the Hydrological Open Air Laboratory (HOAL) in Petzenkirchen, Lower Austria (Fig. 2) (48.15° N, 15.15° E). The HOAL is a lowland catchment (268–323 m above sea level), with a mean slope of 8 % (Blöschl et al., 2016). The climate is humid. The long–term (2002–2018) mean annual air temperature and precipitation were 9.8 °C and 723 mm, respectively. Seasonal maxima of air temperature, rainfall amount and intensity typically occur in the summer (Fig. 3 in Blöschl et al., 2016). The catchment is characterized by clayey soils with dominant soil types of Cambisols (57 %), Kolluvisols (16 %) and Planosols (21 %), and Gleysols (6 %) close to the stream (Blöschl et al., 2016; FAO et al., 1998). The catchment is dominated by agricultural land use, the rest of the catchment is forested, paved or used as pasture. The weather station is located on a grassed patch surrounded by agricultural fields (Fig. 2). The crops are mainly winter wheat, maize, winter barley and winter oilseed rape.

2.1.2. Research plot in an urban park in Ljubljana, Slovenia

The second study site is a research plot in a small urban park (600 m^2), located in the city of Ljubljana, Slovenia (46.04° N, 14.49° E). The research plot is situated 292 m above sea level. It is characterized by a sub-alpine climate with well-defined seasons. The long term (2002–2018) average yearly air temperature is 11.7 °C and yearly average precipitation amount is 1385 mm. The highest air temperatures, above 20 °C on average, are observed in summer, while the most precipitation is delivered in autumn (ARSO, 2024). The terrain of the wider area of the plot was flattened and elevated after the year 1945, using mostly alluvial soils and a small portion of construction debris (urban/anthropogenic soil). The soil in the plot is classified as loam (L) and silt loam (SL) in most of the identified horizons (Zabret et al., 2023). The study plot area is covered with regularly cut grass. There is a clearing in the eastern part of the plot and larger trees in the western part (Zabret et al., 2023). The park is surrounded by buildings and parking lots (Fig. 3). The rainfall gauges are located at the clearing on the eastern side of the plot and on the southern part of the building, while the disdrometer is located at the rooftop above the trees (Zabret et al., 2017).

2.2. Data

Five-year period (2014–2018) was selected for the analysis, when sensors, the sensors' locations, and measurements at both study sites were consistent and relatively continuous.

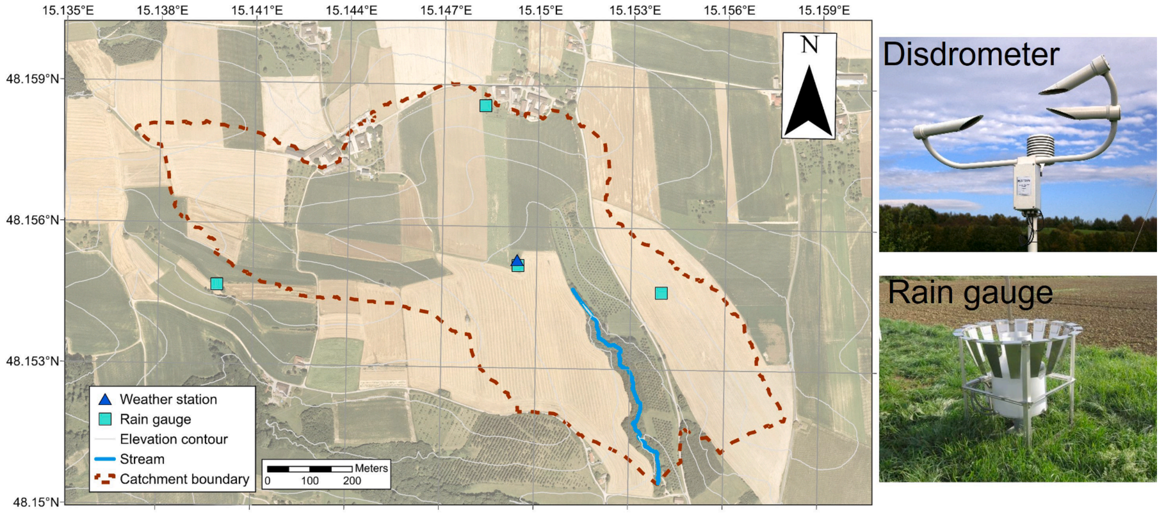

Fig. 2. Hydrological Open Air Laboratory (HOAL), Austria (disdrometer was located at the weather station), measurement equipment on the right: Campbell Scientific Present Weather Sensor 100 disdrometer and OTT Pluvio^2 rain gauge.

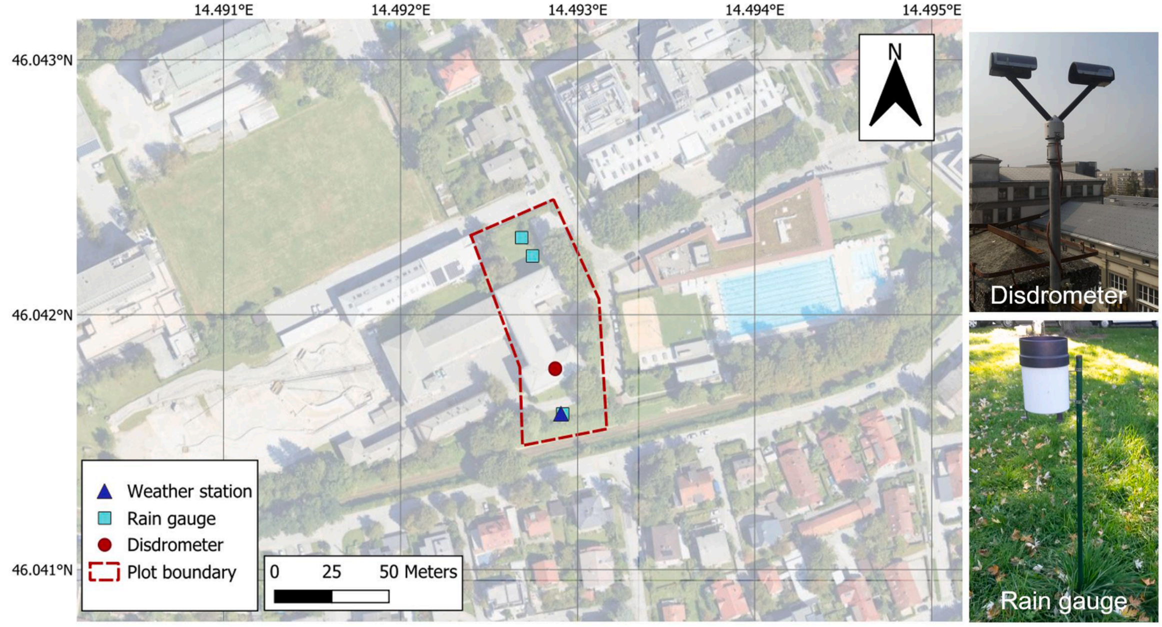

Fig. 3. Urban park experimental plot in Ljubljana, Slovenia with measurement equipment on the right: OTT Parsivel disdrometer and HOBO tipping bucket rain gauge.

2.2.1. *The HOAL, Austria*

In the Hydrological Open Air Laboratory precipitation was measured with one-minute temporal resolution by four OTT Pluvio^2 weighing rain gauges, with a collecting area of 400 cm^2, located at three points within the catchment and at an additional point very close to the catchment boundary (Fig. 2).

The size and velocity of the water droplets in the air were measured by a Campbell Scientific PWS100 laser-based present weather sensor located at the weather station. The measuring area of the sensor is 40 cm^2. The disdrometer provided measurements with 1-min temporal resolution. The device measured particle sizes from 0.1 mm to 30 mm and particle velocities from 0.16 m/s to 30 m/s. For each minute, the particles were classified into 34 diameter and velocity classes. The average values of the class boundaries were used for the data analysis. An extended data gap occurred between the summer of 2016 and spring 2017 when the sensor had to be repaired due to the misalignment of the laser beam. A detailed analysis of the PWS100 disdrometer as compared to other equipment in the HOAL was carried out by Johannsen et al. (2020).

Air temperature (HMP 155) was measured at 2 m height with half-hourly resolution and time-lapse photographs with one-minute temporal resolution were taken by a camera (Sanyo VCC-MCH5600P) installed at the weather station.

2.2.2. *Research plot in Ljubljana, Slovenia*

Precipitation at the urban park location in Ljubljana was measured with two tipping bucket rain gauges (Onset RG2-M, 0.2 mm/tip), positioned on the same line approximately 20 m apart on the eastern part of the plot. Additionally, rainfall was measured with a Hellmann rain gauge and another tipping bucket at the meteorological station (Fig. 3). Air temperature and snow conditions were collected at the Ljubljana-Bežigrad meteorological station operated by the Slovenian Environment Agency, which is representative for the location of the study plot (Zabret et al., 2018).

Drop size distribution was measured by an OTT Parsivel disdrometer located at the rooftop of the nearest building at 14.5 m height. The measuring area of the disdrometer is 54 cm^2. The measured values were allocated to one of the 32 drop diameter classes (between 0.312 mm and 24.5 mm) and velocity classes (between 0.05 m/s and 20.8 m/s), while for the data analysis the average values of the classes were used (Zabret et al., 2017). The temporal resolution of the instrument is one minute. There was a data gap between July 2014 and July 2015 due to an instrument failure.

2.3. *Methods*

2.3.1. *Identification of rainfall events*

Precipitation measurements at the HOAL by the four weighing rain gauges were averaged as the differences between the gauges were minor. For the event selection, the one-minute data were aggregated to hourly values by taking the sum of the readings. The exact beginning and end of each event was extracted from the catchment average precipitation data with one-minute temporal resolution.

In Ljubljana the rainfall data from the rain gauges in the eastern part of the park were used. Two rain gauges were taken into account for data verification. Due to the tipping-bucket measuring concept of the gauges, the time stamp of each 0.2 mm rainfall tip was used for the events selection and definition of the start and the end of the event.

Rainfall events were identified, if all five criteria as follows were met:

1) Rainfall intensity was at least 0.025 mm/h.
2) The period between events without rainfall was at least 4 h.
3) Total event rainfall exceeded 2 mm.
4) Days with snow or frost were removed from the list of selected events as these types of precipitation require different measurement techniques and are characterized by different properties. Days with snow cover in the HOAL were identified using the time-lapse photos, while in case of the plot in Ljubljana, observations of snow precipitation and snow cover at the Ljubljana-Bežigrad meteorological station were used.
5) Events for which the average temperature was below 0°C were also discarded.

2.3.2. Rainfall characteristics

For both sites, the following three rainfall characteristics were extracted for the identified events using the rain gauge data:

1) Rainfall amount *Ra* (mm),
2) Rainfall duration *Rd* (h),
3) Rainfall intensity *Ri* (mm/h).

Disdrometer data were available for approximately 70 % of the selected events for both sites after controlling for data gaps. As different disdrometers were used at the two sites with different classification of raindrops into size and velocity classes (Figs. 2 and 3), we calculated the following characteristics for each event, that were comparable between the two devices:

1) Average drop velocity *DropV* (m/s),
2) Average drop diameter *DropD* (mm),
3) Median Volume Diameter *MVD* (mm), i.e., the diameter for which 50 % of the total volume of liquid precipitation consists of drops with diameters larger or smaller than that (Finstad et al., 1988; Nanko et al., 2016).

2.3.3. Hierarchical clustering

Hierarchical clustering was used to assess which factors, such as the location of the measurements or the season, were associated with the event characteristics. Hierarchical clustering is a method which assigns events based on their similarity (similarity between associated event characteristics) to clusters. Grouping and splitting of the clusters was based on Euclidean distance as a measure of dissimilarity between sets of observations (Zaki and Meira, 2014) and the Ward's minimum variance method using the distance matrix. Clustering was performed twice, once taking into account rainfall characteristics defined based on the rain gauge measurements (*Ra*, *Rd*, *Ri*) and once considering characteristics, determined by the disdrometer measurements (*DropD*, *DropV*, *MVD*). The name of the event was constructed from country abbreviation, year and season of the observed event. The number of clusters was set to the lowest number for which the further merging led to no significant changes in the average values of the characteristics per cluster. No data transformation was implemented before the clustering. Hierarchical clustering was performed using the Orange software (Demšar et al., 2013).

The result of the clustering is presented with the Radviz projection, a visualization technique that can display data on three or more variables in a 2-dimensional projection (Orange, 2024). The events are presented with the points inside the circle according to the influence of the corresponding variable, which is connected to its amount. Higher the value of the variable for the event, closer the point is positioned to the side of the circle, represented by that variable.

2.3.4. Rainfall erosivity assessment

The Rainfall Intensity Summarization Tool (RIST) software was used to estimate rainfall erosivity *EI30* (USDA, 2019). For both study sites, the same RIST settings were applied in order to make the results directly comparable. Previous studies used different time steps for rainfall erosivity calculations between 1 and 60 min (e.g., Panagos et al., 2017; Porto, 2016). Several studies used 30 min as a compromise (e.g., Ballabio et al., 2017; Panagos et al., 2015, Yin et al., 2007). However, some studies suggested to use time steps shorter than 30 min (e.g., Yue et al., 2020). For this reason, we used 10-min rainfall inputs. For the HOAL, the aggregation was performed from 1 min to 10-min time steps, while for Ljubljana, the aggregation of the tips in a 10-min time interval was used. Storms with less than 2 mm rainfall were omitted and storms were separated by at least 4 h. This means that storms with less than 12.7 mm rainfall amounts were also included in the analysis. The estimated rainfall erosivity would have been approximately 20 % lower if only storms with more than 12.7 mm rainfall amount were included. Rainfall erosivity was estimated based on the Revised Universal Soil Loss Equation (RUSLE) model. The kinetic energy of rainfall was calculated by using the equation of McGregor et al. (1995) as this resulted in comparable rainfall erosivity estimates to previously observed results in Slovenia (e.g., Bezak et al., 2021a, 2021b; Zore et al., 2022). The annual and monthly *EI30* were estimated as the sum of the event-based *EI30* estimates over each year and month, respectively.

3. Results

3.1. Rainfall characteristics

3.1.1. Rainfall and precipitation amounts

We selected 316 rainfall events in the Hydrological Open Air Laboratory, Austria, and 337 events in Ljubljana, Slovenia for the analysis. For 217 events in Austria and 234 events in Slovenia we also analyzed the drop size distribution DSD characteristics.

Compared to the long-term (2002–2018) precipitation in the Hydrological Open Air Laboratory, Austria (723 mm/year), the years 2015 and 2018 were rather dry (Fig. 4a). 2016 was a very wet year (896 mm precipitation and 796 mm annual sum of event-based rainfall amount), with exceptionally wet summer months. By excluding all snow events and rainfall amounts that were below the events selection thresholds (Section 2.3.1), the selected events delivered on average 80 % of the annual precipitation amounts (Fig. 4a).

In Ljubljana, Slovenia, 2014 was a very wet year (1798 mm precipitation and 1557 mm annual sum of event-based rainfall amount) and similarly to the HOAL, 2015 was the driest year (1049 mm precipitation and 947 mm annual sum of event-based rainfall amount) (Fig. 4b). Snow and small events contributed on average 16 % to the annual precipitation total (Fig. 4b).

3.1.2. Rainfall characteristics in the HOAL, Austria

The within-year variability of the rainfall characteristics showed some changes over the study period (2014–2018) (Fig. 5a–c). The median rainfall amount was lower in 2015 (4.8 mm) and 2017 (4.9 mm) compared to the other years (6.4–6.7 mm) (Fig. 5a). In all the years, events with larger than 20 mm rainfall amounts were also observed (outliers in Fig. 5a). These events had typically also longer duration, except for a few convective, very intense, short-duration rainfall events occurring in the summer months. The median rainfall duration was the lowest in 2017 (6.7 h) and the highest in 2014 (9.4 h) (Fig. 5b). While the median rainfall intensities were similar between the years, the extremes that can be associated with the largest soil loss, differed more between the years (Fig. 5c). The variability of the rainfall events characteristics had a clear seasonal pattern in the HOAL, Austria (Fig. 5d–f). The rainfall amounts and especially the rainfall intensities tended to peak in the summer months (Fig. 5d and f), while the rest of the year (winter, spring, autumn) was characterized by generally longer-duration rainfall events (Fig. 5e).

Similar to other rainfall characteristics presented above, the mean drop size distribution DSD characteristics varied little between the years (2014–18) (Fig. 6a–c). The average drop diameter, the average drop velocity and the median volume diameter tended to be the lowest in 2017 and 2018 (Fig. 6a–c). Average drop diameters, velocities and median volume diameters tended to peak in the summer (Fig. 6d–f). The different drop size distribution characteristics in the HOAL gradually increased from winter to spring, reached their maxima in the summer months, and then gradually decreased in autumn. These findings imply that rainfall erosivity is the highest in summer in the HOAL, which is related to the occurrence of more intense rainfall events.

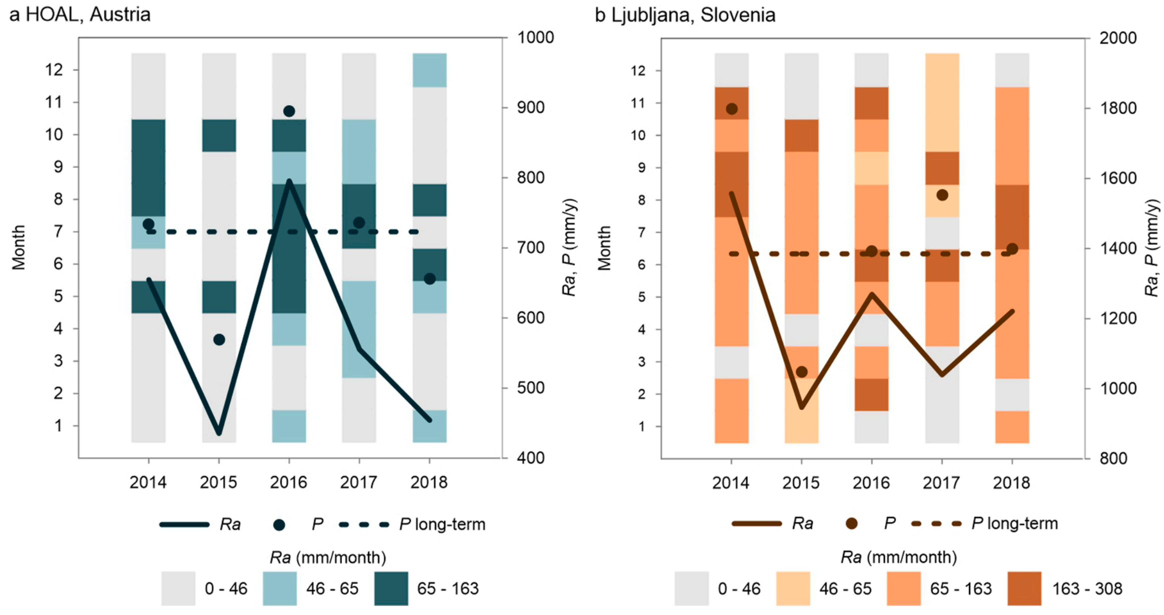

Fig. 4. Annual and monthly sum of event-based rainfall amounts *Ra* over the study period (2014–2018) in a) HOAL, Austria and in b) Ljubljana, Slovenia. Points show the annual precipitation sum *P*, the dashed line shows the long-term (2002–2018) annual average precipitation. The second y-axis limits and the bins of the monthly rainfall amounts differ between a and b.

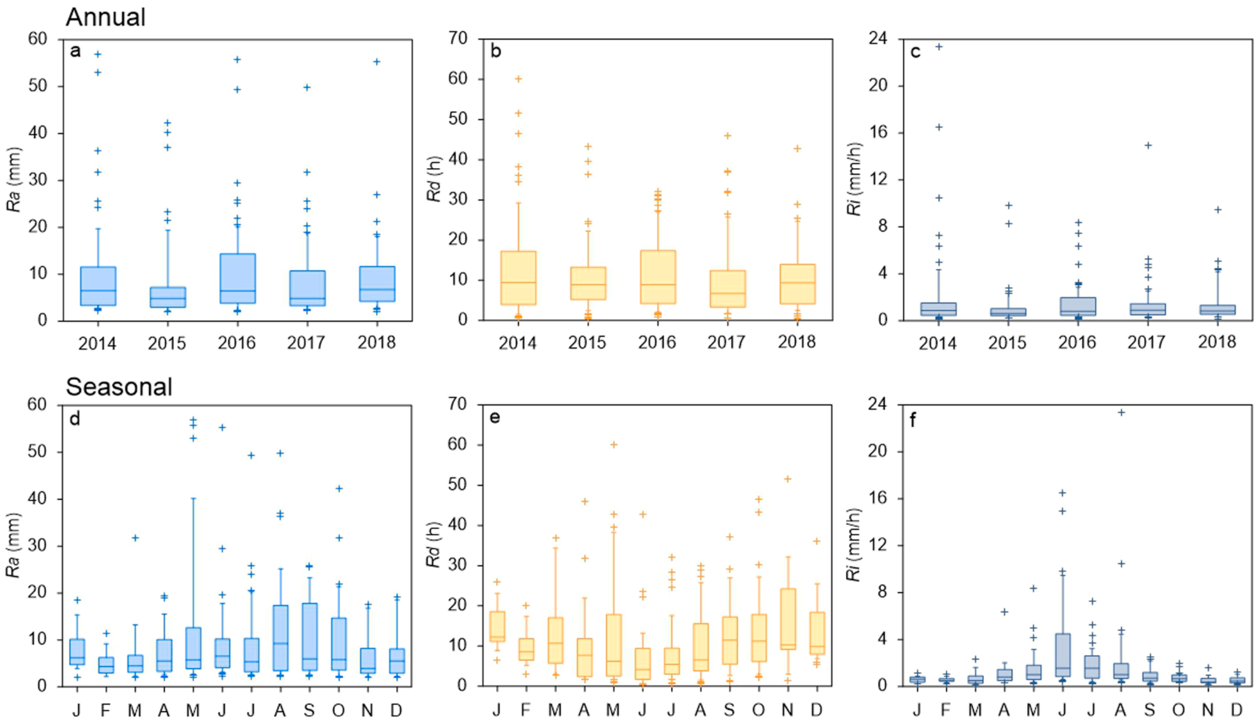

Fig. 5. Annual (top) and seasonal (bottom) variability of rainfall characteristics of all selected rainfall events in the HOAL, Austria: a and d) rainfall amount *Ra*, b and e) rainfall duration *Rd*, c and f) rainfall intensity *Ri*. (The boxes represent the lower and upper quartiles, the horizontal lines within the boxes show the median, the whiskers show the 10 % and 90 % percentiles, the plus-signs show the outliers.).

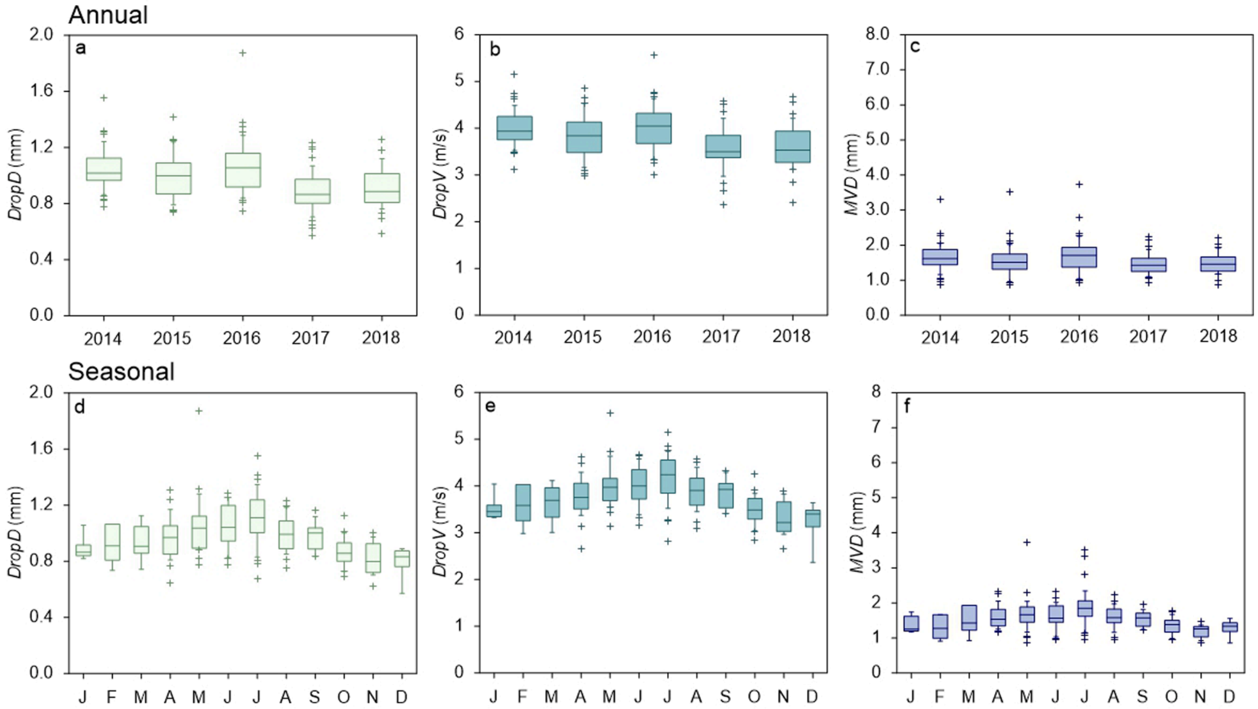

Fig. 6. Annual (top) and seasonal (bottom) variability of drop size distribution DSD characteristics of all rainfall events where DSD information was available in the HOAL, Austria: a and d) average drop diameter *DropD*, b and e) average drop velocity *DropV*, c and f) median volume diameter *MVD*.

3.1.3. Rainfall characteristics in Ljubljana, Slovenia

Similar to the HOAL, the rainfall characteristics at the research plot in Ljubljana did not vary significantly between the years (Fig. 7a-c). The median rainfall amount was the lowest in 2015 (9.4 mm) and the highest in 2018 (11.2 mm) (Fig. 7a). In all years several events delivering more than 40 mm (most outliers in Fig. 7a) were observed that were also typically long in duration except for a few short-duration events occurring mostly in summer, at the end of spring and the beginning of autumn. The median rainfall duration was the lowest in 2014 (6.3 h) and the highest in 2015 (9.1 h) (Fig. 7b). The median rainfall intensity ranged between 1.2 and 2.0 mm/h (Fig. 7c). Rainfall amounts tended to be the highest in the autumn and summer (Fig. 7d). Rainfall duration tended to be the lowest in the summer months (Fig. 7e) resulting in larger rainfall intensities (Fig. 7f).

The DSD characteristics had small variability between the years (2014–18) in Ljubljana (Fig. 8a–c). The average drop diameter was the highest in 2014 (0.9 mm) and the lowest in 2018 (0.6 mm) (Fig. 8a). The average drop velocity ranged between 3.5 and 3.9 m/s and the median volume diameter between 1.5 and 2.0 mm over the years (Fig. 8b and c). Similar to the HOAL, the seasonal variability of the drop size distribution of the rainfall events had a clear seasonality in Ljubljana (Fig. 8d–f). Average drop diameters, velocities and median volume diameters peaked in the summer, when the largest rainfall intensities were also observed.

3.1.4. Comparison of the rainfall characteristics between the two sites

The rainfall events observed in Ljubljana, Slovenia were generally larger, more intense and longer than the rainfall events observed at HOAL, Austria (Figs. 5–8). However, to determine whether the characteristics of rainfall events are as different between the two locations as the general yearly and monthly statistical values indicated, we performed hierarchical clustering of all events together regardless of the location.

Clustering of the general rainfall event characteristics of the 653 rainfall events rendered five clusters to be optimal (Table 1). The first cluster (C1) combined events from both countries characterized by high average rainfall amount and duration but low rainfall intensity (Table 1). Most of the large rainfall events in the HOAL were classified in this cluster. The second cluster (C2) contained only the rainfall events observed in Ljubljana which delivered more than 54 mm of rainfall with intensities between 2 mm/h and 20.5 mm/h. In the HOAL, only three events with more than 54 mm were observed, and all of them were assigned to C1, as they were characterized by intensities lower than 1.8 mm/h. The third cluster (C3) was the largest, containing 64 % of all the events observed at both study sites. The events had quite diverse durations and intensities, while rainfall amount was lower than 20 mm per event and was, on average, equal to 5.9 mm. The fourth cluster (C4) combined events with larger rainfall amounts than those in cluster C3, also expressing higher intensities and longer duration (Table 1). The fifth cluster (C5) consisted of events with a similar range of rainfall amounts as those grouped in C3, but longer duration and therefore lower intensities. Events grouped in C5 delivered between 4 mm and 34 mm of rainfall, while events in cluster C3 between 2 mm and 20 mm. Additionally, rainfall intensities covered a much narrower set of values in the case of C5 (between 0.1 mm/h and 1.6 mm/h) than in C3 (between 0.1 mm/h and 27 mm/h), which corresponded to on average long duration events in C5 (Table 1).

Clustering of the events according to the general rainfall characteristics confirmed that larger and more intense rainfall events occurred in Ljubljana than in the HOAL. This is illustrated by the events with more than 54 mm of rainfall, grouped in cluster C2 (Fig. 9). In the HOAL the largest rainfall event observed in the 5-year period delivered 57 mm of rainfall (Fig. 5). All the other clusters combined events from both sites which expresses similar characteristics and indicates that if the events are smaller (i.e., not extreme), their characteristics are similar regardless of location. No significant influence of the season on clustering was observed.

Clustering based on drop size distribution characteristics included 451 rainfall events due to the data gaps at both study sites. Four clusters were identified to sufficiently quantify the characteristics of the events (Table 2). The first cluster (C1) contained approximately 40 % of all events, similarly distributed between both study sites. The average drop characteristics of the events in cluster C1 were similar to the average characteristics of all the considered events (Figs. 6 and 8). The second cluster (C2) consisted of fewer events, which had smaller and slower raindrops on average than in any other cluster. The majority of these events occurred in autumn (49 %). The third cluster (C3) was the biggest one, containing almost 50 % of all the events. The average characteristics of the rain drops of these events were similar to the ones, grouped in C1. However, these events had slightly larger and faster raindrops. The drop velocity of events in C1 ranged between 3.0 m/s and 4.0 m/s, while drops of events in C3 had average velocities up to 4.7 m/s. Similarly, the average drop diameter of events in both clusters was larger than 0.5 mm. However, events in cluster C1 reached an average diameter equal to 0.95 mm, while in C3, the largest average diameter was equal to 1.34 mm. The fourth cluster (C4) was the smallest, containing 24 events from Slovenia and 4 events from Austria, which were characterized by the largest rain drops with *MVD* above 2.6 mm. The majority of these events occurred in summer (57 %).

The clustering of the events according to drop size characteristics did not show any direct connection to the location of the observations. However, a graphical presentation of the results (Fig. 9) shows that events observed in a particular country form an additional group inside the clusters. For all the clusters the average drop characteristics were lower in the case of events observed in Slovenia. Additionally, for these events the standard deviation of the drop velocity, size and *MVD*, grouped in the clusters were larger than for events observed in Austria (Fig. 9). For example, in cluster C2, the average drop velocity measured in the HOAL ranged between 2.4 m/s and 3.3 m/s and the drop diameter between 0.6 mm and 0.8, while in Ljubljana, it ranged from 1.6 m/s to 3.5 m/s and 0.4 mm to 0.9 mm, respectively.

3.2. Comparison of the rainfall erosivity between the two sites

Rainfall erosivity *EI30* (Fig. 10) generally was higher in the years with higher rainfall amounts (Fig. 4). Rainfall erosivity was higher in Ljubljana than in the HOAL in all years (Fig. 10). *EI30* was the lowest in the HOAL in 2015 (323 MJ•mm/ha•h) and the highest in

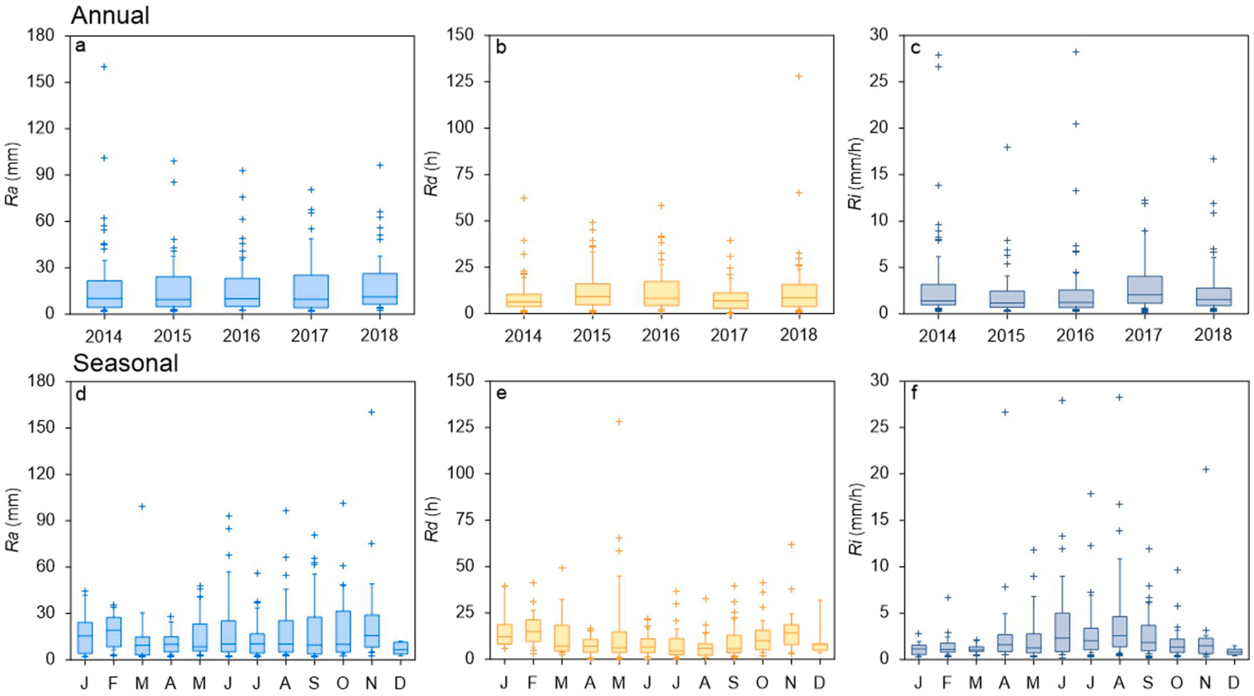

Fig. 7. Annual (top) and seasonal (bottom) variability of rainfall characteristics of all selected events in the research plot in Ljubljana, Slovenia: a and d) rainfall amount *Ra* (mm), b and e) rainfall duration *Rd* (h), c and f) rainfall intensity *Ri* (mm/h).

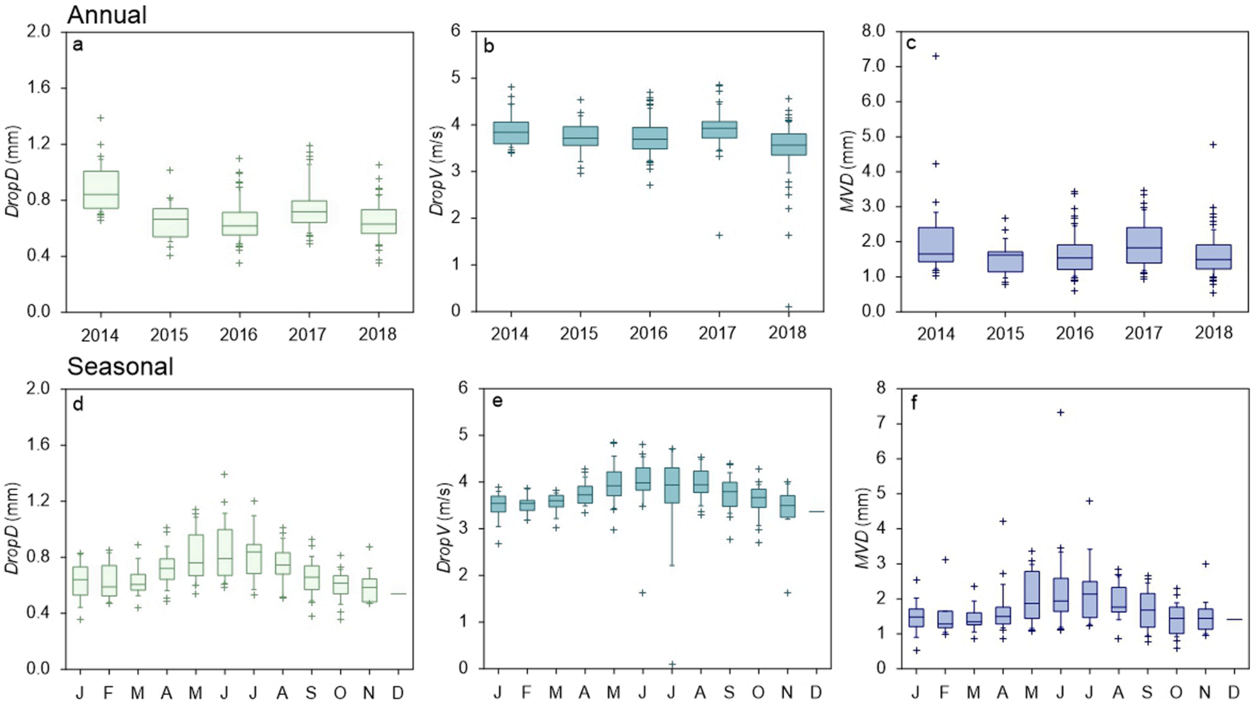

Fig. 8. Annual (a–c) and seasonal (d–f) variability of drop size distribution DSD characteristics of all rainfall events where DSD information was available in Ljubljana, Slovenia: a and d) average drop diameter *DropD*, b and e) average drop velocity *DropV*, c and f) median volume diameter *MVD*.

Table 1

Summary statistics of clustering: average rainfall amount *Ra*, rainfall duration *Rd* and rainfall intensity *Ri* of each cluster C1–C5.

cluster	Number of events in HOAL	Number of events in Ljubljana	Percentage of all events (%)	*Ra* (mm)	*Ri* (mm/h)	*Rd* (h)
C1	8	10	3	48.59	1.21	45.31
C2	0	15	2	81.80	6.61	20.74
C3	224	194	64	5.87	1.71	5.94
C4	11	62	11	29.32	3.69	10.65
C5	73	56	20	15.89	0.77	22.18
All	316	337	100	13.39	1.84	11.10

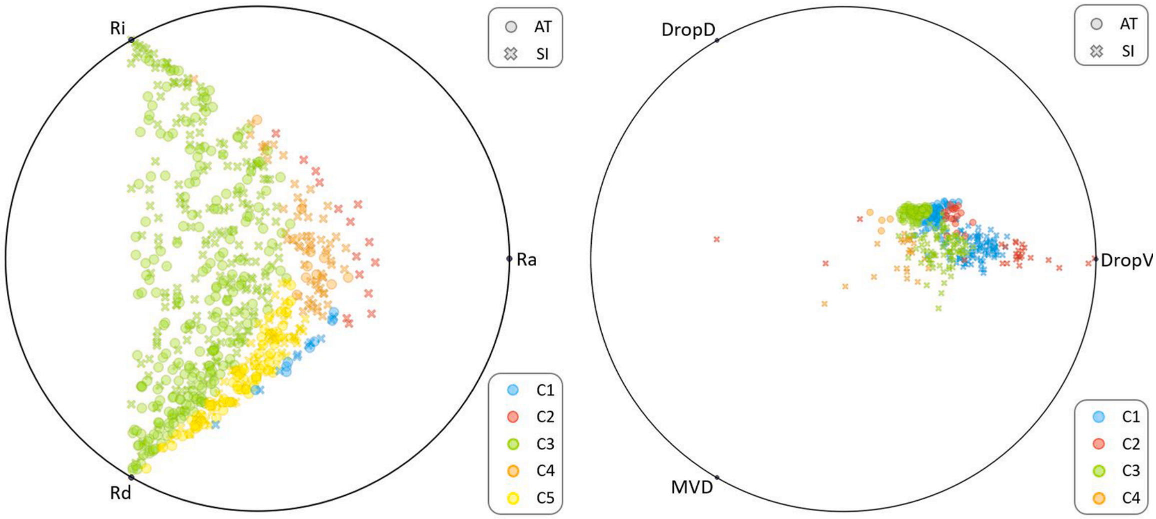

Fig. 9. Influence of the variables on clustering of the events, considering general rainfall characteristics. Circles show the events from Austria, crosses illustrate the events observed in Slovenia. Tables 1 and 2 show the properties of the clusters. The proximity of a data point to an axis indicates the influence of the corresponding variable on the clustering of the point.

Table 2

Summary statistics of clustering: average drop diameter *DropV*, average drop diameter *DropD* and mean volume diameter *MVD* of each cluster C1–C4.

Cluster	Number of events in HOAL	Number of events in Ljubljana	Percentage of all events (%)	*DropV* (m/s)	*DropD* (mm)	*MVD* (mm)
C1	76	96	38	3.61	0.63	1.39
C2	19	26	10	2.90	0.50	1.06
C3	118	88	46	3.97	0.78	1.97
C4	4	24	6	4.24	0.99	3.24
All	217	234	100	3.77	0.84	1.67

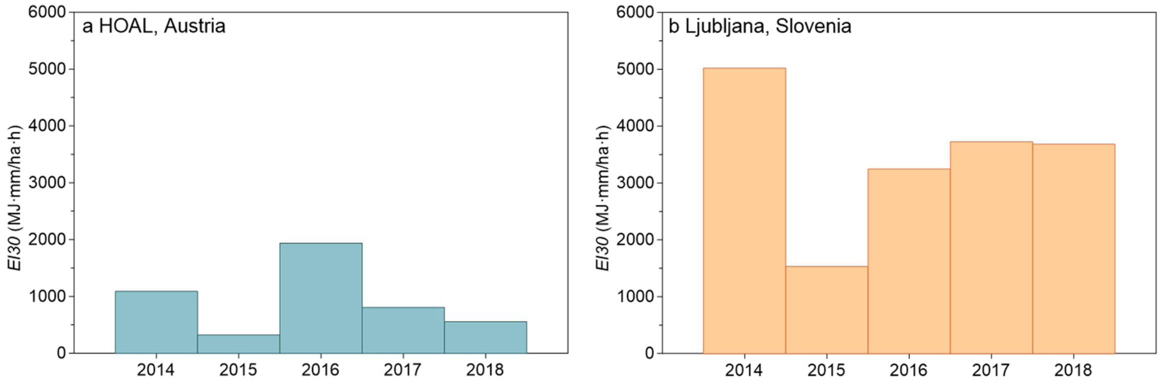

Fig. 10. Rainfall erosivity *EI30* according to years for a) HOAL, Austria and b) Ljubljana, Slovenia.

2016 (1937 MJ•mm/ha•h) (Fig. 10a). While for Ljubljana, *EI30* was also the lowest in 2015 (1529 MJ•mm/ha•h) but it was the highest in 2014 (5019 MJ•mm/ha•h) (Fig. 10b).

Rainfall erosivity is a highly nonlinear process. Because of this, the differences in rainfall erosivity between the months over each year, and between the years for a particular month had often magnitudes of differences (Fig. 11). For each year, there was a clear seasonal pattern in rainfall erosivity at both sites (Fig. 11) which was a consequence of rainfall intensities (Figs. 5c and 7c), mean drop diameters and velocities and median volume diameters (Figs. 6 and 8) peaking in the summer.

4. Discussion

4.1. Rainfall event characteristics in Austria and Slovenia

By comparatively assessing the two study sites in terms of rainfall characteristics, we found both similarities and differences between the research plots in Austria and Slovenia. We found a number of similarities between the sites, which seem to be related to the position in the same climate zone, the same altitude and the open nature of the sites. The intra-annual differences in rainfall event characteristics (rainfall amount, duration, intensity and drop size distributions) were negligible for both sites. According to the hierarchical clustering analysis, the event characteristics (rainfall amount, intensity and duration) were similar for smaller, not-extreme events, regardless of location. The seasons did not influence the clusters. Rainfall intensities tended to peak in summer, while rainfall durations were the shortest in the summer months in both countries. Besides these similar characteristics, we also found a number of differences. The long-term annual precipitation sum was almost double in Ljubljana compared to the HOAL which resulted in 2–7 times larger rainfall erosivity in Ljubljana. Ljubljana was characterized by longer, more intense and larger rainfall events. The clustering analysis showed that very intense events with more than 54 mm of rainfall grouped in cluster C2 were only observed in Ljubljana. Events belonging to this cluster were not observed in the HOAL. Event-based rainfall amounts were the highest in summer in the HOAL, while in Ljubljana rainfall amounts peaked both in autumn and summer. According to the clustering analysis based on drop size distribution, the average drop characteristics were higher in the HOAL, however, the majority of the events belonging to cluster C4 characterized by the largest rain drops with *MVD* above 2.6 mm, was observed in Ljubljana. Although on average drop size and velocity were lower for Ljubljana, single larger and faster raindrops were observed there in comparison to HOAL.

The findings in the HOAL are consistent with those of Vasquez et al. (2024) who compared the rainfall characteristics of erosive events and rainfall erosivity amongst larger agricultural production areas of Austria. The HOAL, with an even longer time series between 1937 and 2019 was one of their study sites. For their selected erosive events that had larger than 10 mm rainfall amount, they found 9.6 mm/h mean maximum 30-min rainfall intensity, 19.7 h mean rainfall duration and 1.8 MJ/ha.h mean erosivity density. While these are much higher than the rainfall characteristics calculated in this study, if we excluded events that had precipitation amounts larger than 10 mm, we received comparable results: 8.1 mm/h mean maximum 30-min rainfall intensity, 11.3 h mean rainfall duration and 1.4 MJ/ha.h mean erosivity density. Examining extreme precipitation events, Seibert et al. (2007) found summer maxima of the heavy events observed between 1979 and 1993 in the Wald-Mühlviertel region of Austria, peaking in June. In this study, we analyzed all events in the period 2014–18, not only the extreme events and rainfall amounts which also tended to peak in the summer but with a maximum in August. Such summer events are local and short in duration and they are mainly induced by convective rainfall. In contrast to winter, different regions of Austria cannot be clearly related to precipitation regimes and airflows in the summer (Matulla et al., 2003). In the winter months, the HOAL is mainly under the influence of continental airflows. In all seasons, the Alps are a barrier of airflow (Matulla et al., 2003) which partly also explains the differences in precipitation characteristics between the study sites. In Ljubljana, the precipitation regime is influenced by both Mediterranean and continental air masses receiving between 1200 and 1600 mm of precipitation per year, with most rainfall occurring in summer and autumn (Milošević et al., 2016) consistent with the findings of our study and the results of de Luis et al. (2014). Accordingly, the rainfall erosivity for this study plot was the highest in the summer months as also observed by Ciaccioni et al. (2016) and Petek et al. (2018).

4.2. Rainfall erosivity in Austria and Slovenia

At both study locations the rainfall erosivity was generally high (Figs. 10 and 11) compared to the northern parts of Europe (Panagos et al., 2015). In Ljubljana, Slovenia rainfall erosivity was found to be between 2 and 7 times larger in each year between 2014 and 18 than in the HOAL, Austria. In the HOAL we found an average annual rainfall erosivity *EI30* of 942 MJ.mm/ha.h.y, while for Ljubljana *EI30* was 3440 MJ.mm/ha.h.y. Panagos et al. (2023) reported an R-factor of 700–1150 MJ.mm/ha.h.y typical for the area of Austria where the HOAL is located and 3625 MJ.mm/ha.h.y for Ljubljana.

For the Alpine foothills agricultural production zone that also comprises the HOAL, Klik and Konecny (2012) reported an R factor of 849 MJ.mm/ha.h.y. Vásquez et al. (2024) found an R factor of 794 MJ.mm/ha.h.y for the HOAL which was much lower compared to the mean R factor of the entire Alpine foothills agricultural production zone reported in their study (1100 MJ.mm/ha.h.y) or by Johannsen et al. (2022) (1190 MJ.mm/ha.h.y) and also lower than the average annual rainfall erosivity found in our study (942 MJ.mm/ha.h.y). This difference is surprising since Vásquez et al. (2024) selected only the potentially erosive rainfall events, i.e., when the rainfall amount per event exceeded 10 mm. In our study we excluded only those storms which had less than 2 mm rainfall amount. Furthermore, Vásquez et al. (2024) used a much longer time period in their study, 1937–2019. The rainfall erosivity in the period between 1937 to now underwent considerable variations. There is evidence, that in the 1950s rainfall erosivity was high, then decreased until the end of the 1980s, and it started to increase since then. This explains the smaller erosivity values when considering the whole period from 1937 until now (Wang et al., 2022). In our study, only the recent five years, 2014–2018 were included and as

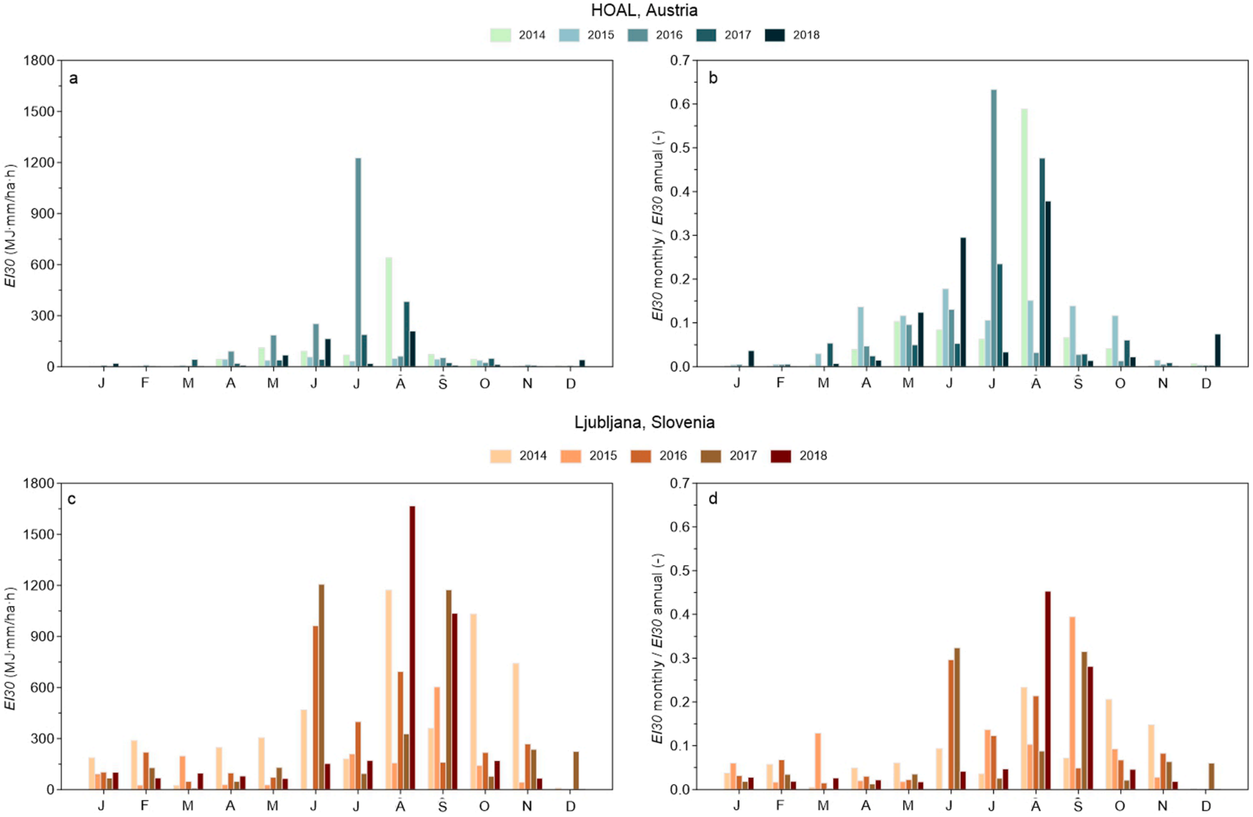

Fig. 11. Rainfall erosivity *EI30* for the months of the year (left) and ratio of monthly rainfall erosivity to annual rainfall erosivity (right) according to years for HOAL, Austria (top) and Ljubljana, Slovenia (bottom).

Klik and Konecny (2012) and Vásquez et al. (2024) indicated rainfall erosivity had been increasing over the years. Another important difference was that Vásquez et al. (2024) used a different form of equation to calculate the kinetic energy of rainfall, i.e., with different coefficients in the rainfall intensity–kinetic energy relationship, which also had a large influence on the results (Johannsen et al., 2022; Nearing et al., 2017).

Slovenia including Ljubljana is one of the areas in Europe with the highest rainfall erosivity, similarly to Italy (Bezak et al., 2015, 2021a, 2021b; Panagos et al., 2015; Petek et al., 2018). Our results agreed well with the monthly rainfall erosivity values estimated by Ciaccioni et al. (2016) who used disdrometer data in Ljubljana for a few months between 2013 and 2015. Petan (2010) found an R factor of 3625 MJ.mm/ha.h.y for Ljubljana which also agrees very well with our findings (3440 MJ.mm/ha.h.y). Compared to Petek et al. (2018), we found larger seasonal differences and larger summer rainfall erosivity in our study. The reason for this difference could be that Petek et al. (2018) used much longer time series (1948–2017). Additionally, they used a different form of the kinetic energy equation.

4.3. Drivers of the difference in rainfall event characteristics and rainfall erosivity

Numerous studies pointed out that rainfall characteristics do not only vary between climate regimes (e.g., Kozu et al., 2006; Protat et al., 2019; Ryu et al., 2021; Saharia et al., 2021) but may be substantially different within the same climate zone (e.g., Dolšak et al., 2016; Pu et al., 2020; Tapiador et al., 2010). Seasonality and topography significantly influence rainfall amounts and other characteristics of rainfall (Vásquez et al., 2024). Besides seasonality and altitude, geographical latitude can greatly influence rainfall amounts and hence erosivity (Panagos et al., 2015). Atmospheric circulations can cause significant local differences in precipitation amounts (Milošević et al., 2016). According to Pu et al. (2020) human factors, such as differences in the surrounding area and buildings could result in different drop size distributions.

When comparing the two study sites, the agricultural catchment HOAL in Austria and the urban park in Ljubljana, Slovenia, we found distinct differences in rainfall amounts, typical rainfall types and hence, rainfall erosivity. Both study locations belong to the oceanic temperate climate (Cfb) according to the Köppen Geiger climate classification. Still, there are large differences in terms of precipitation between the two sites. Slovenia is one of the rainiest countries in Europe. Even though this area is characterized by an oceanic temperate climate, it is close to the humid subtropical climate zone featuring continental characteristics. This means Slovenia has a transitional climate (de Luis et al., 2014). According to Ogrin (1996), in Ljubljana, temperate-continental climate (Type II) prevails. Furthermore, Ljubljana is located in a region where the frequency of thunderstorms is exceptionally high (van Delden, 2001). Three factors promote the emergence of thunderstorms in this region: 1) a high moisture level in the atmosphere due to the closeness of the Mediterranean Sea; 2) potential instability due to advection of warm air in the lower troposphere and accumulation of moisture, mountains that block the advection of cold air masses, heating through solar radiation; 3) forcing that lifts the air to the boundary layer (van Delden, 2001). Such differences in climate and weather characteristics between the two sites apparently result in distinct differences in rainfall characteristics and, hence, rainfall erosivity, as our study confirmed.

The results of the study show which rainfall characteristics might be similar between sites in the study regions. The seasonality of rainfall characteristics was very similar between the sites. Rainfall characteristics of small events were similar at the two sites. However, rainfall characteristics were not similar when examining larger events, since larger and more intense events were only observed in Ljubljana. At the annual time scale, rainfall characteristics were again found to be different between the sites because, annual rainfall amounts and the erosivity of rainfall were significantly larger in Ljubljana than in the HOAL. Our study, therefore, aims to highlight the importance of monitoring and comparatively assessing the spatial differences in rainfall characteristics between different regions because such differences can significantly impact soil erosion, and more generally, sustainable water resources management.

4.4. Methodological aspects

In this study, based on field experience, we refined certain thresholds that are often adopted as standard settings for rainfall erosivity calculations. We found that certain standard RUSLE settings, e.g., rainfall threshold and break between the events, might be too high for the study sites.

This manuscript it the first outcome of a collaborative project between TU Vienna and the University of Ljubljana (project IRISE) that compares the influence of vegetation and interception on soil erosion between the HOAL and Ljubljana. As the follow-up studies will explore interception, the rainfall threshold were set in a way to ensure consistency through the whole project. Instead of 6 h, a 4-h dry period between the storms was selected based on field experience and to be consistent both with past (e.g., Zabret et al., 2018, 2023; Zabret and Šraj, 2021) and future studies. The 4-h long dry period was observed to be optimal to split events based on rainfall, for the throughfall to stop and for the leaves to dry off.

Generally, events are considered to be erosive above a rainfall amount of 12.7 mm (Renard et al., 1997a, 1997b) and on average 11 % of all erosive events contribute to 50 % of the total erosivity (Bezak et al., 2021a, 2021b). When we used 12.7 mm rainfall threshold with 6 h breaks between the storms, we obtained 794 MJ.mm/ha.h.y annual average rainfall erosivity for the HOAL (similarly to Vásquez et al., 2024) and 3315 MJ.mm/ha.h.y for Ljubljana. This would mean 16 % and 5 % less annual rainfall erosivity on average for the two sites, respectively, and also the majority of winter, spring and autumn events would be omitted. We believe this would not correspond to a realistic erosivity estimate, i.e., the 12.7 mm rainfall threshold would be too coarse for the HOAL. Even though smaller than 12.7 mm events were not so erosive as events above this threshold, field observations confirmed that also smaller events result in soil erosion in small agricultural catchments in Austria.

5. Conclusion

This study compared the variability of rainfall event characteristics between two experimental sites located in the Danube River Basin, between the Hydrological Open Air Laboratory (HOAL), Austria and Ljubljana, Slovenia. Our results show that:

- Annual average precipitation sum in Ljubljana was almost twice as high as in the HOAL.
- Rainfall intensities tended to peak in the summer months at both sites, when rainfall durations were shorter, and drops were larger and faster. Event-based rainfall amounts tended to peak in the summer in the HOAL, with secondary peak in winter, while they peaked in autumn in Ljubljana with a secondary peak in summer.
- For small rainfall events, rainfall characteristics were similar at the two locations. However, for larger events, the Ljubljana site showed larger and more intense rainfall than in the HOAL.
- The average drop sizes and velocities tended to be lower in Ljubljana, but the range of drop size distributions was larger in Ljubljana than in the HOAL.
- Rainfall erosivity was substantially different between the sites. Annual average rainfall erosivity was 2–7 times larger in Ljubljana than in the HOAL. This is because of the more intense rainfall, and larger range of drop size distributions, i.e., faster and larger drops during rainfall events.

CRediT authorship contribution statement

Szeles Borbala: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Parajka Juraj:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Šraj Mojca:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Blöschl Günter:** Writing – review & editing, Funding acquisition. **Marjanović Dušan:** Writing – review & editing. **Bezak Nejc:** Writing – review & editing. **Lebar Klaudija:** Writing – review & editing, Data curation. **Vidmar Andrej:** Writing – review & editing, Data curation. **Strauss Peter:** Writing – review & editing, Funding acquisition. **Krammer Carmen:** Writing – review & editing, Data curation. **Schmaltz Elmar:** Writing – review & editing, Funding acquisition. **Hogan Patrick:** Writing – review & editing, Data curation. **Rab Gerhard:** Writing – review & editing, Data curation. **Zabret Katarina:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

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Data availability

Data will be made available on request.

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