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Temporal response of urban soil water content in relation to the rainfall and throughfall dynamics in the open and below the trees

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Abstract: Rainfall interception process is an important part of the biohydrological cycle, in which vegetation plays an important role by regulating the amount and dynamics of rainfall reaching the ground. In this paper, an event-based analysis is performed to discuss the influence of vegetation on dynamic of temporal response of soil volumetric water content (VWC) in the upper soil layer during rainfall events. More specifically, six events that occurred between 19 November 2021 and 30 June 2022, characterized by different hydro-meteorological and vegetation conditions, are analyzed based on continuous measurements of VWC in the open and below groups of two deciduous (*Betula pendula* Roth.) and two coniferous trees (*Pinus nigra* Arnold), as well as rainfall in the open and throughfall on an urban experimental plot in Ljubljana, Slovenia. VWC values at the upper depth (16 cm) were the highest under the birch tree, followed by the location in the open and under the pine tree. However, in the lowest depth (74 cm) VWC values were the lowest under the birch tree. VWC responses to rainfall and throughfall showed seasonal patterns related to the pre-event wetness conditions, with a faster occurrence of maximum VWC values in the leafless period. Additionally, rainfall amount and its dynamics during the event significantly affect the response, as VWC in general reaches its peak after the occurrence of more intense rainfall. Such an event-based analysis, offering an insight into the dynamics of the event development, is crucial and very beneficial for understanding of the biohydrological processes.

Keywords: Rainfall interception; Volumetric water content; Rainfall event dynamic; Birch; Pine; Urban park.

INTRODUCTION

The elements of the water cycle are strongly related with nature, which was often overlooked in the past, however current research is emphasizing and including this aspect as well. The term biohydrology indicates the importance of the role of vegetation in the water cycle (Lichner et al., 2012). The movement of water, the relationship between precipitation, runoff, and infiltration, as well as the way of managing water are relying on new insights resulting from the biohydrological interpretations. As such, the role of vegetation in reducing erosion (e.g., Levia et al., 2017; Zore et al., 2022), retaining precipitation (e.g., Chen and Jim, 2008; Wu et al., 2020), reducing runoff (e.g., Zabret and Šraj, 2015; Zabret and Šraj, 2019; Selbig et al., 2022) and increasing infiltration (e.g., Cui et al., 2022; Teixeira Lins et al., 2023) has been recognized and used as the way for mitigating the climate change impact. Additionally, the use of vegetation and its role in water management has been widely recognized in concepts of green infrastructure (e.g., Matthews et al., 2015; Vargas-Hernandez and Zdunek-Wielgołaska, 2021), nature-based solutions (e.g., Kato-Huerta and Geneletti, 2022; Zölch et al., 2017), and sponge cities (e.g., Yuan et al., 2022; Zhang et al., 2019).

An important part of the biohydrological cycle is the rainfall interception process. It was first mentioned by Hoppe in 1896 (Hoppe, 1896); however, research in this field has started in the second half of the 20th century (e.g., Ford and Deans, 1978; Stout and McMahon, 1961). In the process of rainfall interception, vegetation regulates the amount and dynamics of rainfall reaching the ground. When precipitation encounters vegetation, it is intercepted and redistributed by its parts (e.g., Staelens et al., 2008; Xiao et al., 2000; Zabret and Šraj, 2021). In the case of trees, some precipitation intercepted by the canopy never reaches the ground and eventually evaporates to the atmosphere. This is called intercepted precipitation. Precipitation can reach the ground beneath the tree by falling directly through the gaps in the canopy or dripping from the branches and leaves. This component is known as throughfall (TF). Eventually, some rainfall can also flow down the tree trunk, which is known as stemflow.

The process of interception decreases the amount of precipitation reaching the ground. The reduced amount of precipitation further affects other elements of the hydrological cycle such as surface runoff and soil infiltration (e.g., Livesley et al., 2014; Šraj et al., 2008; Zabret and Šraj, 2019). Reduction of surface runoff due to precipitation interception was demonstrated in many studies. Reduction in surface runoff by a single *Acer campestre* tree on a parking lot was estimated to be between 38% and 43% in winter and summer, respectively (Armson et al., 2013). Inkiläinen et al. (2013) have shown a 9% to 21% runoff reduction by an urban residential forest with high canopy coverage of especially oaks and pines during summer and fall, respectively. Up to 17% reduction according to the yearly average interception can be expected by *Pinus nigra* trees planted on 35% of the parking lot area in the city of Ljubljana, Slovenia (Zabret and Šraj, 2015) and up to 11% per year by a plantation forest (*Picea sitchensis*) in a small headwater catchment in the Scottish Borders, UK (Peskett et al., 2021). Also, interception in forests plays a significant role in runoff and infiltration reduction. For example, a healthy spruce forest (*Picea abies* L. Karst.) in West Tatras intercepted 70.6% of rainfall in the growing season, while a dead stand still intercepted 59.9% of rainfall (Bartík et al., 2016). Jančo et al. (2021) also monitored rainfall interception by a Norway spruce forest in West Tatras during the growing season, however they reported interception equal to 45.7%–51.6%

of rainfall. An even lower interception of 34.5% was observed during the growing season in a Norway spruce forest in Bohemian Forest, Czech Republic (Dohnal et al., 2014).

Soil water content is influenced by vegetation both indirectly by precipitation interception and directly by using water for transpiration (Špulák et al., 2021). Therefore, infiltration and consequently soil moisture conditions are related to various types and characteristics of vegetation (Tao et al., 2021; Yang et al., 2018). In this context, Rahman et al. (2019) investigated soil infiltration potential under the canopies of two different urban tree species, namely *Robinia pseudoacacia* and *Tilia cordata* near two streets in Munich, Germany. They observed approx. 1.5-times higher infiltration rates under the canopy of *R. pseudoacacia* compared to *T. cordata.* Additionally, in the case of measurements further from the trunk, the infiltration rates of *R. pseudoacacia* were higher than in the control grass experiment. The reason was attributed mainly to finer rooting system and its higher biomass of *R. pseudoacacia* enhancing infiltration rates. Špulák et al. (2021) investigated the topsoil moisture response to precipitation during the growing season under young Norway spruce, white birch, and a grass-dominated treeless gap. They reported that soil water content is higher under the gap vegetation compared to both tree species. Additionally, topsoil under spruce was significantly more saturated than under birch, where the seasonal effect was prominent. Bialkowski and Buttle (2015) investigated the influence of branch architecture on delivery of throughfall and stemflow to the forest floor, contributing to soil-water recharge beneath sugar maple and red pine trees located in a managed forest with humid mid-latitude climate (Ontario, Canada). They found that both distribution of recharge in sandy to sandy-loam soil profiles as well as throughfall and stemflow differed among different trees. However, they note that seasonal differences in recharge can be expected due to phenological transitions of individual tree species. Relationship between throughfall and soil-water response in the forest floor was confirmed also by Molina et al. (2019) who found that the response was activated after 10 mm of cumulative rainfall, regardless of the initial soil-water conditions at most of the locations in oak and pine forest plots (NE Spain with a Mediterranean climate) characterized by silty-clay-loam and silty-loam soil texture, respectively. Additionally, Dai et al. (2022) observed that in case of upper soil layers the variations in soil moisture reflected the temporal variations in precipitation, regardless of the vegetation type and season.

In general, understanding the soil water content behavior is essential for forest management (e.g., Rascón-Ramos et al. 2021), groundwater recharge (e.g., Post et al., 2022), biogeochemical cycling (e.g., Moslehi et al. 2019), and many other related processes. Researchers confirmed both the importance of the vegetation type as well as characteristics of the rainfall event for understanding the soil moisture values. Regardless of the many studies investigating the impact of vegetation on changes in soil moisture (e.g., Li et al., 2018; Post et al., 2022; Stevens et al., 2020; Tao et al., 2021), few studies include a more detailed insight into the temporal response. Additionally, these analyses mainly consider rainfall amount and dynamics, measured in the open, although under the vegetation these characteristics are different due to the rainfall interception process. Therefore, the aim of this study is to include throughfall and to analyze the dynamic temporal response of soil volumetric water content (VWC) during the events. More specifically, based on the continuous measurements of VWC in the open and below deciduous and coniferous trees, an in-depth rainfall and throughfall event-based analysis is made. In this way, we evaluated the influence of the rainfall interception process on VWC response according to the reduced amount and changed dynamics of throughfall under different hydro-meteorological and vegetation (seasonal) conditions. This article also discusses extreme prolonged drought conditions in terms of soil water content in the early summer of 2022.

MATERIALS AND METHODS

Study plot

The temporal relationship of the volumetric water content (VWC) in relation to the rainfall and throughfall input was measured at a study plot in the city of Ljubljana, Slovenia (46.04° N, 14.49° E). The sub-alpine climate with four well-defined seasons is typical for the area. According to the Köppen Climate Classification it belongs to the temperate oceanic climate (Cfb) category. The long-term (1992–2021) average annual temperature is 11.5 °C and varies on average from 1.0 °C in January to 21.9 °C in July (ARSO, 2022). The average long-term annual amount of precipitation in Ljubljana is 1,377 mm. The autumn months (September, October, and November) are the wettest with an average of 150 mm of precipitation per month. From November to March, also snow precipitation can be observed. However, the number of days with snow cover has been decreasing in recent years (ARSO, 2022).

The study plot is located in a small urban park with flat terrain and covers approximately 600 m^2 of a grassy area with two groups of trees (Figure 1). The park is surrounded by buildings on the south and west side and by parking lots on the north and east side. The east side of the plot serves as the clearing, covered only with regularly cut short grass. On the north-west side of the plot the group of two pine trees (*Pinus nigra* Arnold) is growing. The trees reach up to a height of 13.1 m, their total projected canopy area is equal to 22.7 m^2, the total basal area is equal to 38 cm^2, the diameter at the breast height on average equals 19 cm, the branches are directed towards the ground and the bark surface is rough with a high storage capacity up to 4 mm of rainwater (measured according to methodology, described in Pérez-Harguindeguy et al. (2013)). Unrelated to the pine trees, the group of two birch trees (*Betula pendula* Roth.) is growing in the south-western part of the study plot. The birch trees are up to 16.7 m high with a total projected canopy area of 42.2 m^2, total basal area of 35.8 cm^2, average diameter at breast height of 17.9 cm, upward growing branches and thinner and smoother bark surface with storage capacity up to 1 mm of rainwater (measured according to methodology, described in Pérez-Harguindeguy et al., (2013)). The birch trees also have the distinct phenophases (leaf area index ranging from 0.46 in leafless period to 2.86 in leafed period; measured with LAI-2200 plant canopy analyzer, Li-Cor Inc.), while the changes in leaf area index for pine trees are smaller (3.4 in leafless and 4.3 in leafed period).

After the year 1945, the terrain of the wider area of the plot was flattened and elevated by using mostly alluvial soils and a small portion of construction debris (urban/anthropogenic soil). According to the Slovenian soil classification (Vrščaj et al., 2019), the upper 0/25–30, 0–22, 0–33 centimeters in the open, under the pine and under the birch, respectively, are humus-accumulative horizons (A), while deeper layers correspond to urban horizons (U) characterized by anthropogenic admixtures (e.g., particles of bricks, concrete). Soil layers are moderately alkaline with pH between 7.85 and 8.5 and are classified as eutric and medium heavy soils. The soil in the plot at the three locations is classified as loam (L) and silt loam (SL) in most of the identified horizons. In the laboratory, the physical properties of the soil were determined based on the undisturbed samples (Kopecky rings), which were taken at the depths that allowed such sampling. In the upper soil layers, the average saturated VWC is

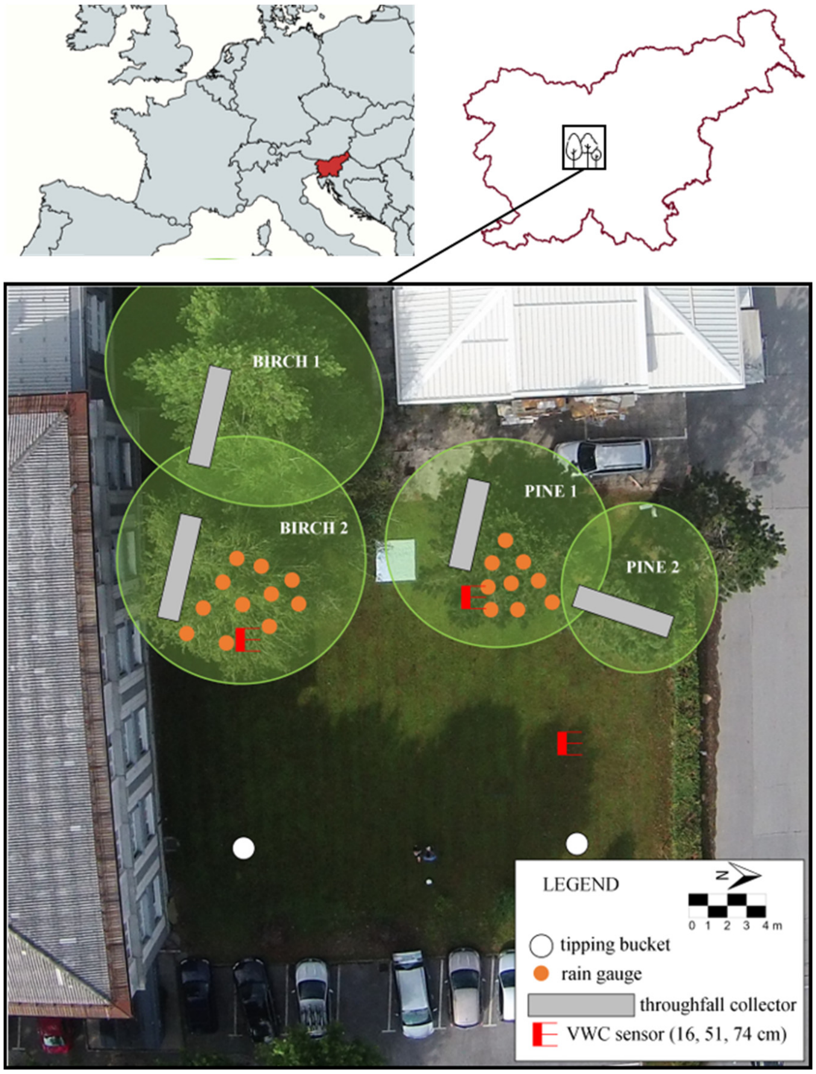

Fig. 1. Location of the study plot and positioning of the installed measuring equipment. Equipment symbols are not shown in scale.

0.55±0.01 m^3/m^3 in the open and under the birch tree (5–10 cm), while under the pine, the average saturated VWC is 0.45±0.003 m^3/m^3 (10–15 cm). Corresponding dry bulk densities are 1.14 g/cm^3, 1.26 g/cm^3, and 1.32 g/cm^3 in the open, under the birch and under the pine tree, respectively. Soil bulk density characterizes the infiltration rate; in soils with a higher bulk density lower infiltration rate can be expected.

Measurements and data analysis

The first measuring equipment for monitoring the rainfall interception process was installed at the study plot in 2013. The measurements have been ongoing since January 2014 and include collecting data of rainfall in the open, as well as throughfall and stemflow under both tree species (Zabret and Šraj, 2021; Zabret et al., 2017; Zabret et al., 2018). For the purpose of this study, we used data from the ongoing measurements of rainfall and throughfall under birch and pine trees. Rainfall in the open was measured using 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 (Figure 1). Two rain gauges were used for data verification and replacement in case of malfunction of one of the devices. For the same purpose, throughfall (TF) was measured with two steel through gauges (0.75 m^2) positioned from the tree trunk towards the edge of the canopy under each group of trees. Throughfall from one trough was automatically recorded using a tipping bucket flow gauge (Unidata 6506G, 50 mL/tip, Onset HOBO Event data logger). Throughfall from the other steel through gauge was collected in a 10 L container, connected to an additional 50 L container, emptied manually after each rainfall event. The data from the rain gauge and automatic throughfall collector were used to define the rainfall events, while data from manually collected gauges were used for data control. In November 2021, sensors for volumetric soil water content (VWC) were installed in three locations, namely under the birch, under the pine, and in the open area (Figure 1). The location of the sensors under the trees was selected away from the trunk, towards the edge of the crown. In each location, there are three sensors (TEROS 10) in the following depths: 16–20 cm (highest), 51–54 cm (middle), and 74–76 cm (lowest). The sensors are connected to ZL6 data loggers where data are recorded every 20 min. The accuracy of the sensors is ± 3% VWC.

The period chosen for the analysis was from 19 November 2021 to 30 June 2022. The VWC measurements started in beginning of November 2021, so reliable data were available from mid-November. The measurements are still ongoing, however, in June an extremely dry period started, observed in summer 2022 in this part of Slovenia, and there were hardly any rainfall events available for analysis after that. The selected period includes different phenoseasons and rainfall events with different characteristics. From November to April, the birch tree canopy was leafless, while it was fully leafed from mid-April on. Therefore, the study period was divided into two parts, the leafless period from November to mid-April and the leafed period from mid-April to June. In total, 80 events were recorded. Some snow events were detected in mid-December, January and February, which were excluded from further analysis. The melting of snow and dripping under the trees was detected with trough gauges with a time delay (shown in Figures 3–5). The raw time series data, collected from the loggers, were first divided into the rainfall events. The events were separated by a 4-hour dry period of both, throughfall and rainfall (Zabret and Šraj, 2021). The significance of the difference between the data sets was tested with two-tail t-test. From the list of all the events we selected six events characterized by different hydro-meteorological and vegetation (seasonal) conditions, for which the complete time series for rainfall in the open, throughfall under the trees, and VWC in all three locations were available (Table 2, Figure 7, Figure 8).

For the selected period, the average VWC per location and per depth was evaluated based on 20-min VWC data. The period average VWCs was further used to analyze the temporal response of VWC to rainfall. The relative deviation of the VWC to the period average at individual locations ($VWC_{rel,t,l}$) was calculated as follows:

$$VWC_{rel,t,l} = \frac{VWC_{t,l} - VWC_{mean,l}}{VWC_{mean,l}}$$

where $VWC_{t,l}$ is volumetric water content measured at 20-min time step t at individual depth and location l. The negative values $VWC_{mean,l}$ indicate “dry conditions” (less than average), and vice versa. However, one should be aware when interpreting the data that dry/wet conditions depend greatly on the selected period for calculating average values and the amount of rainfall observed in the selected period. In this context, dry/wet conditions are expressed relatively to the average of the selected period and may also differ for the analyzed study case depending on a different selected measurement period.

In order to determine the temporal relationship between rainfall (throughfall) and VWC for the six selected precipitation events, the data were first analyzed graphically. The values, presented on the graphs, have 20-min time step. The events were selected to include different seasonal conditions, different rainfall amounts and durations, as well as antecedent dry/wet conditions. In this way, at the event and location level, the temporal relationship between precipitation and the response of soil water content was analyzed in detail. Data preparation and analysis were performed using MS Office Excel and R software (R Core Team, 2020).

RESULTS AND DISCUSSION

From 19 November 2021 to 30 June 2022, we observed 75 rainfall events, 39 in leafless and 36 in leafed period (Table 1). In total, the rainfall events delivered 590.6 mm of rainfall. The average duration of the rainfall events was 7.8 hours. The rainfall events in the leafless period were longer and delivered more rainfall, as on average their duration was 10.6 hours, the total amount of rainfall was equal to 416.6 mm (10.7 mm on average per event) and the average rainfall intensity per event was 1.4 mm/h. In the leafed period, the average duration of rainfall events was 5.2 hours, while the average amount of rainfall equalled 4.8 mm per event, indicating a higher rainfall intensity per event (1.6 mm/h on average). Throughfall under the birch tree was detected during 54 events. On average, it accounted for 60.0% of rainfall in the open and started 1.5 hours after the beginning of rainfall in the open. Throughfall under the birch tree was significantly higher ($p < 0.01$) in the leafless than in the leafed period, 71.8% and 51.5% on average per event, respectively. TF under the pine tree was detected during 47 rainfall events and on average accounted for 39.0% of rainfall in the open. No significant difference was observed in TF under the pine tree during the leafed and leafless periods. Throughfall under the birch tree during the shorter selected period (from 19 November 2021 to 30 June 2022) in this study was similar to the long-term measurements in the same months between 2014 and 2017, when an average TF of 55% was observed, while TF values under the pine tree were slightly higher than the observed values (30%) during the long-term measurements (Zabret et al., 2017; Zabret et al., 2018).

Table 1. Characteristics of rainfall and throughfall events, detected during the analyzed period (19 November 2021 – 30 June 2022).

	Leafed	Leafless	Whole period
Number of rainfall events	36	39	75
Amount of rainfall [mm]	174.0	416.6	590.6
Average rainfall duration [h]	5.2 ± 5.3	10.6 ± 10.3	7.8 ± 8.5
Average rainfall intensity [mm/h]	1.6 ± 2.0	1.4 ± 0.7	1.5 ± 1.5
Throughfall under the birch [%]	51.5 ± 21.6	71.8 ± 24.0	60.0 ± 24.8
Throughfall under the pine [%]	33.6 ± 32.1	45.1 ± 32.7	39.0 ± 32.9

Table 2. Amount of rainfall and throughfall needed during a single event for VWC to start increasing and the delay from the start of rainfall/TF to the start of VWC values increase. The values refer to the upper soil layer (16 cm depth).

		Event 1 1–3 Dec 2021	Event 2 4 Dec 2021	Event 3 19 Feb 2022	Event 4 21 Apr 2022	Event 5 1–2 May 2022	Event 6 7 Jun 2022
Open location	Rainfall [mm]	2.0	2.6	3	13.6	12.4	11.2
	Delay [h]	5.0	5.3	4.3	8.7	2.3	3.0
Under the birch	TF [mm]	3.7	3.3	4.6	6.1	2.8	2.0
	Delay [h]	11.7	8.3	7.0	7.0	1.7	0.7
Under the pine	TF [mm]	5.5	7.3	3.7	8.0	11.0	11.8
	Delay [h]	15.0	9.7	18.3	12	9.7	8.3

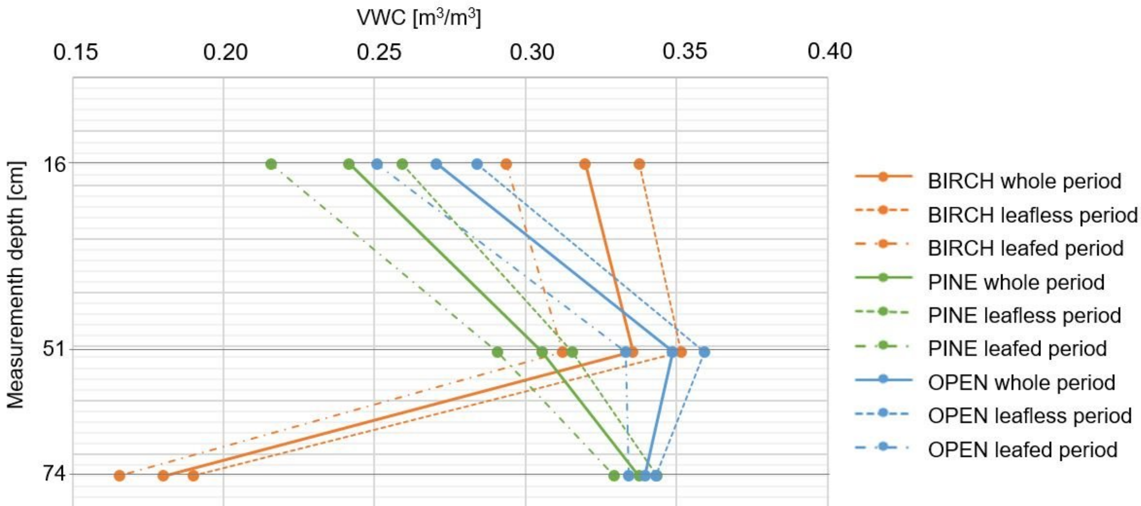

Fig. 2. The average VWC values at three locations (under the birch, under the pine and in the open) and three measurement depths (16 cm, 51 cm and 74 cm) for the analyzed period (19 November 2021 – 30 June 2022).

Using 20-min data for the selected period, the VWC value in the open location was on average the highest in the middle (0.35 m^3/m^3), followed by the lowest (0.34 m^3/m^3) and the highest depth layer (0.27 m^3/m^3). Dai et al. (2022) observed a similar distribution of soil moisture with depth on an alpine meadow. However, for the alpine shrub location Dai et al. (2022) reported an increasing VWC value with the measurement depth throughout the year, corresponding to the values measured under the pine tree (Figure 2). The average VWC value under the birch tree was similar at the highest and the middle depth profile, while on average the VWC value in the deepest profile under the birch tree was the lowest among all the measured values (0.18 m^3/m^3). The values were close to those observed in the middle depth on the clearing and were the highest compared to the other two locations (Figure 2). This is in contrast with observations by Špulák et al. (2021), who reported the lowest topsoil water content values below the birch tree and the highest in the open during the growing period. One of the possible reasons for the different findings may be the age/height of the observed birch trees, which was in the study of Špulák et al. (2021) considerably lower (3.5 m on average) than in our case (16.7 m) and can be further associated with the roots' depth being denser in the topsoil of younger trees and growing deeper with time. Therefore, higher water uptake from the topsoil can be expected and thus lower soil VWC under younger trees. Another aspect that must be considered when comparing the results is the different soil texture, which in our case is finer; therefore, the soil has a greater water-retaining capacity. The VWC values in the leafless period were higher and in the leafed period lower than the average, regardless of the depth or location (Figure 2). As leafless period can be characterized as wet and leafed period as dry (Zabret and Šraj, 2021), these results correspond to the one presented by Yang et al. (2018) who reported that soil water storage in the wet season was significantly higher than that in the dry season.

The response of VWC to the rainfall and throughfall input

The response of VWC to rainfall was analyzed regarding the relative deviation of the VWC to the period average (VWC_{rel}). The values of VWC_{rel} were in general positive until 16 May 2022. Thereafter, they dropped under zero regardless of the location, indicating "dry conditions" according to the period average. The "dry conditions" occurred due to the lack of rainfall since the beginning of 2022. In January, 32.3 mm of rainfall was detected; additionally, only 53.3 mm of rainfall was recorded in February, and 6.8 mm in March. This resulted in the first significant drop in the VWC values in March (Figures 3–5). April was a wetter month, as during 17 rainfall events 141.8 mm of rainfall was delivered. This rainfall restored the VWC conditions to a limited extent (Figure 3). However, a lack of rainfall was observed again, resulting in a significant drop in VWC values in mid-May (Figures 3–5).

As expected, the most pronounced response to the rainfall and throughfall input was observed in the upper profiles at all three locations, regardless of the vegetation period. The direct increase of VWC_{rel} values to rainfall and TF was observed during the leafless phase and the response was the fastest in the open, followed by the location under the birch and pine trees (Figures 3–5). This also coincides with the timing of the rainfall start and delayed start of TF under the trees. However, during the drier leafed period the response in the highest soil depth was observed only in the open and under the birch tree, and even then only after the most intense rainfall events. However, for the growing period, Špulák et al. (2021), who measured soil water content of the topsoil under young Norway spruce, white birch, and a grass-dominated treeless gap, did not report any differences in soil moisture response dynamic according to rainfall input for the tree locations. In the case of the locations in the open and under the birch tree, VWC_{rel} values were the highest on average in the highest profile, followed by the lower two depths. During the drier period, the lowest profile was the wettest in the open and under the pine, while the VWC values in the two upper profiles differed more from the average. Additionally, under the pine tree, VWC_{rel} values were more similar in the lower two profiles. At the beginning of the drier period in May, one can notice relatively high VWC_{rel} values in the deepest layer under the birch tree (Figure 4), even exceeding the values in the upper layer. Since the average VWC value in the observed period in the mentioned layer is significantly lower than in all other layers and locations, the same absolute change of the VWC results in higher VWC_{rel} values in the deepest layer under the birch was obtained. Regardless of the location, the VWC_{rel} values in the middle profile followed the values in the top profile with a delay. Therefore, the mid-depth values exceeded the VWC_{rel} values in the top profile when they started to decrease after the longer period without rainfall (Figures 3–5).

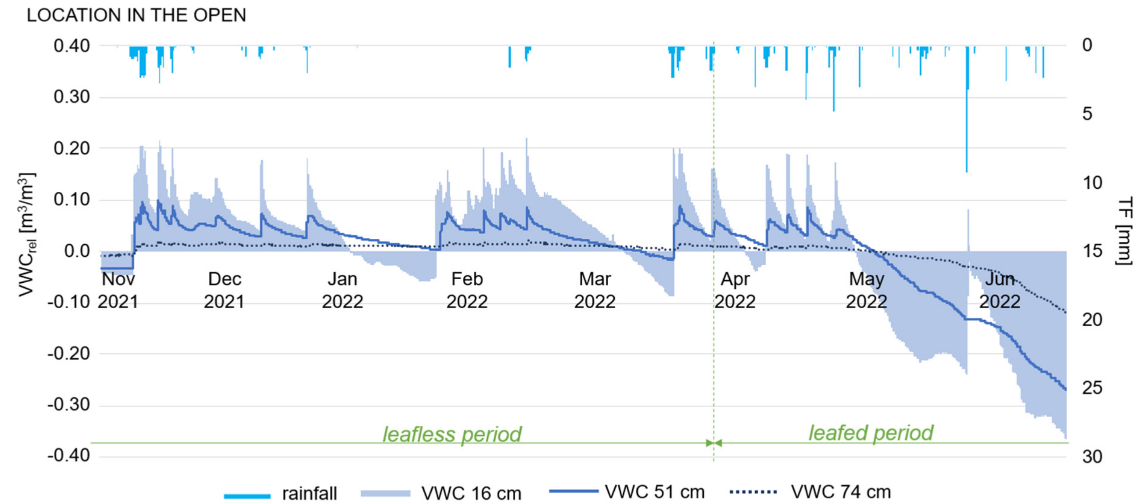

Fig. 3. Response of VWC_{rel} in the open location at three depths (16 cm, 51 cm and 74 cm) in relation to rainfall input for the analyzed period (19 November 2021 – 30 June 2022).

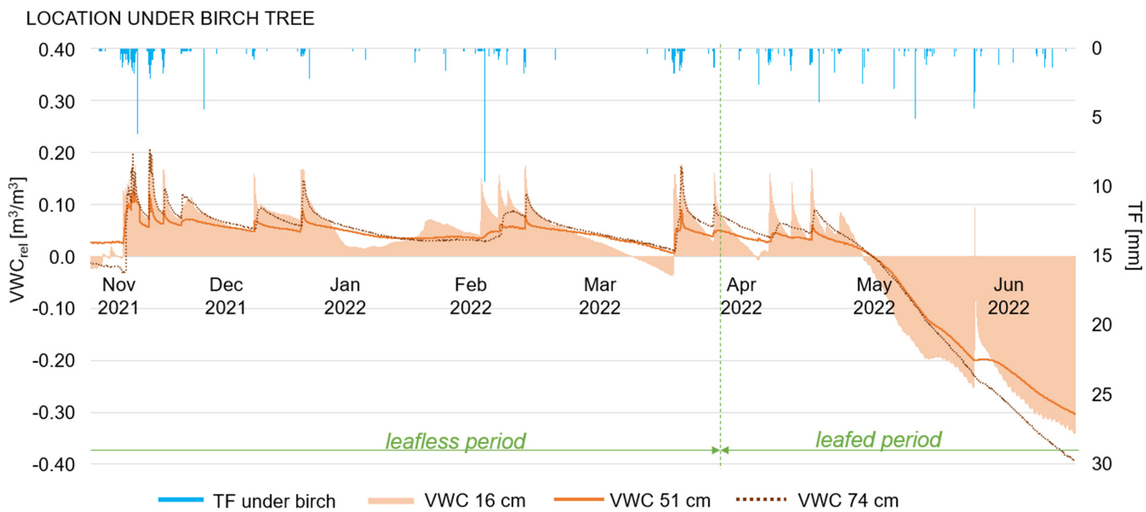

Fig. 4. Response of VWC_{rel} under the birch tree at three depths (16 cm, 51 cm and 74 cm) in relation to throughfall input for the analyzed period (19 November 2021 – 30 June 2022).

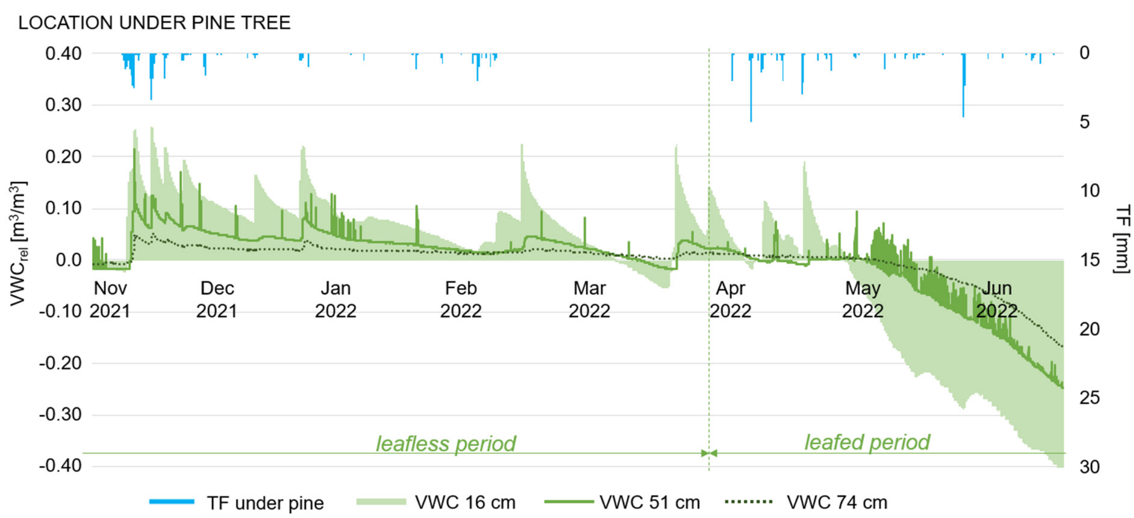

Fig. 5. Response of VWC_{rel} under the pine tree at three depths (16 cm, 51 cm and 74 cm) in relation to throughfall input for the analyzed period (19 November 2021 – 30 June 2022).

For the whole analyzed period, the response of VWC to rainfall in the open was the fastest among all three locations. At the highest profile, the lowest amount of rainfall that caused an increase in VWC value was equal to 0.8 mm, however on average 5.8 mm (standard deviation ± 5.0 mm) of rainfall was needed for VWC values to start increasing. In this profile the VWC value increase was observed during one third of all detected rainfall events in the study period, on average 3.3 hours (± 2.4 hours) after the beginning of rainfall. However, at the two lowest depths VWC increased slower and after a larger amount of rainfall input, averaging 17.4 mm (± 15.1 mm) and 22.1 mm (± 21.1 mm) of rainfall in the middle and the lowest depth, respectively. Especially for the lowest depth, which is 74 cm below the surface, a delayed response of VWC in comparison to rainfall in the open is observed, averaging 9.7 hours (± 4.6 hours) (Figure 3). Therefore, changes in VWC values in the lower two depths cannot be assigned to a single rainfall event often.

The response of VWC values under the birch was similar to the one at the open location, occurring during the same events as in the open (Figure 4). The lowest throughfall amount in the study period needed to cause an increase in VWC was 1.6 mm. On average, the values at the uppermost depth started to increase when 4.0 mm (± 2.7 mm) of TF was delivered, corresponding to an average of 5.1 hours (± 4.1 hours) after the beginning of TF. TF under the birch tree on average started after 1.7 hours (± 1.2 hours) from the beginning of the rainfall in the open. At the middle depth, an average of 8.7 mm (± 6.7 mm) of TF was needed to cause an increase in the VWC value, which was observed 10 hours after the beginning of TF. The response at the lower depth was observed on average 2.9 hours after the increase at the middle depth.

VWC values under the pine tree had the slowest reaction to the external influence (Figure 5). The VWC value at the uppermost depth started to increase after at least 1.8 mm of TF, while an average of 4.5 mm (± 2.7 mm) of TF was needed and the increase was observed on average after 7.2 hours (± 4.0 hours) from the beginning of TF. TF under the pine tree in general started 3.8 hours (± 6.3 hours) after the start of rainfall in the open. In the lower two depths there was almost no response of VWC to direct TF input, as an increase of VWC values was detected only during 11 rainfall events in the considered period. VWC values in the middle layer show significant fluctuations throughout the year (Figure 5). This cannot be directly attributed to the sensor failure, as the mean daily values in the middle depth follow the mean daily values in the other two depths. In the further analysis we focus on the VWC values, measured in the upper depth, therefore this phenomenon will be addressed in later studies, using a longer available data set.

Comparing the response of VWC to the rainfall and TF input, the difference between the periods before and after 16 May 2022 is evident (Figures 3–5). When pre-event soil moisture was higher than average ($VWC_{rel} > 0$), VWC started to increase after a certain amount of rainfall or throughfall was delivered, and this was observed at all three measurement depths and locations. After VWC_{rel} dropped below zero, a quick response, on average faster than in the wetter period, was observed only in the upper layer, while VWC values did not change in the lower two depths, regardless of the location. The VWC response was related to the rainfall amount rather than the rainfall duration. This is in accordance with findings of He et al. (2012) who investigated soil moisture responses to rainfall events in grassland and meadows. The rainfall event size (amount) and duration of the rainless period were found to be influential for the soil moisture increase. More specifically, they found that events with more than 15 and 20 mm of rainfall triggered the VWC in 20 and 40 cm soil depth, respectively. Additionally, Yan et al. (2021) observed the lowest rainfall threshold needed to induce the soil moisture response in grassland areas in comparison to other vegetated locations, which is in accordance with the rainfall and TF threshold values observed in this study. However, when VWC_{rel} values dropped below the average, a much higher amount of rainfall or TF was required for VWC values to start increasing (Figures 3–5).

Dynamic of VWC response in the upper soil layer

The general response of VWC values according to the rainfall input during eight months shows that the way of the response can be assigned to long-term general soil moisture conditions. In drier periods VWC will react only to larger rainfall events and the reaction will be shorter, while in normal conditions a certain amount of rainfall is needed to induce the VWC value increase. Additionally, the dynamic of VWC values in the most responsive uppermost depth (16 cm) during a single rainfall event was analyzed. For this purpose, we selected six rainfall events (Figure 6, Table 2). Three of them occurred in the leafless period before the first drought in March. They were quite long, however they delivered different amounts of rainfall (events 1, 2, and 3). The other three rainfall events were observed in the leafed period. They are categorized with a similar amount of rainfall but have different durations (events 4, 5, and 6).

Event 1 was observed on 1 December 2021. During 44.3 h, 65 mm of rainfall was delivered. Throughfall (TF) under the birch tree was equal to 86% of rainfall (i.e., 55.7 mm of rainfall reached the ground under the birch tree) and under the pine tree it was equal to 63%. VWC in the open location started to increase after 5 hours, when 2 mm of rainfall was delivered (Table 2). Throughfall under the birch tree started one hour after rainfall in the open and under the pine tree it started after nine hours. The maximum VWC value during this event was reached at the same time, regardless of the location, 18.3 hours after the beginning of the rainfall. Maximum values were reached right after the occurrence of more intense rainfall, equal to 3 mm/20 minutes. During this event, also a longer time frame (11 h) without rainfall in the open was detected, however TF under the trees did not stop. This might be also the consequence of the fog drip and high air humidity, recorded at this time. However, this is reflected also in VWC values dynamic. When rainfall in the open started to fall again, VWC values in the open started to increase, while no response was observed under the trees (Figure 7).

Event 2 started 33 hours after the end of event 1, on 4 December 2021. It lasted for 21.1 hours and delivered 19.8 mm of rainfall with 81% TF under the birch and 50% TF under the pine tree. Similar amounts of rainfall and TF under the birch and under the pine trees were needed for an increase of VWC values as during event 1, (difference to the threshold values observed during event 1 were +0.3 mm, –0.4 mm and +1.8 mm, respectively; Table 2). Maximal VWC values in the open and under the birch tree were detected at the same time (14.7 h after the beginning of the event), right after rainfall of higher intensity occurred (1.4 mm in 20 minutes; on average 0.3 mm fell in 20 minutes during the event). Under the pine tree, the peak in VWC values was reached 1.5 hours later (Figure 7).

Event 3 occurred on 19 February 2022. It was 17.8 hours long and delivered 13 mm of rainfall, 74% of which contributed to TF under the birch tree and 29% to TF under the pine tree. The peaks of VWC values were not as distinct as during events 1 and 2. However, in the open and under the birch tree VWC values started to increase sooner (Table 2), and the peaks were reached at the same time (12 hours from the beginning of the event), again after occurrence of a bit more intense precipitation (1 mm/20 minutes; event average is equal to 0.2 mm/20 minutes).

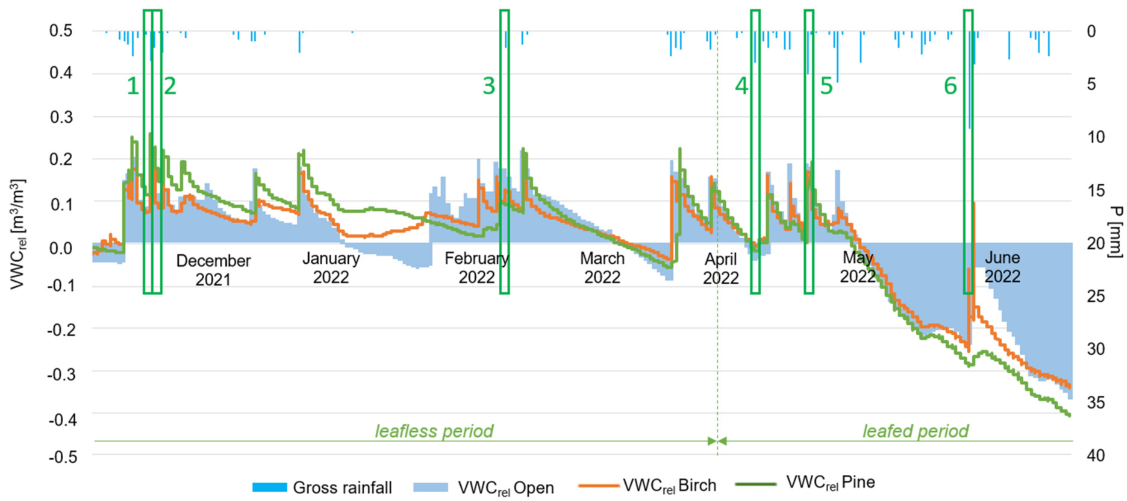

Fig. 6. VWC_{rel} measured at the 16 cm depth and rainfall input during the observed period (19 November 2021 – 30 June 2022); rainfall events, selected for further analysis, are marked with green rectangles and numbered.

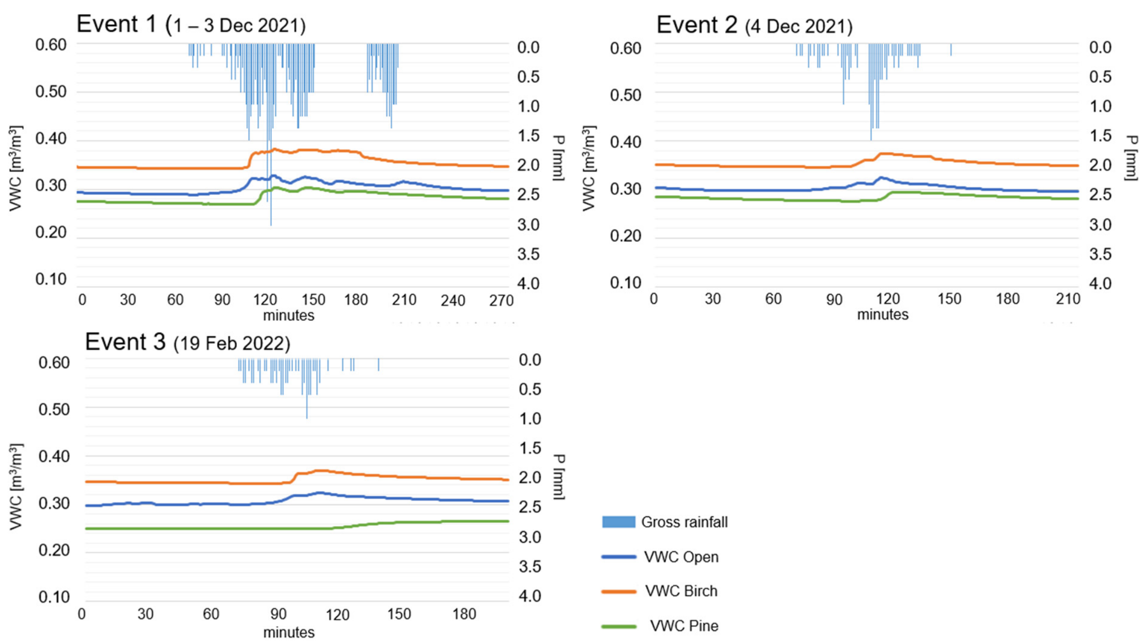

Fig. 7. Response of VWC to rainfall during selected rainfall events in leafless period.

There was no significant peak of VWC values under the pine tree (Figure 7).

Event 4 occurred on 21 April 2022 in the leafed period. During 24.3 hours, there was 23.4 mm of rainfall delivered, TF under the birch tree and under the pine tree accounted for 67% and 42% of rainfall in the open, respectively. Three peaks of more intense precipitation characterized the event. The first peak occurred two hours after the beginning of the event, the second one after 8.4 hours and the third one after 14 hours (Figure 8). Although before the first intensity peak, 3.2 mm of rainfall already reached the ground in the open, it did not induce any VWC response (Table 2). Only after the second peak, VWC values in the open and under the birch tree started to increase and also reached their maximum values. VWC under the pine tree started to increase after the third intensity peak, corresponding to 9.5 mm of TF input.

From 1 to 2 May 2022, a 14.7 hours long event occurred, delivering 27.2 mm of rainfall (event 5) (Table 2). Throughfall under the birch tree and under the pine tree in total accounted for 89% and 49% of rainfall, respectively. The event started with high intensity precipitation. In the first hour, 10.2 mm of rainfall was detected. This induced a slow increase of VWC values on the open plot and under the birch tree, while no response was observed under the pine tree. However, the peak values on all three plots were observed at the same time, after the third more intense rainfall input 11 hours from the start of the event (Figure 8). To reach the highest VWC value during this event, in the open plot 25.8 mm of rainfall, under the birch tree 20.2 mm of TF and under the pine tree 13.1 mm of TF was needed.

Event 6 started on 7 June 2022 in the dry period, when VWC_{rel} was already negative (Figures 3–5). It lasted for 10.5 hours and delivered 24.2 mm of rainfall. TF under the birch tree was equal to 79% and under the pine tree 51% of rainfall in the open. It started with gentle rain as in the first 1.5 hours only 1.2 mm of rainfall was measured, which has not reflected at low VWC values at all. However, after that a short and intense rainfall of 9.2 mm in 20 minutes occurred, resulting in an immediate increase

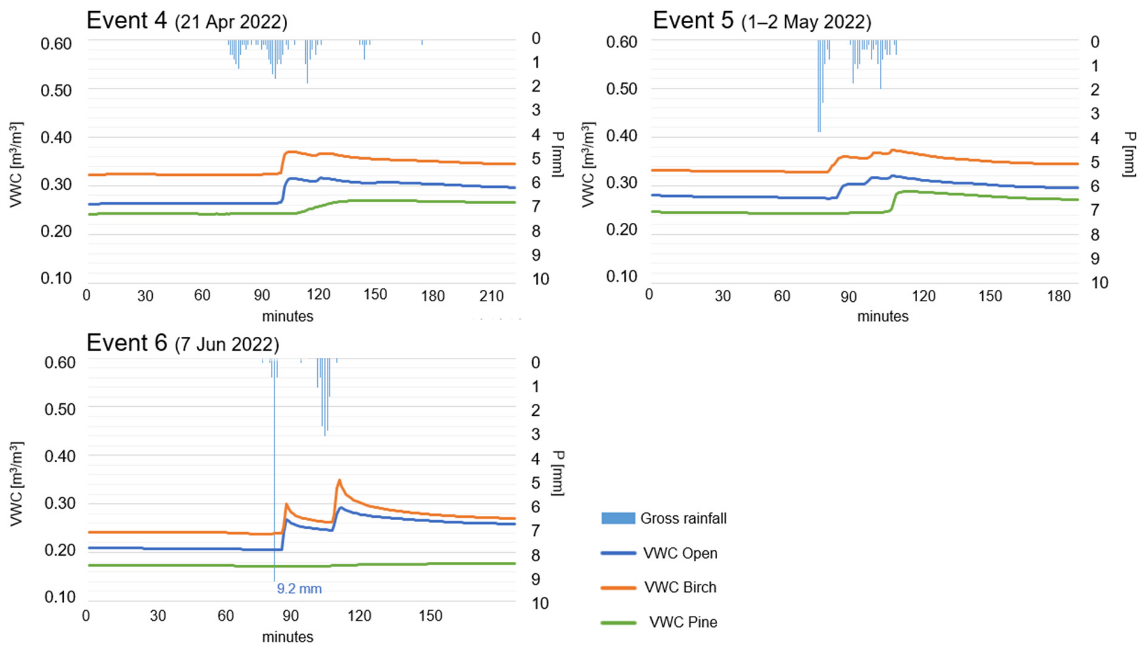

Fig. 8. Response of VWC to rainfall during selected rainfall events in leafed period.

of VWC values in the open and under the birch (Table 2). In the short cessation of the rainfall that followed, VWC values at these two plots started to decline (Figure 8). The second heavier rainfall input (12.6 mm in 1.5 hours) again increased the VWC values in the open plot and under the birch tree, which also reached the maximum values.

Under the birch and in the open, the response of VWC during the rainfall events was similar. At these locations, an increase in the VWC values as well as its dynamics was similar (blue and orange lines in Figure 7 and Figure 8). Under the pine, the response was in general delayed compared to the other two locations and during events 2, 3, 4 and 6, the increase in VWC was also considerably lower. This may be the result of (otherwise minor) differences in the composition of the soil in the upper layers, which have a direct contact with the input (rainfall or throughfall). The uppermost soil layer under the pine tree has a bit lower porosity and higher bulk density than at the other two locations. The relationship between the infiltration rate and porosity (bulk density) is well investigated. For example, in the study of Dos Santos et al. (2018) a positive relationship between infiltration rate and porosity was clearly indicated, while evaluating soil physical properties and infiltration rates for different land uses. Similar was found by Bi et al. (2014), who investigated changes of infiltration rates due to mining which was reflected in a changed bulk density but differently for different vegetation types. In general, the bulk density was negatively correlated with infiltration rates. Another factor that can influence the slower and reduced soil infiltration under the pine tree is water repellency. For example, Iovino et al. (2018) and Hewelke et al. (2022) both reported that pine species can induce soil water repellency. Additionally, according to study of Buczko et al. (2006), water repellency in pine-beech forests varies intra-annually with the highest values in summer months. Similar was reported by Hewelke et al. (2018), who observed increased soil water repellency due to prolonged dry periods. This could explain the almost negligible response in VWC values during event 6 that occurred in June under the pine tree. Finally, also the antecedent weather conditions (e.g., air temperature and rainless period) could influence the water repellency and therefore infiltration rates (Buczko et al., 2007).

The VWC response according to rainfall and throughfall input during development of the event showed characteristic dynamics according to the pre-event conditions. The first three events (Figure 7) were observed during the leafless period, which was also characterized by wetter VWC conditions and consecutive rainfall events. For these three events the maximal VWC value was reached after the more intense rainfall occurred. The consistent precipitation and soil moisture temporal variations were observed also by Dai et al. (2022), who reported significant seasonal patterns. Additionally, Yan et al. (2021) observed a strong soil moisture response to the rainstorm event, which was noticeable especially during moderate events and rainstorms, e.g., events with a higher rainfall intensity. The other three events (Figure 8) were measured in the leafed period, when VWC values were lower and longer periods without rainfall were observed. For these events the previously observed response pattern is no longer present.

In this context, a detailed analysis of only a few selected rainfall events presented in this study shows that in the future, in order to draw more certain conclusions about the factors influencing the dynamics of changes in soil VWC, it will be necessary to consider and verify the above-mentioned aspects. Of course, a larger sample of events and a denser network of sensors is also needed, covering different before and inter-event conditions. Nevertheless, we argue that an event-based analysis is crucial and also very beneficial for long-term investigations. When using individual statistical values (e.g., mean event VWC) of the variables for a single event, important information, offering insight into the process, can be missed.

CONCLUSIONS

The paper presents the preliminary results of the influence of precipitation and throughfall on the response dynamics of the soil volumetric water content (VWC). Based on the simultaneously and continuously measured rainfall, throughfall, and soil moisture data on the experimental plot with two groups of birch and pine trees in a small urban park, six rainfall events were selected for an in-depth analysis.

The response of VWC values was the fastest in the upper depth, followed by the lower two depths regardless the plot. Responses in the upper depth can be directly associated with the occurrence of precipitation events, however in lower depths the dependence is not so direct. Especially during the leafless period, the response cannot be assigned to a single event. This indicates seasonal differences in the response, which were observed also in the rate of maximum VWC occurrence, which was faster in the leafless season, characterized by a greater antecedent soil moisture. The increase of VWC values was delayed under the trees in comparison to the open location. The delay in VWC response was even longer than that of TF according to the start of rainfall in the open. The response of VWC under the trees is not delayed only because of the later beginning of TF but also because of the different dynamics of TF compared to rainfall.

The importance of the changing rainfall dynamics on the increase of VWC values during an event was shown by an event-based analysis. For all analyzed events, we observed that the peak of VWC values appeared after more intense precipitation. However, in the leafless period the lower rainfall intensities induced a response of VWC values in all three locations. The influence of antecedent soil moisture conditions is therefore shown when comparing the response with the events in the leafed period. At that time, the VWC response was influenced not only by the increased rainfall intensity, but also by the total delivered rainfall amount.

Combination of the analysis of short time step data during the entire measurement period with the event-based analysis provides interesting insights into the response of VWC values according to rainfall and TF inputs. Understanding also the responses during an event is crucial and beneficial for understanding of the biohydrological processes.

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