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SHORT-TIME MEASUREMENTS OF INTERCEPTION IN MOUNTAIN SPRUCE FOREST

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Open area rainfall and throughfall measurements in the Western Tatra Mountains (altitude about 1500 m a.s.l.) made by tipping bucket gauges were used to estimate the usefulness of the short-time data in analysis of spruce interception. The 10-minute data from period 13 May–13 October 2009 did not reveal meaningful correlations between the open area rainfall and throughfall. Aggregated measurements representing individual rainfall events were more useful. They showed linear relationship between open area rainfall and throughfall for events with total rainfall depth in the open area exceeding 5 mm. Correlation between open area rainfall and throughfall for rainfall events with duration above 120 minutes was significantly better than for the shorter ones. Mean values of interception (percentage of open area rainfall which did not appear in throughfall) of individual rainfall events was high. When we excluded events for which throughfall was higher than the open area rainfall, mean interception for larger and longer rainfall events was 46% and 48%, respectively. For smaller (runoff depth below 5 mm) and shorter events (duration below 2 hours) the mean interception was 70% and 72%, respectively. However, the data revealed very high variability of interception.

KEY WORDS: Interception, Short-time Data, Mountain Spruce Forest.

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Príspevok sa zaoberá hodnotením užitočnosti krátkodobých meraní zrážok na otvorenej ploche a v smrekovom lese pri určovaní intercepcie. Vychádza z merania zrážok preklápacími zrážkomermi v Západných Tatrách v nadmorskej výške okolo 1500 m n.m. Desaťminútové údaje merané v období 13.5.–13.10.2009 neposkytli použiteľné korelácie medzi dažďom na otvorenej ploche a v lese. Lepšie výsledky boli získané pre sumárne úhrny zrážok pre jednotlivé dažde. Ak úhrn dažďa na voľnej ploche prekročil približne 5 mm, veľkosť podkorunových zrážok rástla lineárne s veľkosťou zrážok na voľnej ploche. Korelácia medzi zrážkami na voľnej ploche a v lese pre dažde s dĺžkou trvania nad 120 minút bola podstatne lepšia, ako pre kratšie dažde. Priemerná hodnota intercepcie (vyjadrenej ako percento zrážok na voľnej ploche, ktoré sa neobjavilo v lese) pre jednotlivé zrážkové udalosti bola vysoká. Po vylúčení udalostí, pre ktoré bol v lese nameraný vyšší úhrn zrážok ako na voľnej ploche, bola priemerná intercepcia pre väčšie dažde 46 % a pre dlhšie dažde 48 %. Pre menšie (úhrn pod 5 mm) a kratšie (trvanie pod 2 hodiny) dažde bola priemerná intercepcia 70 % a 72%. Hodnoty intercepcie pre jednotlivé udalosti však mali veľkú variabilitu.

KĽÚČOVÉ SLOVÁ: intercepcia, krátkodobé údaje, horský smrekový les.

Introduction

Vegetation influences hydrological cycle in many ways. One of them is the influence on partitioning of water inputs into the catchment (soils) by precipitation interception. Hundreds studies were devoted to interception worldwide. In Europe, the comparative studies of precipitation in forested and open areas were performed already in the 19th century in Germany, Austria, Switzerland, France and Russia (e.g. *Krečmer*, 1952). The review given by *Helvey* and *Patric* (1965) shows that interception has been of much interest in the United States since the first third of the 20th century and the description of canopy interception was made already in 1893. Throughfall and stemflow values for different tree species depending on the amount of rainfall were given by Hoppe already in 1896 (in *Krečmer*, 1952). Similar studies were repeated many times. Yet, *Savenije* (2004) noted that many hydrological models still disregard or underestimate interception, although it is one of the most important processes in hydrological modeling.

Studies based on comparison of open area rainfall and throughfall usually give the longer-time, e.g. seasonal or annual values of interception. Such values are useful, e.g. in the analysis of water balance. In other applications, e.g. in hydrological modeling, understanding of runoff formation in the catchment, soil moisture distribution or erosion, the knowledge of interception in the short time intervals (during individual rainfalls) may be more important (e.g. *Horvát* et al., 2009). Since the longer-term values known from field measurements can not be directly used in such applications, interception modeling is necessary. Several approaches were developed to model the rainfall interception. A brief description of the models including the empirical ones was earlier provided e. g. by *Xiao* et al., 2000. A more detailed review of physically based interception modeling was recently made by *Muzylo* et al. (2009). They reported on 15 physically based interception models, the youngest of which was proposed in 2007.

Generally, the physically based interception models can be divided into several groups (e.g. *Muzylo* et al., 2009). The Rutter type models (e.g. *Rutter* et al., 1971; *Benetin*, 1983; *Massman*, 1983; *Liu*, 1988; *Xiao* et al., 2000) represent interception by water balance of rainfall input, storage and output (drainage, evaporation):

$$\frac{dC}{dt} = (1 - f_g - f_s)p - D_0 \exp(b(C - S)) - e \,, \quad (1)$$

where C is canopy water storage [mm], f_g – a gap fraction that controls the precipitation contributing to free throughfall, f_s – the precipitation fraction contributing to stemflow, D_0 and b – empirical drainage parameters, S – the canopy storage capacity [mm], p – precipitation rates [mm], e – evaporation rates [mm], respectively (*Xiao* et al., 2000).

Gash's type models (*Gash*, 1979; *Mulder*, 1985; *Zeng* et al., 2000, *Murakami*, 2007) are analytical models that provide a simplified solution to the Rutter's model (*Muzylo* et al., 2009). Rainfall input is represented as a series of discrete storms between which the canopy and stems completely dry. Gash's model can be written (*Xiao* et al., 2000):

$$\sum_{j=1}^{N+M} IL_j = N(1 - f_g - f_s)P' + \frac{\overline{E}}{\overline{R}} \sum_{j=1}^{N} (P_j - P') + (1 - f_g - f_s) \sum_{j=1}^{M} P_J + E_{trunk} \quad (2)$$

$$E_{trunk} = JS_t + f_s \sum_{j=1}^{M+B-J} P_j \,, \quad (3)$$

$$P' = -\frac{\overline{R}S}{\overline{E}} \ln(1 - \frac{\overline{E}}{\overline{R}(1 - f_g - f_s)} \,, \quad (4)$$

where IL is total interception loss [mm], $\overline{E}$ and $\overline{P}$ – mean evaporation and rainfall rates [mm], S_t – trunk storage capacity [mm] and J – the number of events above the critical rainfall (S_t/f_s). M is the number of events that are insufficient to saturate the canopy surface completely, N – the number of events that are large enough to completely saturate the canopy surface.

Calder (1986) developed a conceptually different model which employs Poisson probability distribution to estimate the number of raindrops that strike the canopy and are retained by it (*Muzylo* et al., 2009).

The above equations give an idea on parameters of different models. Basically, the parameters characterize water storage, canopy structure, water partitioning and other, e.g. number of drops, raindrop volume, threshold of rainfall intensity, etc. (*Muzylo* et al., 2009). *Vrugt* et al. (2003) noted that parameters of the interception models have often to be only calibrated, because it is difficult to validate them by measurements. They also stated that relatively limited research has been conducted to validate the interception models or estimate its parameters from measurements. Inadequate validation of the models, few comparative studies and the uncertainties of measurements and parameters variability were also mentioned by *Muzylo* et al. (2009).

There are some parameters of interception models which could be inferred from the field measurements. For example, all physically-based interception models reviewed by *Muzylo* et al. (2009) include some parameter representing the threshold amount of rain that can be stored in the canopy. The main objective of this study was to compare the short-term open area rainfall and throughfall measurements in a mountain spruce forest to obtain information on the interception of individual rainfall events and assess the usefulness of the short-time measurements in estimation of the canopy storage capacity. The study strives to supplement the results of numerous studies conducted in the Western Carpathians by foresters and hydrologists (e.g. *Zelený* and *Tichý*, 1968; *Majerčáková*, 1983; *Benetin* et al., 1986; *Valtýni*, 1986; *Tužinský*, 1995; *Lančarič* et al., 2001; *Minďáš*, 2001; *Pekárová* et al., 2005, *Halmová* et al., 2006; *Miklánek* et al., 2006; *Holko* et al., 2009) by focusing on the short-time resolution (10-minutes) rainfall and throughfall data in a high-mountain forest.

Description of study area and measured data

The study was performed at a small research plot in the Jalovecký creek catchment, the Western Tatra Mountains, northern Slovakia. Open area precipitation was measured in the 10-minutes interval by the tipping bucket raingaiuge at the altitude 1500 m a.s.l. Throughfall was measured by the tipping bucket gauge in the nearby mature forest spruce (mean age 110 years). Our previous measurements on the site using a number of manually operated rain gauges (*Holko* et al., 2009) revealed high variability of interception even at the same typical locations (forest window, dripping zone, near stem zone). Therefore, the tipping bucket rain gauge used in this study was placed into a forest window which showed the smallest spatial variability of throughfall in the previous study. Open area and throughfall measurements from period 13 May–13 October 2009 were compared in two steps. First, the short-time interval (10-minutes) data were compared. Second, the data for individual rainfall events were aggregated and compared.

Results

Most rainfalls in the studied period had intensities of up to about 3 mm per 10 min (Fig. 1). Fig. 1 (left panels) shows that the 10-minutes rainfall in the forest was generally smaller than in the open area, started and terminated with small delays after the open area rainfall. Small open area rainfalls were often not registered in the forest. Such a behavior was expected. However, the 10-minutes data did not provide meaningfull correlations of the open area and throughfall rainfalls (Fig. 1 right panel). No correlation between open area rainfall and throughfall exists for rainfall intensities below about 2 mm/10 min. Rainfall compartments of higher intensities tend to have the expected tendency toward more precipitation in the open area, but the scatter is very large.

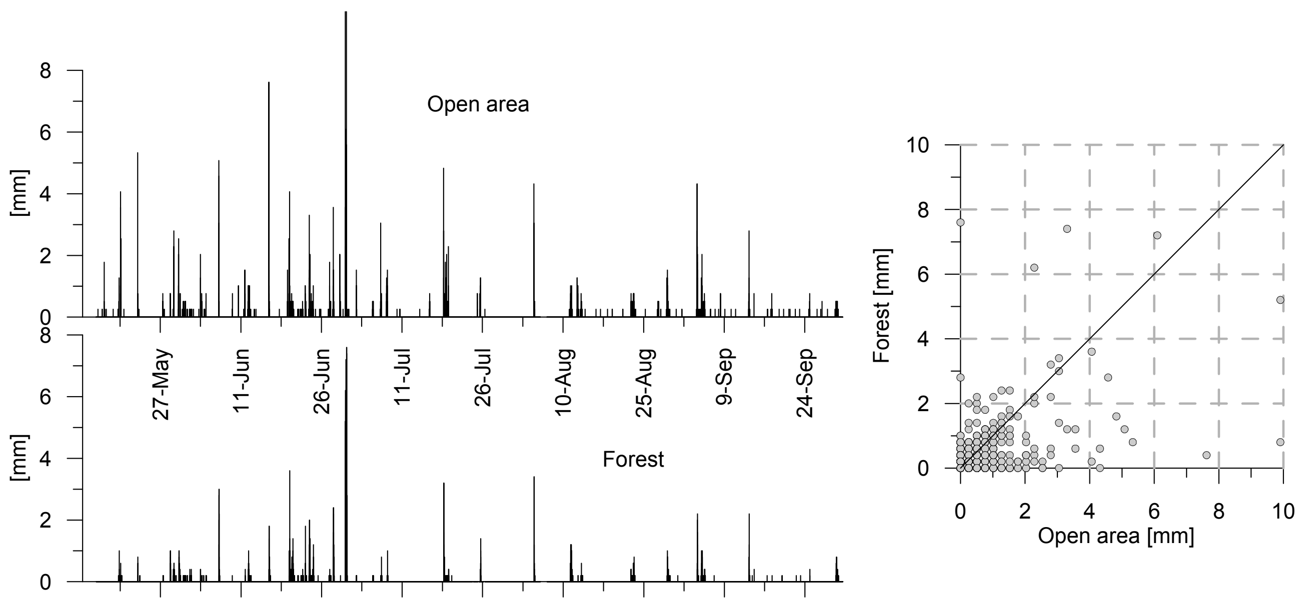

Fig. 1. 10-minute precipitation in the open area and in the forest between 13 May and 13 October 2009; the diagonal in the right panel represents the 1 : 1 line.
Obr. 1. 10-minútové úhrny zrážok na voľnej ploche a v lese v období 13. 5.–13. 10. 2009; uhlopriečka v pravom obrázku predstavuje čiaru 1 : 1.

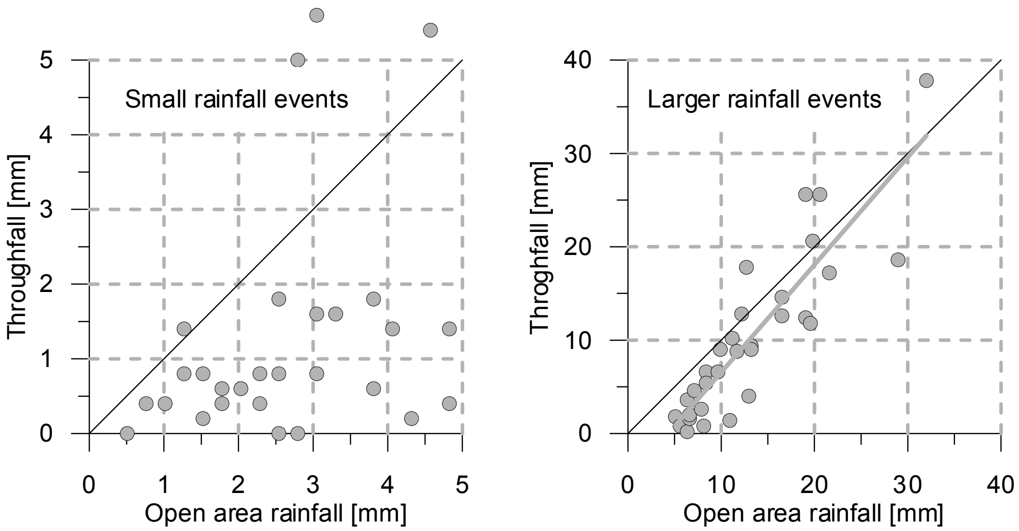

Fig. 2. Rainfall amount and interception; relationship between open area rainfall and throughfall for 59 rainfall events measured between 13 May and 13 October 2009; left – rainfall in the open area reached 0–5 mm; right – rainfall in the open area exceeded 5 mm; the diagonals represent the 1:1 lines; the grey line in the right panel represents the regression line (R^2 = 0.778).
Obr. 2. Úhrn dažďa a intercepcia; vzťah medzi zrážkami na voľnej ploche a v lese pre 59 zrážkových udalostí meraných v období 13. 5. –13. 10. 2009; vľavo – zrážkové úhrny na voľnej ploche v intervale 0–5 mm; vpravo – zrážkový úhrn na voľnej ploche prekročil 5 mm; uhlopriečky predstavujú čiary 1 : 1; sivá čiara v pravej časti obrázka predstavuje regresnú čiaru (R^2 = 0.778).

Better relationships between the open area rainfall and throughfall appeared when total amounts of rainfall per individual events were aggregated and compared. We have analysed 59 events from period 13 May–13 October 2009. Fig. 2 shows the influence of rainfall amount on interception (percentage of rainfall which did not appear in throughfall). If the open area rainfall during an event was below 5 mm, the correlation with throughfall was weak (Fig. 2 left). Nevertheless, except three outliers, throughfall in such instances never exceeded 2 mm and for most events it was below 1 mm. It indicates that maximum canopy storage capacity was about 3–4 mm. When the open area rainfall during a rainfall event exceeded the threshold of 5 mm, throughfall became well correlated with the open area rainfall (Fig. 2 right). Linear regression explained 78% of variability of the data. It indicates the canopy storage capacity of about 4 millimeters.

Fig. 3 shows the effect of rainfall duration in the open area rainfall-throughfall relationship. Rainfall durations for the 59 events varied between 30 and 1480 minutes. About one third of the rainfalls were shorter than 120 minutes and about one third of them were longer than 6 hours. Correlation of throughfall with open area rainfall was much better for the rainfall events longer than 120 minutes than for the shorter ones (Fig. 3). This “rain duration effect” is obviously partially connected also with the effect of total amount of the rainfall during an event described above. Canopy storage capacity indicated in the right panel of Fig. 3 is about 3 millimeters. Fig. 3 shows that summer storms bringing a lot of rain in a short period did not occur at the studied site in the studied period.

Statistics of the interception for individual events is given in Tab. 1. Individual rainfall events were divided according to rainfall depth and duration. Mean values indicate that studied forest had a significant influence on throughfall. However, very high variability of interception for individual rainfall events (Tab. 1, Fig. 4) should not be omitted.

Correlation between mean intensities of individual rainfall events in the open area and in the forests was not very strong (Fig. 5). As expected, the intensities in the open area were mostly higher than those in the forest.

Discussion

The existence of no correlation between the 10-minutes open area rainfall and throughfall shown in Fig. 1 confirms findings of *Vrugt* et al. (2003) who demonstrated that measured throughfall dynamics contained limited information for calibration of an interception model and were particularly inadequate to identify the canopy storage capacity. Similar concerns were recently raised also by *Zimmerman* et al. (2010).

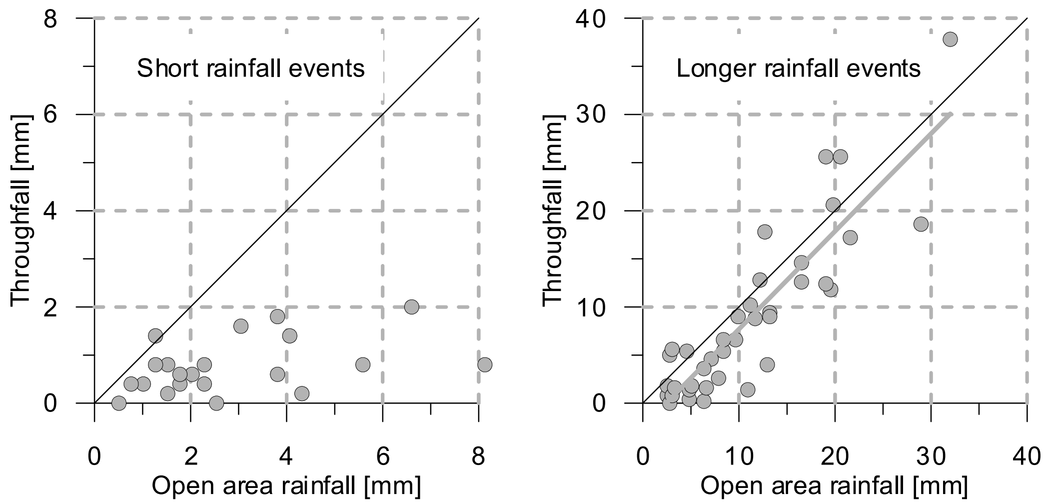

Fig. 3. Rainfall duration and interception; relationships between open area rainfall and throughfall for events with different duration; left – rainfalls shorter than 120 minutes; right – rainfalls longer than 120 minutes; the diagonals represent the 1:1 lines; the grey line in the right panel represents the regression line (R^2 = 0.781).
Obr. 3. Dĺžka trvania dažďa a intercepcia; vzťah medzi zrážkami na voľnej ploche a podkorunovými zrážkami pre udalosti s rôznou dĺžkou trvania; vľavo – zrážky kratšie ako 120 minút; vpravo – zrážky dlhšie ako 120 minút; uhlopriečky predstavujú čiary 1 : 1; sivá čiara v pravej časti obrázka predstavuje regresnú čiaru (R^2 = 0.781).

T a b l e 1. Interception of individual rainfall events; N1 – number of all rainfall events, N2 – number of rainfall events for which the interception was negative, i.e. throughfall exceeded the open area rainfall; other statistics (mean, minimum, maximum, standard deviation and *Cv*) are given first for all events (i.e. N1), second only for events with positive interception (i.e. N1–N2).
T a b u ľ k a 1. Intercepcia (percento zrážok zachytených lesom) jednotlivých zrážkových udalostí; N1 – počet všetkých zrážkových udalostí, N2 – počet zrážkových udalostí, pre ktoré bola negatívna intercepcia, t.j. podkorunové zrážky prevyšovali zrážky na voľnej ploche; ďalšie štatistiky (priemer, minimum, maximum, smerodajná odchýlka, koeficient variácie) sú vypočítané najprv pre N1 a potom pre N1–N2.

	Rainfall amount		Rainfall duration	
	Below 5 mm	Above 5 mm	Below 2 hours	Above 2 hours
N1	28	31	21	38
N2	4	6	1	9
Mean [%]	53/70	33/46	68/72	28/48
Minimum [%]	–84/29	–40/9	–10/37	–84/9
Maximum [%]	100/100	97/97	100/100	100/100
St. deviation [%]	48/20	37/27	26/19	45/27
C_v	0.90/0.29	1.12/0.60	0.38/0.26	1.58/0.57

Usefulness of the short time resolution data became more evident when the data for individual rainfall events were processed. The short-time resolution data allow detection of individual rainfall events which may not be recognized in data with longer time resolution, e.g. daily data. Correlations between the open area rainfall and throughfall in this study became detectable for the rainfall events exceeding certain rainfall depth (about 5 mm in the open area) or for rainfall events longer than 2 hours.

The canopy storage capacity for individual events varied. Its upper limit (about 4 mm) is close to the value of 5 mm found in previous research in the region based on daily data (*Majerčáková*, 1983). *Minďáš* et al., 2001 in their review paper on the water balance of the forest ecosystem in the Carpathians reported that the canopy stogare capacity of the forests reach approximately 10 mm. We did not analyze influence of other factors such as wind speed on canopy storage capacity.

Mean values of interception given in Tab. 1 indicates high influence of the forest on throughfall. However, Fig. 4 and statistics in Tab. 1 show a very high variability and decreasing role of the forest for higher rainfall depths. Thus the mean values given in Tab. 1 should be taken with care.

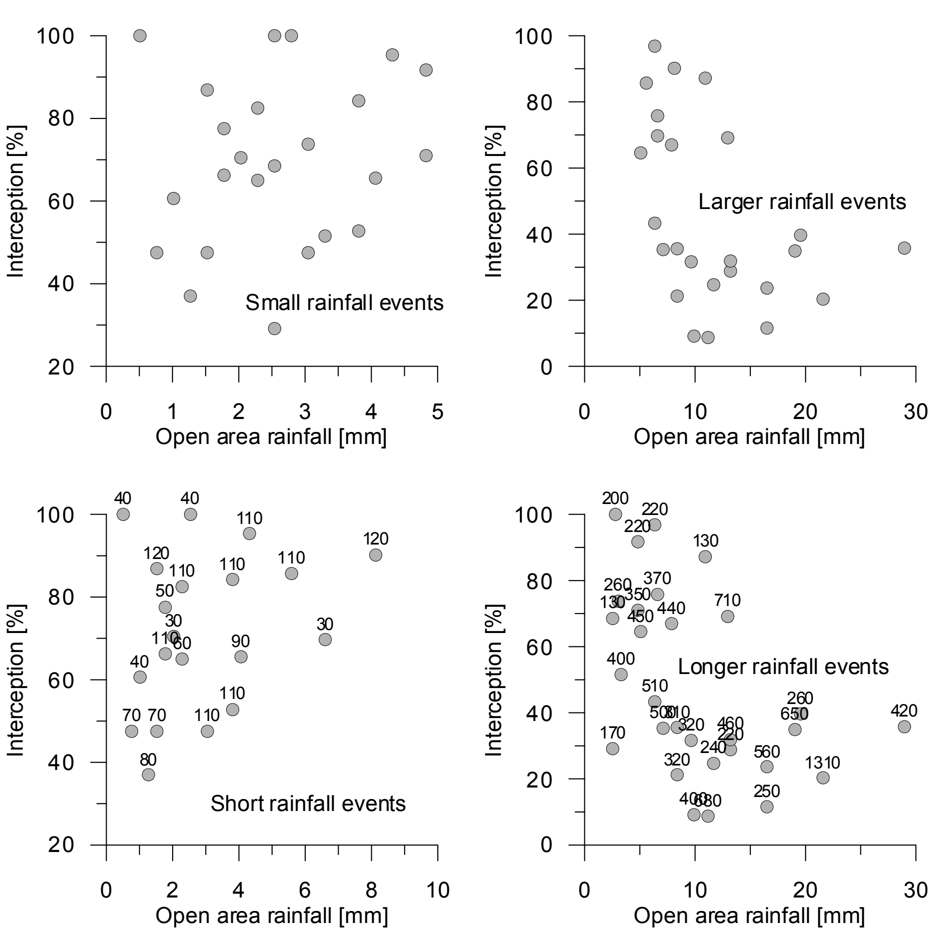

Fig. 4. Variability of interception for individual rainfall events against rainfall depth and duration; only the events with positive interception are shown, labels in the lower panel denote rainfall durations in minutes.
Obr. 4. Variabilita intercepcie pre jednotlivé zrážkové udalosti v závislosti od úhrnu a dĺžky trvania dažďa; znázornená je len pozitívna intercepcia; čísla v spodnej časti obrázku ukazujú dĺžku trvania dažďa v minútach.

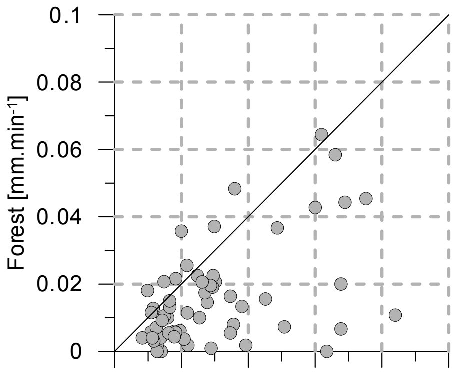

Fig. 5. Mean rainfall intensities of individual rainfall events in the open area and in the forest (59 events); the diagonal represents the 1 : 1 line.
Obr. 5. Priemerná intenzita jednotlivých zrážkových udalostí na otvorenej ploche a v lese (59 udalostí); uhlopriečka predstavuje čiaru 1 : 1.

Interception of individual rainfall events seems to be higher than the values calculated from bi-weekly data in our previous study (*Holko* et al., 2009). However, in this study we could use only one raingauge to measure throughfall. A much higher number of gauges at more locations would be necessary to generalize the results presented here. Although *Keim* et al (2005) showed that the spatial patterns of throughfall variability tend to persist, a large number of raingauges (either fixed or moving) is needed to describe it (e.g. *Holwerda* et al., 2006). Use of recording clusters of long troughs was proposed by *Zimmermann* et al. (2010) as a more promising sampling scheme. New measuring approaches represent other options. For example, *Vrugt* et al. (2003) reported that microwave-measured canopy water storage dynamics provided sufficient information for identification of parameters of a physically based interception model. *Friesen* et al. (2008) recently presented the results of a new direct and nondestructive method to measure the whole-tree interception based on measurement of trunk compression by mechanical displacement sensors.

Conclusions

The short-time rainfall and throughfall data allow some analyses which can not be performed with data measured in the longer time resolution (e.g. delay of throughfall onset and termination, elimination of small rainfalls by the forest, comparison of rainfall intensities, analyses of interception during individual rainfall events). The 10-minutes data did not provide exact values which could be directly used as parameters of interception models, e.g. canopy storage capacity. However, unlike the longer-term measurements they allow discrimination of individual events which are more useful in the assessment of the thresholds. Information on varying canopy storage capacity during individual rainfall events could be used in validation and constraining of modeled interception giving the ranges in which the simulated results should vary. The study showed that interception of smaller rainfall events (under 5 mm) was on average about doubled compared to interception of rainfall events with total depth exceeding 5 mm. It can therefore be supposed that high interception values reported in many studies for annual or seasonal values indicate that most rainfalls in the studied areas were relatively small (below certain thresholds). Further studies at more locations and with better instrumentation would be useful to generalize the results presented in this study.

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MERANIE INTERCEPCIE V HORSKOM SMREKOVOM LESE V KRÁTKOM ČASOVOM KROKU

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Intercepcia je jedným z procesov, ktorým vplýva vegetácia na hydrologický cyklus. Výskumom intercepcie sa zaoberali a zaoberajú stovky štúdií na celom svete. V Európe sa porovnávacie merania zrážok na otvorenej ploche a v lese vykonávali už v 19. storočí (*Krečmer*, 1952), v USA od prvej tretiny 20. storočia (*Helvey*, *Patrick*, 1965). Výsledky takýchto štúdií často charakterizujú priemernú intercepciu za dlhšie časové odobie, napr. rok alebo sezónu. Takéto údaje sú užitočné napríklad pri analýze hydrologickej bilancie, ale v iných prípadoch, napr. pri hydrologickom modelovaní, výskume tvorby odtoku v povodí, rozdelenia vlhkosti pôdy alebo erózie sú užitočnejšie poznatky o intercepcii v kratšom časovom intervale (napr. intercepcia jednotlivých dažďov). V takýchto prípadoch býva obyčajne potrebné využitie matematického modelovania. Modelovanie intercepcie sa postupne vyvíjalo od empirických a štatistických modelov k fyzikálne založeným modelom, ktoré sa môžu rozdeliť zhruba do troch skupín (*Xiao* et al., 2000; *Muzylo*, 2009):

- modely typu *Ruttera* (1971),
- modely typu *Gasha* (1979),
- modely *Caldera* (1986).

Základné vzťahy pri modeloch prvých dvoch typov sú opísané rovnicami (1)–(4). Ako vidieť, tieto rovnice obsahujú veľa parametrov, ktoré sú často len kalibrované, lebo sa ťažko overujú meraniami (*Vrugh* et al., 2003). Cieľom tohto príspevku bolo porovnanie meraní zrážok na voľnej ploche a v smrekovom lese, vykonávaných v krátkom časovom kroku, vyhodnotenie intercepcie jednotlivých zrážkových udalostí a užitočnosti takýchto meraní pri určovaní parametrov fyzikálne založených modelov interecpcie spojených napr. s množstvom vody zachyteným vegetáciou.

Merania boli vykonávané v povodí Jaloveckého potoka v Západných Tatrách v nadmorskej výške 1500 m n.m. a v blízkom smrekovom lese (priemerný vek 110 rokov) v teplej časti roka 2009 pomocou preklápacích zrážkomerov. Podľa predchádzajúcich meraní (*Holko* et al., 2009) bola variabilita intercepcie v porastových oknách na danej lokalite menšia ako v iných typických lokalitách (zóna odkvapu, zrážky pri kmeni). Preto bol preklápací zrážkomer v lese umiestnený v porastovom okne. Porovnanie 10-minútových dažďov neukázalo dobrý vzťah medzi zrážkami na voľnej ploche a v lese (obr. 1). Lepšie výsledky boli získané pri porovnávaní sumárnych úhrnov za jednotlivé zrážkové udalosti (obr. 2 a 3). Pri prekročení určitého úhrnu (cca 5 mm) alebo dĺžky trvania dažďa (cca 120 minút) sa vzťah medzi zrážkami na voľnej ploche a v lese výrazne zlepšil. Výsledky práce ukázali, že okamžité, resp. 10-minútové údaje nepriniesli informácie, ktoré by pomohli pri priamom určení parametrov fyzikálne založených modelov intercepcie. Spracovanie krátkodobých údajov pre jednotlivé dažde síce tiež neurčilo jednoznačne hodnotu retenčnej kapacity vegetácie, ale ukázalo približne jej rozsah, resp. maximum na skúmanej lokalite (cca 5 mm). Priemerná intercepcia dažďov, pri ktorých celkový úhrn na voľnej ploche prekročil hodnotu 5 mm, bola približne polovičná v porovnaní s dažďami, ktoré mali úhrn menší ako 5 mm (tab. 1, obr. 4). Preto sa dá predpokladať, že výsledky štúdií, pri ktorých boli zistené veľké hodnoty ročnej alebo sezónnej intercepcie, poukazujú na to, že väčšina dažďov v skúmaných lokalitách bola pomerne malých (pod určitou „kritickou“ hodnotou). Priemerná intercepcia jednotlivých zrážkových udalostí bola veľká, ale tab. 1 a obr. 4 ukazujú aj jej veľkú variabilitu.