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Rainfall variability in the mountain forest catchments of Černá Opava tributaries in the Jeseníky Mountains

Vít Šrámek, Věra Fadrhonsová, Kateřina Neudertová Hellebrandová*

Forestry and Game Management Research Institute, Jíloviště-Strnady, Czech Republic

**Corresponding author: sramek@vulhm.cz*

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Abstract: An unprecedented bark beetle outbreak has led to a significant decline in forest cover in Central Europe in the last 10 years, affecting an area estimated at more than 200 000 ha in the Czech Republic. Among the many ecological threats associated with extensive clearings, the potential alteration of hydrological processes is one of the most important. Therefore, after 2022, the precipitation–runoff balance in three catchments in the Jeseníky Mts. area was studied. This study focuses on the rainfall variability within the area, which was measured using 24 rain gauges deployed to cover different altitudes as well as the geographical exposures of the mountain catchments. Precipitation data was evaluated based on seven-day totals within the frost-free period. There was a significant increase in precipitation with altitude (12% increase for every 100 m a.s.l.) but only in less than half (48.7%) of the evaluated periods. No significant trend was demonstrated in the remaining periods, and a negative trend in precipitation with altitude was identified in 8.9% of cases. Additionally, the role of exposure was insignificant, although a tendency towards slightly lower precipitation was found for the eastern exposure at altitudes up to 1 000 m a.s.l., which may be related to the prevailing wind direction. We concluded that even a relatively dense monitoring network is not necessarily sufficient to provide accurate precipitation data in forested catchments, especially in mountain areas. Under such conditions, the use of complex models that also use radar data is recommended.

Keywords: altitudinal gradient; distribution of precipitation; exposure; forest watershed; synoptic situation

The amount and distribution of precipitation across seasons, together with temperature, are the main determining parameters for the occurrence of biomes on Earth. In the Czech Republic, the average annual precipitation varies between 400 mm and 1 700 mm, with the highest amounts in mountain areas (Šrámek, Fadrhonsová 2023). The role of forests in the total amount and redistribution of rainfall in mountain regions has been thoroughly documented, and their essential role in regional and continental water cycles is widely acknowledged (Zelený 1975; Bartík et al. 2016; Keys et al. 2016; Pearce 2020; Van Stan et al. 2020). Recently, the hydrological functioning of mountain forests has become even more important, but it is threatened because of ongoing global climate change (Ellison et al. 2017; Černohous et al. 2018; Gribovszki et al. 2019; Teuling et al. 2019). Pro-

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nounced drought periods in 2015 and 2018 contributed significantly to the vast bark beetle outbreak that spread through Central Europe, causing temporal deforestation of areas dominated by artificially planted Norway spruce stands (Šustek et al. 2017; Hlásny et al. 2021; Lukasová et al. 2021; Thornfeld et al. 2022). The total area of clearcuts after salvage felling during 2018–2023 has been estimated to be more than 205 000 ha in the Czech Republic (Křístek et al. 2024). One of the most heavily affected areas is the Northern Moravia region, including the eastern part of the Jeseníky Mts., where the outbreak has recently spread to the higher altitudinal zone (Zahradník, Zahradníková 2019; Lubojacký et al. 2024).

Forest management can affect the hydrological functioning of the landscape (Hawthorne et al. 2013; Buttle et al. 2018) both in positive and negative ways. Significant deforestation leads to higher and more fluctuating outflow from the catchment (Hornbeck et al. 1997; Hubbart et al. 2007) and a decreased ability to mitigate extreme situations, including floods (Yu et al. 2015). To study the effect of salvage felling on the hydrological processes in mountain forested catchments, three streams in the Jeseníky Mts. have been monitored since 2020 (Šrámek et al. 2023). Our study focused on the variability in precipitation in the complex terrain of mountain catchments.

Measurement of precipitation, especially in mountain areas, is quite complex and usually limited by the low number of rain gauges (Buytaert et al. 2006; Ly et al. 2013; Kozak et al. 2019). We try to use a dense network of measurement points to evaluate the effect of altitude, exposure and synoptic situation on the rainfall amount. We hypothesised to find a gradual increase of rainfall with altitude, lower precipitation at eastern slope exposure, and higher amounts of precipitation during cyclonal atmospheric conditions.

MATERIAL AND METHODS

Research area. In 2020, three watersheds in the Hrubý Jeseník Mts. were selected for hydrological monitoring (Figure 1). Hrubý Jeseník is a major mountain range in Silesia and northern Moravia in the northeastern part of the Czech Republic with the highest peak Praděd (1 491 m a.s.l.), that geologically belongs to the Bohemian massive. The parent rock is usually formed by gneiss, amphibolite, granite or slate. This region is relatively cold, with an average annual temperature from 0.9 °C at the highest peak to 6.3 °C in the lower parts of the mountains and average annual precipitation from 1 000 mm to 1 380 mm (Plíva, Žlábek 1986). The catchments of Slučí stream (SL), Sokolí stream (SO) and Suchý stream (SU) are right-bank tributaries to the upper course of Černá Opava River in the northeastern part of the mountain region. The individual catchment area is 417 ha (SL), 401 ha (SO) and 280 ha (SU); overall, they are covered by Norway spruce stands of different ages. There are numerous clearcuts because of bark beetle outbreaks, especially at lower altitudes (< 800 m a.s.l.). Clearcuts are gradually reforested, usually by European beech and, to a lesser extent, Norway spruce or native broadleaves (maple and mountain ash). The highest part of catchments is on the mountain range, with peaks at Orlík (1 204 m a.s.l.) and Medvědí vrch (1 216 m a.s.l.). The outflow measurements (the lowest point of the catchment) are located at altitudes of 640 m a.s.l. (SL) and 630 m a.s.l. (SO, SU), and the flow direction is oriented to the east.

Distribution of meteorological measurements and instrumentation. Three meteorological stations were installed within the research area in 2020 to characterise local conditions. As the catchments are quite close to each other, the location of individual stations was chosen to primarily cover the altitudinal gradient, and they are located at 1 125 m a.s.l. (SO), 830 m a.s.l. (SL) and 590 m a.s.l. (SU). The stations measured the air temperature, air humidity, global solar radiation and precipitation amount continuously in 10-minute intervals. Stations were run from batteries powered by solar panels. The precipitation gauges were not heated; thus, the information about winter precipitation (in the form of snow) was supplied by 9 totalisers (3 per catchment) with 3-month readings located at altitudes from 600 m a.s.l. to 1 090 m a.s.l. Winter precipitation, however, is not evaluated in this study.

To cover the precipitation variability in the catchments, we divided the area into 21 zones according to elevation (each zone covering 100 m) and exposure (characterised by three main directions – south, east, or north). Using recent aerial photographs, suitable open spaces for installing rain gauges in these zones were identified. Although it was easy to identify appropriate open plots in the lower part of our catchments where bark beetle

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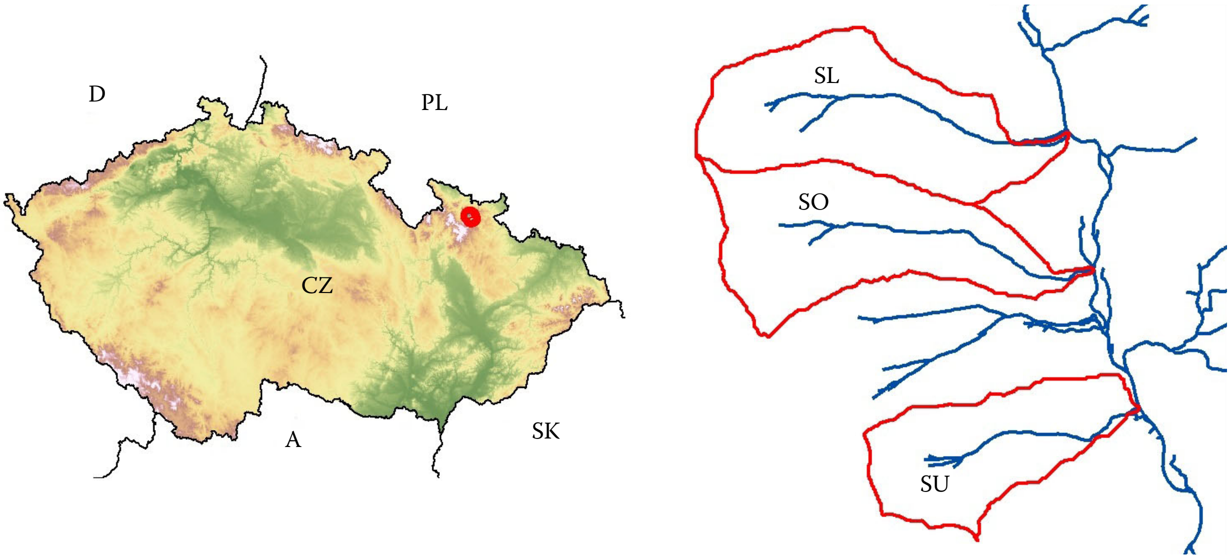

Figure 1. Location of the three monitored catchments Slučí stream (SL), Sokolí stream (SO) and Suchý stream (SU) in the Jeseníky Mountains

outbreaks led to clearcutting, it was quite complicated to find suitable open spaces in the upper parts of the mountains, as this area is fully forested. Since August 2022, precipitation measurement has been supplemented by 21 autonomous rain gauges covering all zones (Figure 2).

Precipitation was measured using a Pronamic Pro (Pronamic, Denmark) rain gauge with a 200 cm^2 collection area and 0.2-mm resolution. At the meteorological stations, the rain gauge was connected to a Greybox N2N datalogger (EMS Brno, Czech Republic), where a 10-min sum of rainfall was stored. Meteorological stations were equipped with a GSM modem and uploaded data to cloud storage on a daily basis. In the case of autonomous rain gauges, the Pronamic Pro was connected to a Minikin Eri event recorder (EMS Brno, Czech Republic), which registered the date and exact time of the event (tipping of the bucket, i.e. every 0.2 mm) with 1-s resolution. These dataloggers were powered by a long-lasting (≈3 years) battery and downloaded manually by infrared connection approximately every 3 months.

Synoptic situation. The type of synoptic situation – i.e. the position of atmospheric pressure systems over Europe – was assessed according to the national catalogue (CHMI 1972). Daily synoptic data for 2022 and 2023 were obtained from the Czech Hydrometeorological Institute website (CHMI 2025). Preliminary data for 2024 were provided by CHMI based on an individual request. For seven-day periods, we determined the most numerous synoptic situations on rainy days, which then entered the evaluation.

Data evaluation. Because the rain gauges were not heated, only the period without snowfall could be evaluated in terms of variability for the investigated area. Given this restraint and term of installation and last reading of the equipment, we evaluated rainfall for three continuous periods: Aug 18 – Oct 31, 2022; Apr 15 – Oct 31, 2023; and Apr 1 – Aug 15, 2024; i.e. 412 days in total, which 'in sum' cover two vegetation seasons. To evaluate the effect of altitude and exposure on precipitation, we had to choose an appropriate time interval. Daily sums appeared to be disadvantageous as numerous days with little precipitation amount complicated the statistical evaluation. However, the monthly sums were too general. For this reason, we used a seven-day rainfall total as the basis for the evaluation. In addition to the sum of precipitation, we also use 'relative' precipitation, which represents the ratio of the value of a specific rain gauge to the average value of all rain gauges, expressed as a percentage. The quality check, as well as the exclusion of some measurements from the analysis, is described in the results chapter.

All statistical data evaluations were carried out using STATISTICA software (Version 13.5.0.17, 2018). For correlation analyses, the Pearson R coefficient was used, and data comparison was performed graphically (box graphs and scatter plots).

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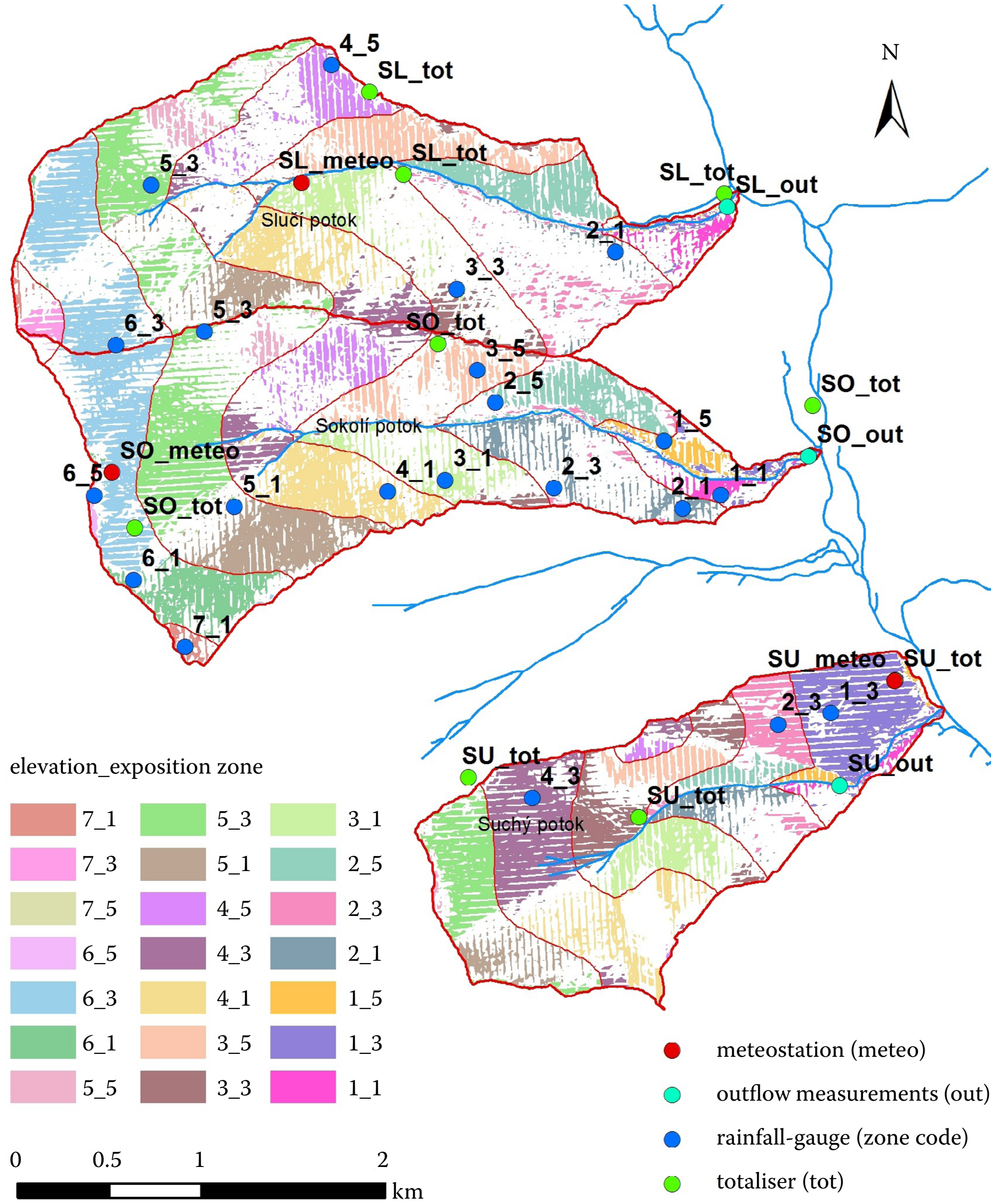

Figure 2. Location of the meteorological stations, totalisers and rainfall gauges in catchment areas of Slučí stream (SL), Sokolí stream (SO) and Suchý stream (SU) in the Hrubý Jeseník Mountains

First number – elevation zone (1: 595–700 m a.s.l.; 2: 700–800 m a.s.l.; 3: 800–900 m a.s.l.; 4: 900–1 000 m a.s.l., 5: 1 000–1 100 m a.s.l.; 6: 1 100–1 200 m a.s.l.; 7: 1 200+ m a.s.l.); second number – exposition (1 – north; 3 – east; 5 – south)

RESULTS

All rain gauges exhibited the same pattern of cumulative rainfall amount, as shown in Figure 3. The recorded sum of precipitation was 111.6–259.2 mm during the period Aug 18 – Oct 31, 2022; 371.2–615.0 mm during the period Apr 15 – Oct 31, 2023; and 328.2–513.8 mm during the period Apr 1 – Aug 15, 2024.

Relationship between precipitation and altitude. We expected the precipitation amount to generally increase with the altitude, but the data revealed a significant positive correlation between these two factors in only 21 out of 56 seven-day periods. There were even 4 cases when the correlation was significant but negative. We considered several possible explanations: (*i*) immediate damage to the rain gauges, e.g. by being thrown off balance

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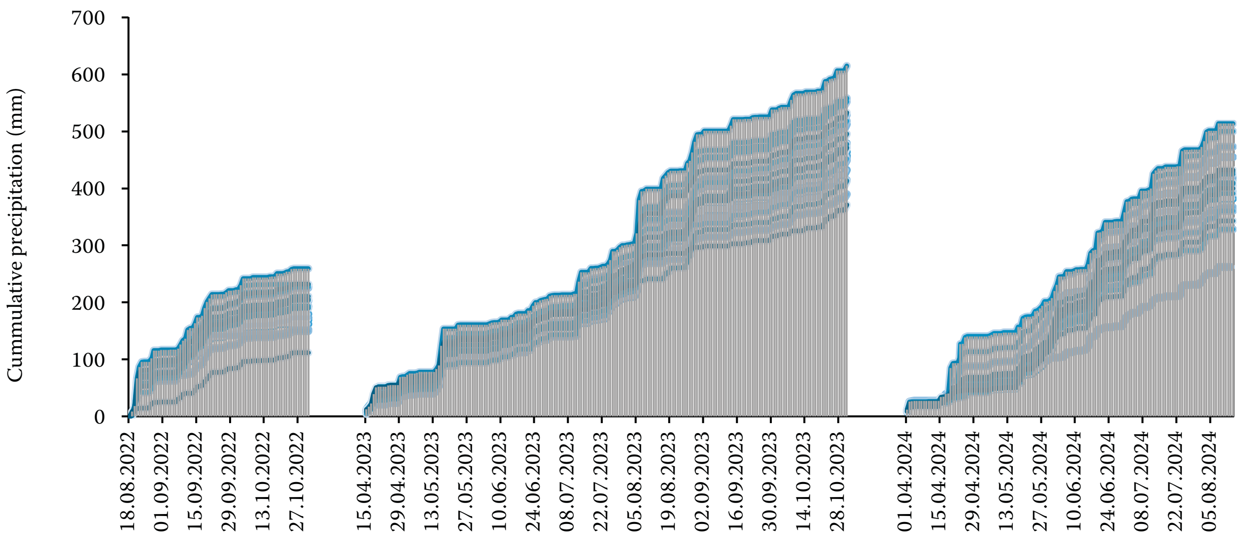

Figure 3. Cumulative precipitation during the measuring (non-frost) periods for 24 installed rain gauges (raw data before validation)

by animals or strong wind; (*ii*) incorrect readings by individual sensors; (*iii*) different sizes and 'qualities' of open areas at which the rainfall was measured; or (*iv*) real local differences in rainfall. During the observation period, we excluded data affected by rain gauge damage (which was identified by *in situ* visits), and in two cases, we added parallel measurements in cases of 'suspiciously' low rainfall amounts. In one case (rain gauge 71 in the highest part of the mountain range – 1 202 m a.s.l.) we did not observe any differences in the two rain gauge readings (R^2 = 0.988, slope = 1.071, intercept = –0.291). In the second case, we identified a malfunction in the original rain gauge (meteostation SU), which underestimated the amount of precipitation by nearly 30%; erroneous data were excluded from the evaluation.

To improve the evaluation, we divided the measurement sites into four groups according to their openness and tested the influence on our results. These groups were defined as follows: (*i*) rain gauges installed in the open area with a diameter of at least 2 heights of neighbouring forest stands [Word Meteorological Organisation (WMO) standard] with the exception of mountain ridge locations (9 locations); (*ii*) rain gauges with the same parameters of open area but on the mountain ridge where we expected a possible influence of wind turbulences (2 locations); (*iii*) rain gauges on smaller open areas with a diameter of 1–2 heights of the neighbouring forest (10 locations); and (*iv*) rain gauges on an open area smaller than 1 height of the neighbouring forest (3 locations). We then recalculated the dependence of rainfall amount on altitude using single categories as well as their different combinations. The best results were achieved by the combination of groups (*i*) and (*ii*) with 11 rain gauges located at altitudes from 639 m a.s.l. to 1 125 m a.s.l. although their representation between 850 m a.s.l. and 1 050 m a.s.l. was rather low due to the dense forest cover in this part of our catchment. For this combination of groups, we found a significant positive correlation in 27 out of 56 seven-day periods. In these periods, relative precipitation for individual rain gauges was calculated in relation to the average precipitation amount during the individual period within the study area. After that, the overall dependence of the relative values on the altitude for all evaluated periods in 2022–2024 was processed (Figure 4). As the intercept of the correlation was low (0.02), we concluded that the 'average' increase in precipitation with altitude in our area was 12% for every 100 m. When we considered the total precipitation during the vegetation period for the 11 rain gauges from groups (*i*) and (*ii*), we found a strong positive correlation in years 2022 and 2023 but with a lower increase in precipitation with altitude: from 5.2% to 7.5% for every 100 m (Table 1). For 2024, the correlation was less insignificant.

We compared the seven-day periods with significant increases in precipitation with altitude with those in which the relationship was not significant or was significantly negative (decrease in precipita-

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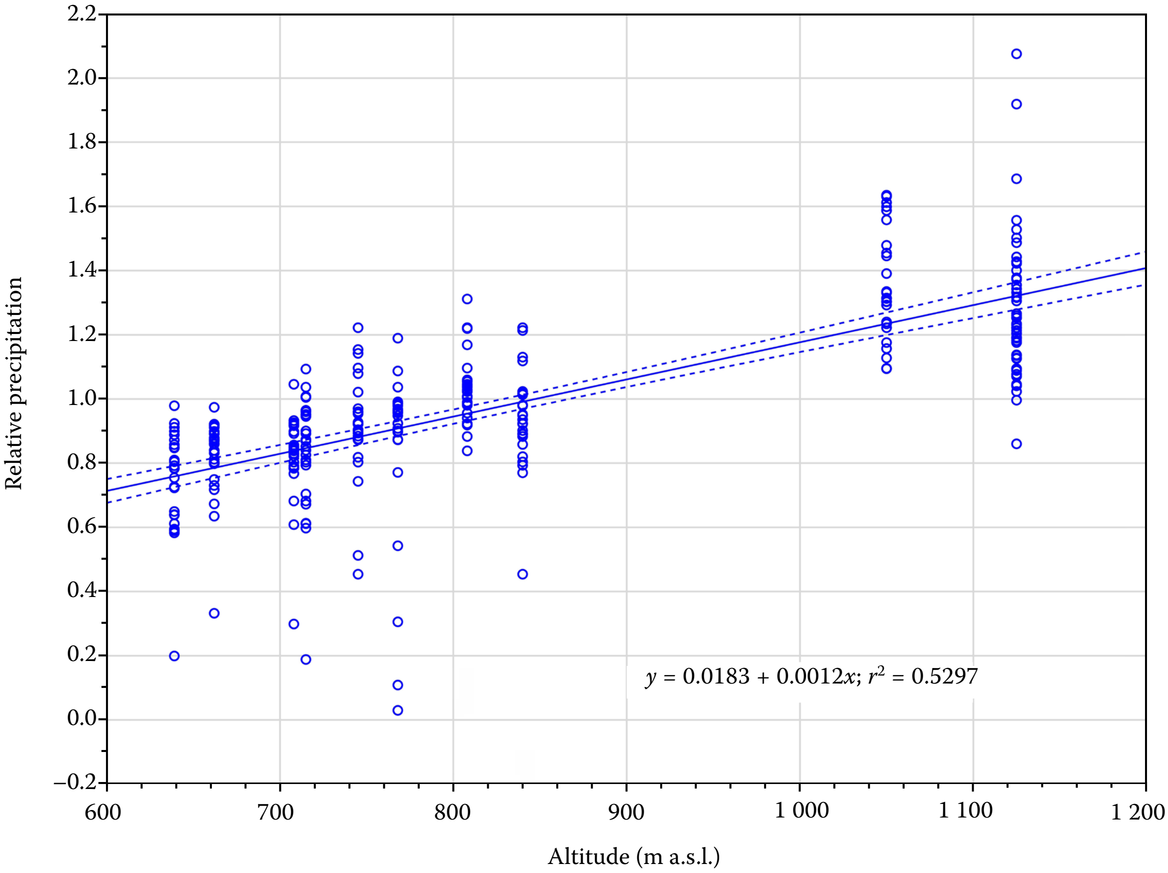

Figure 4. Increase in relative precipitation (precipitation measured by individual rain gauge/average amount of precipitation within the catchment area) based on seven-day periods in 2022–2024

tion amount with altitude). There were no differences in rainfall amount within these situations (Table 2); however, some differences were observed in the synoptic situation distribution (Figure 5). The most typical synoptic situation for periods with a significant increase in precipitation with altitude was a trough of low air pressure or central cyclone over central Europe, representing 69% of cases. These synoptic situations represented only 39% of the periods when the relation was insignificant. Out of these cases, 53% were represented by cyclones located from the southeast to the northwest of the Czech Republic. The periods with a negative relationship between precipitation and altitude were too few to be evaluated; nevertheless, it did not seem that they were connected to typical synoptic situations.

Relationship between precipitation and exposure. To evaluate the role of exposure on precipitation, the seven-day rainfall totals at sites with

Table 1. Increase in precipitation with altitude derived from the vegetation season totals – parameters of partial correlations

Period	Aug 18 – Oct 31, 2022	Apr 15 – Oct 31, 2023	Apr 1 – Aug 15, 2024
R^2	0.738	0.572	0.422
P	0.001**	0.007**	0.030*
Slope	0.00075	0.00052	0.00040
Intercept	0.388	0.590	0.703
Increase in precipitation per 100 m a.s.l.	7.5%	5.2%	4.0%

**significant at $P < 0.01$; *significant at $P < 0.05$

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Table 2. Precipitation distribution within seven-day periods with a significantly positive, insignificant or significantly negative relationship between rainfall amount and altitude

Relation of precipitation to altitude	Significant – positive	Insignificant	Significant – negative
n	27	23	5
Median (mm)	18.3	18.1	11.8
Percentile 80% (mm)	35.4	28.5	21.4
Percentile 20% (mm)	5.5	5.3	7.5

n – number of cases

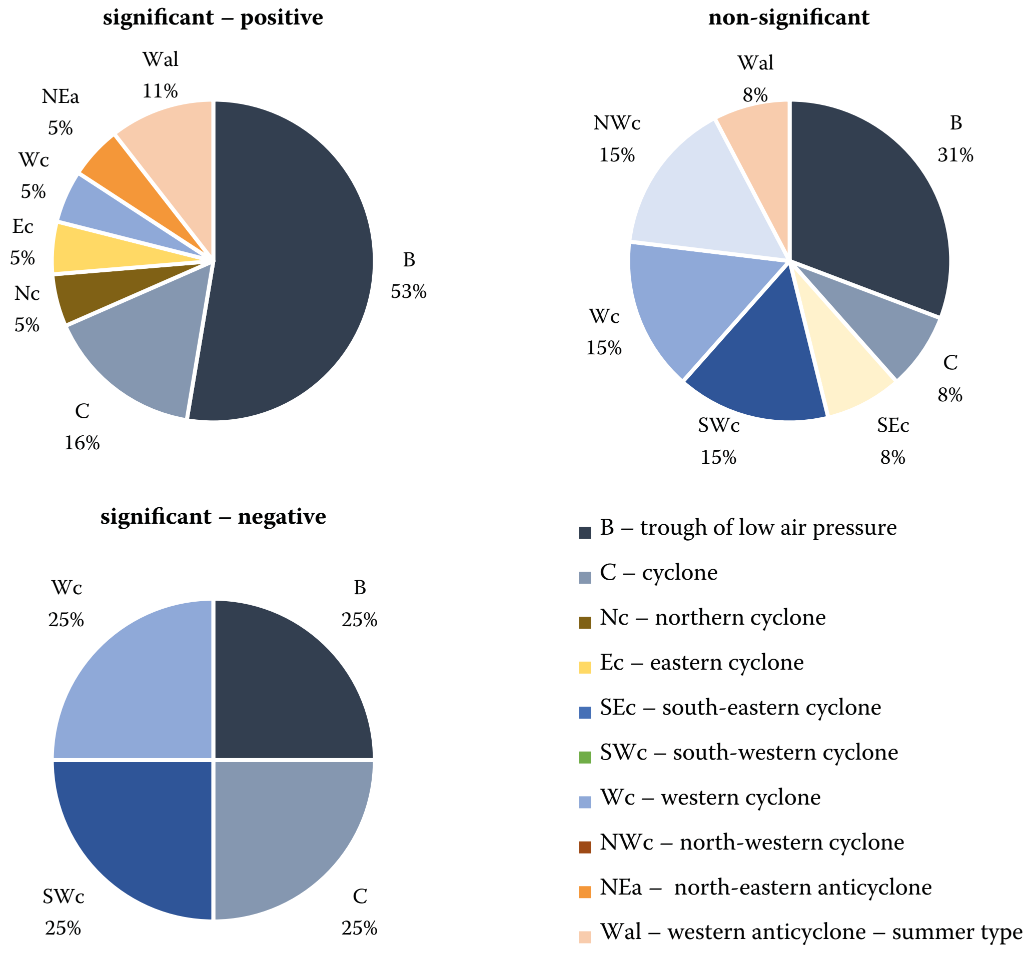

Figure 5. Representation of prevailing synoptic situations within seven-day periods with significantly positive, insignificant and significantly negative relationships between rainfall amount and altitude in 2022–2023

northern (N), eastern (E) and southern (S) exposures were compared. All catchments were oriented from the mountain ridge in the west to the Černá Opava River in the east; thus, western exposure did not occur in the studied region. The comparison was made using all 24 measuring sites and sub-selection of 11 sites with an appropriate 'open' plot [groups (*i*) and (*ii*)] with the same results. We obtained results for a total of 24 sites that better covered the altitudinal gradients in all exposure categories. In general, no differences were found between individual exposures (Figure 6). When we divided the measurement into three altitudinal zones – the catchment bottom (630–800 m a.s.l.),

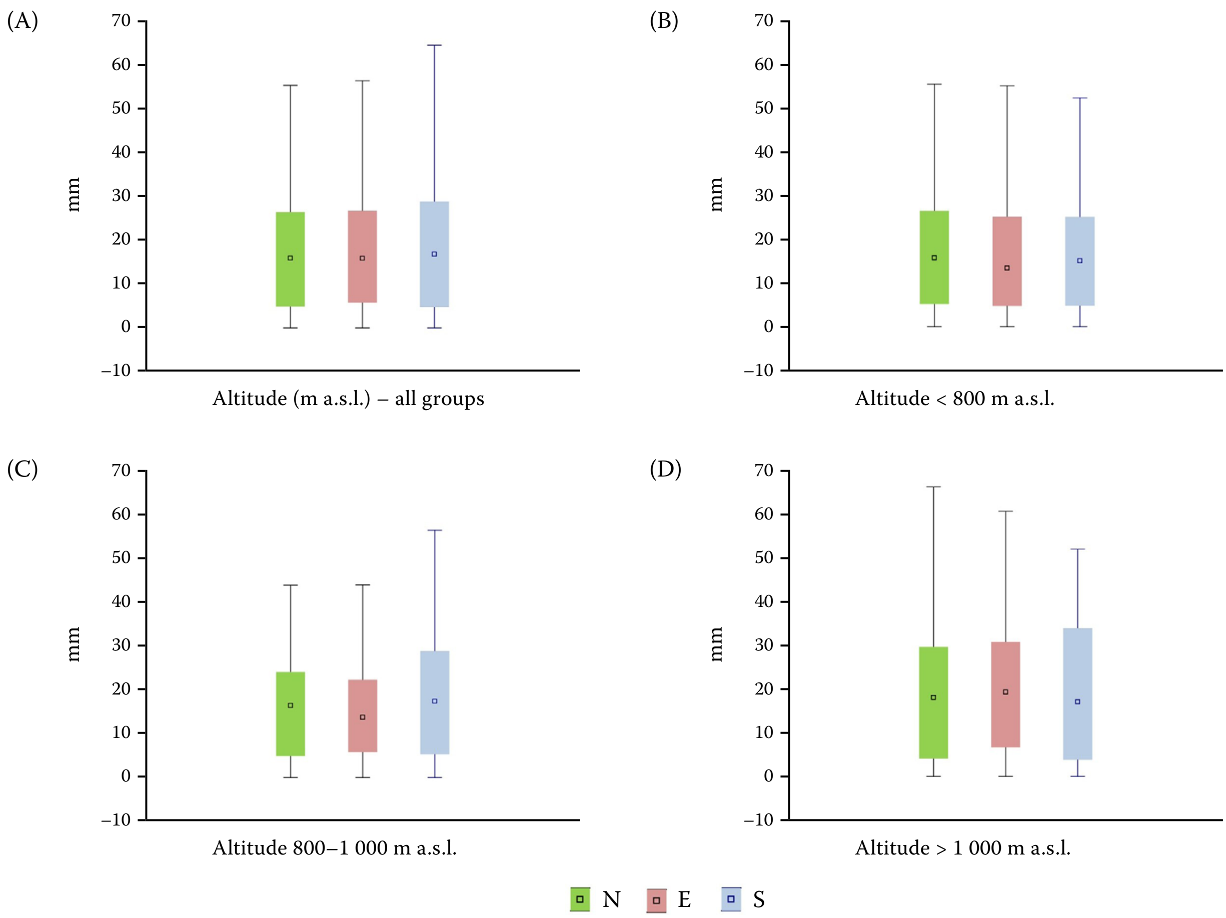

Figure 6. Precipitation amount in seven-day periods in 2022–2024 according to the geographical exposure at the measuring sites: (A) complete dataset; (B–D) rain gauges according to altitudinal zones

N – northern exposure; E – eastern exposure; S – southern exposure

the middle part (800–1 000 m a.s.l.) and the ridge positions (1 000–1 200 m a.s.l.), we observed a tendency for a slightly lower precipitation amount (≈16%) in the eastern exposure for the bottom and middle part of catchments, compared to N and S exposure. This can be explained by the prevailing wind direction from the west and northwest. However, in the ridge positions, the eastern exposure showed slightly higher precipitation than the southern or northern exposures. In no case did any of these differences prove to be statistically significant.

DISCUSSION

Precipitation is a complex meteorological phenomenon that is highly variable in space and time and is, therefore, not easy to measure or quantify correctly. Although the temperature altitudinal gradient is well described and easy to model, the increase in precipitation with altitude is more complicated and not always accurate – especially in complex mountain orography (Smith, Barstad 2004; Collados-Lara et al. 2018). In general, most studies identified a typical increase in precipitation with altitude (Johnson, Hanson 1995; Roe, Baker 2006), especially for snow (Grünewald et al. 2014; Bohne et al. 2020), but often with significant reservations. The problem of evaluating the actual precipitation amount usually starts with the optimal distribution of the rain gauge network and the reliability of the measurement (Hunziger et al. 2018; Suri, Azad 2024). In the studied Jeseníky Mts. catchments, we removed potentially incorrect readings from rain gauges located too close to forest edges, and we still found a significant increase in precipitation with altitude in only 48.2% of the seven-day periods, and 8.9% of periods showed

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a significant decrease in precipitation with altitude. This result, however, is consistent with the findings of Benoit et al. (2024), who found an increase in precipitation with elevation as the prevailing pattern in just 47.5% of cases (of this linear increase in only 15%), an absence of any trend with altitude in 37.5% and a decrease in precipitation in 15% of cases in the Swiss Alps. The occurrence of various gradients – even inverse – of precipitation with altitude was also found by Kozak et al. (2019) in the Western Beskids. Although the amount of precipitation in a short period can influence the relationship with altitude – reverse gradient by high-intensity precipitation (Marra et al. 2022; Dallan et al. 2023) – we did not observe differences in rainfall amount during periods with positive or negative or insignificant orographic gradients. This phenomenon may be recognised by evaluating individual rainfall episodes but was not evident in our assessments of seven-day periods. During the seven-day periods with a positive altitudinal gradient, the increase in precipitation was 12% for every 100 m of elevation. When we calculated the relationship for the whole frost-free period, a highly significant increase of 7.5% was found in 2022, a significant increase of 5.2% for each 100 m of elevation in 2023; the increase of 4.0% in 2024 was significant on lower probability level (Table 1). We do not have an explanation for the difference between individual years, but their length and coverage of vegetation period are not fully comparable and, therefore, a longer measurement period would be necessary to explain this phenomenon.

The state of global or continental atmospheric circulation is another factor affecting the local distribution of precipitation amounts (Dettinger et al. 2004; Bohne et al. 2020; Zhang et al. 2024). In the Jeseníky Mts., the positive precipitation gradient with altitude was mostly associated with the trough of low air pressure or cyclonal situation over central Europe. However, the negative gradient did not seem to be related to any particular synoptic situation. Cosma et al. (2002) found that in the Massif Central in France, precipitation was often organised into narrow bands or plumes during the southern Mediterranean flows. Small-scale orography plays a decisive role in forcing precipitation into bands, while upstream moisture conditions mainly affect precipitation intensity and its south-north extent. Our data showed no clear effect of exposure on rainfall amount. Although there was a tendency for lower precipitation (by 16%) in the eastern exposure in the lower and middle parts (>1 000 m a.s.l.) of the catchments, the differences were not statistically significant. The different roles of exposure in mountain ridge areas are consistent with the findings of Collados-Lara et al. (2018) and Kozak et al. (2019).

These results indicate that the estimation of the actual amount of precipitation is complicated, even with a relatively dense network of rain gauges. In such cases, data interpolation may be insufficient to obtain an accurate value of the rainfall in the catchment. As reported by Lundquist et al. (2019) or Sliezak et al. (2023), high-resolution atmospheric models using radar data are needed to approximate the actual precipitation in mountainous areas, as they better represent the situation than a collective network of rain gauges.

CONCLUSION

The results of the study reflect the complexity of measuring precipitation in forested watersheds in mountainous regions. Data evaluation showed the importance of the proper installation of rain gauges in relation to the 'quality' of the surrounding open space. The proximity of rain gauges to nearby obstacles can affect measurement quality, although this is often a critical condition for fully forested parts of watersheds. An increasing gradient of precipitation amount with altitude, which is often used for interpolating data from the (few) meteorological stations in the catchment, was demonstrated in less than half of the evaluated seven-day periods. The 12% increase in precipitation per 100 m of altitude is an indicative value of the orographic gradient in seven-day periods with a significant increase of precipitation with altitude. However, several seven-day periods were also found when the gradient was negative. For the whole frost-free period, the increase of precipitation with altitude was from 5.2% to 7.5% per 100 m only. During periods with a positive gradient, the prevailing synoptic situation over central Europe was a trough of low pressure or cyclone; a negative gradient was not associated with any specific pressure conditions. The effect of exposure on the amount of precipitation was insignificant. The tendency to decrease precipitation by around 16% on the eastern slopes was evident in the lower and middle parts of the catchment. Overall, even a relatively dense monitoring

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network was not able to provide accurate rainfall data in a forested catchment. Usually, one or a few meteorological stations are used for this purpose – providing a relative comparison between seasons rather than an exact total of rainfall in the catchment. To obtain accurate amounts of rainfall and snow precipitation in mountainous areas, the use of complex models utilising radar data is required.

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REFERENCES

Bartík M., Jančo M., Střelcová K., Škvareninová J., Škvarenina J., Mikloš M., Vido J., Dagsson Waldhauserová P. (2016): Rainfall interception in a disturbed montane spruce (*Picea abies*) stand in the West Tatra Mountains. Biológia, 71: 1002–1008.

Benoit L., Koch E., Peleg N., Mariethoz G. (2024): Precipitation-elevation relationship: Non-linearity and space-time variability prevail in the Swiss Alps. Journal of Hydrology, 25: 100186.

Bohne L., Strong C., Steenburgh J.W. (2020): Climatology of orographic precipitation gradients in the contiguous western United States. Journal of Hydrometeorology, 21: 1723–1740.

Buttle J.M., Beall F.D., Webster K.L., Hazlett P.W., Creed I.F., Semkin R.G., Jeffries D.S. (2018): Hydrologic response to and recovery from differing silvicultural systems in a deciduous forest landscape with seasonal snow cover. Journal of Hydrology, 557: 805–825.

Buytaert W., Celleri R., Willems P., De Biévre P., Wyseure G. (2006): Spatial and temporal rainfall variability in mountainous areas: A case study from the south Ecuadorian Andes. Journal of Hydrology, 329: 413–421.

Černohous V., Švihla V., Šach F. (2018): Projevy sucha ve smrkové tyčovině v létě 2015. Zprávy lesnického výzkumu, 63: 10–19. Available at: https://www.vulhm.cz/files/uploads/2019/02/512.pdf (in Czech)

CHMI (1972): Katalog povětrnostních situací pro území ČSSR. Prague, Czech Hydrometeorological Institute: 40. (in Czech)

CHMI (2025): Typizace povětrnostních situací pro území České republiky. Prague, Czech Hydrometeorological Institute. Available at: https://www.chmi.cz/historicka-data/pocasi/typizace-povetrnostnich-situaci (in Czech)

Collados-Lara A.J., Pardo-Igúzquiza E., Pulido-Velazquez D., Jiménez-Sánchez J. (2018): Precipitation fields in an alpine Mediterranean catchment: Inversion of precipitation gradient with elevation or undercatch of snowfall? International Journal of Climatology, 38: 3565–3578.

Cosma S., Richard E., Miniscloux F. (2002): The role of small-scale orographic features in the spatial distribution of precipitation. Quarterly Journal of the Royal Meteorological Society, 128: 75–92.

Dallan E., Marra F., Fosser G., Marani M., Formetta G., Schär C., Borga M. (2023): How well does a convection-permitting regional climate model represent the reverse orographic effect of extreme hourly precipitation? Hydrological and Earth System Sciences, 27: 1133–1149.

Dettinger M., Redmond K., Cayan D. (2004): Winter orographic precipitation ratios in the Sierra Nevada – Large-scale atmospheric circulations and hydrologic consequences. Journal of Hydrometeorology, 5: 1102–1116.

Ellison D., Morris C.E., Locatellie B., Sheilg D., Cohen J., Murdiyarso D., Gutierrez V., van Noordwijk M., Creed I.F., Pokorny J., Gaveau D., Spracklen D.V., Tobella A.B., Ilstedt U., Teuling A.J., Gebrehiwot S.G., Sands D.C., Muys B., Verbist B., Springgay E., Sugandi Y., Sullivan C.A. (2017): Trees, forests and water: Cool insights for a hot world. Global Environmental Change, 43: 51–61.

Gribovszki Z., Kalicz P., Palocz-Andresen M., Szalay D., Varga T. (2019): Hydrological role of Central European forests in changing climate – Review. Idöjárás, 123: 535–550.

Grünewald T., Bühler Y., Lehning M. (2014): Elevation dependency of mountain snow depth. Cryosphere, 8: 2381–2394.

Hawthorne S.N.D., Lane P.N.J., Bren L.J., Sims N.C. (2013): The long term effects of thinning treatments on vegetation structure and water yield. Forest Ecology and Management, 310: 983–993.

Hlásny T., König L., Krokene P., Lindner M., Montagné-Huck C., Müller J., Quin H., Raffa K.F., Schelhaas M., Svoboda M., Viiri H., Seidl R. (2021): Bark beetle outbreaks in Europe: State of knowledge and ways forward for management. Current Forestry Reports, 7: 138–165.

Hubbart J.A., Link T.E., Gravelle J.A., Elliot W.J. (2007): Timber harvest impacts on water yield in the continental/maritime hydroclimatic region of the United States. Forest Science, 53: 169–180.

Hunziker S., Brönnimann S., Calle J., Moreno I., Andrade M., Ticona L., Huerta A., Lavado-Casimiro A. (2018): Effects of undetected data quality issues on climatological analyses. Climate of the Past, 14: 1–20.

Johnson G.L., Hanson C.L. (1995): Topographic and atmospheric influences on precipitation variability over a mountainous watershed. Journal of Applied Meteorology and Climatology, 34: 68–87.

Keys P.W., Wang-Erlandsson L., Gordon L.J. (2016): Revealing invisible water: Moisture recycling as an ecosystem service. PLoS ONE, 11: e0151993.

https://doi.org/10.17221/96/2024-JFS

Kozak J., Cebulak D., Stec T., Jaguś A. (2019): Variation of precipitation gradient in mountain areas based on the example of the Western Beskids in the Polish Carpathians. Journal of Ecological Engineering, 20: 261–266.

Křístek Š., Apltauer J., Dušek D., Kačmařík V., Leugner J., Mlčoušek M., Pařízková A., Souček J., Špulák O., Válek M. (2024): Generel obnovy lesních porostů po kalamitě: Etapa VII. Brandýs nad Labem, Forestry and Game Management Research Institute: 73. Available at: https://www.uhul.cz/wp-content/uploads/Generel_etapa_VII.pdf (in Czech)

Ly S., Charles C., Degré A. (2013): Different methods for spatial interpolation of rainfall data for operational hydrology and hydrological modeling at watershed scale. A review. Biotechnologie, Agronomie, Société et Environnement, 17: 392–406.

Lubojacký J., Samek M., Véle A., Lorenc F., Knížek M., Liška J. (2024): Hlavní problémy v ochraně lesa v Česku v roce 2023 a prognóza na rok 2024. In: Lorenc F., Knížek M. (eds.): Škodliví činitelé v lesích Česka 2023/2024. Zpravodaj ochrany lesa, 27: 18–25. (in Czech)

Lukasová V., Škvareninová J., Bičárová S., Sitárová Z., Hlavatá H., Borsányi P., Škvarenina J. (2021): Regional and altitudinal aspects in summer heatwave intensification in the Western Carpathians. Theoretical and Applied Climatology, 146: 1111–1125.

Lundquist J., Hughes M., Gutmann E., Kapnick S. (2019): Our skill in modeling mountain rain and snow is bypassing the skill of our observational networks. Bulletin of the American Meteorological Society, 100: 2473–2490.

Marra F., Armon M., Morin E. (2022): Coastal and orographic effects on extreme precipitation revealed by weather radar observations. Hydrological Earth System Sciences, 26: 1439–1458.

Pearce F. (2020): Weather makers. Science, 368: 1302–1305.

Plíva K., Žlábek I. (1986): Přírodní lesní oblasti ČSR. Prague, Státní zemědělské nakladatelství: 313. (in Czech)

Roe G.H., Baker M.B. (2006): Microphysical and geometrical controls on the pattern of orographic precipitation. Journal of the Atmospheric Sciences, 63: 861–880.

Smith R.B., Barstad I. (2004): A linear theory of orographic precipitation. Journal of the Atmospheric Science, 61: 1377–1391.

Šrámek V., Fadrhonsová V. (2023): Srážky na volné ploše a v lesním porostu. In: Šrámek V., Pokorný R., Kupec P. (eds): Voda v lesních ekosystémech. Jíloviště, Forestry and Game Management Research Institute: 16–32. Available at: https://www.vulhm.cz/files/uploads/2019/06/Voda-v-lesnich-ekosystemech-2022.pdf (in Czech)

Sleziak P., Jančo M., Danko M., Méri L., Holko L. (2023): Accuracy of radar-estimated precipitation in a mountain catchment in Slovakia. Journal of Hydrology and Hydromechanics, 71: 111–122.

Šrámek V., Unucka J., Jurdič J., Fadrhonsová V., Neudertová Hellebrandová K. (2023): Kůrovcové holiny a voda v lesích – Nový monitoring lesních povodí v Hrubém Jeseníku. Lesnická práce, 102: 38–39. (in Czech)

Suri A., Azad S. (2024): Optimal placement of rain gauge networks in complex terrains for monitoring extreme rainfall events: A review. Theoretical and Applied Climatology, 155: 2511–2521.

Šustek Z., Vido J., Škvareninová J., Škvarenina J., Šurda P. (2017): Drought impact on ground beetle assemblages (*Coleoptera*, *Carabidae*) in Norway spruce forests with different management after windstorm damage – A case study from Tatra Mts. (Slovakia). Journal of Hydrology and Hydromechanics, 65: 333–342.

Teuling A.J., de Badts E.A.G., Jansen F.A. Fuchs R., Buitink J., van Dijke A.J.H., Sterling S.M. (2019): Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe. Hydrology and Earth System Sciences, 23: 3631–3652.

Thonfeld F., Gessner U., Holzwarth S., Kriese J., da Ponte E., Huth J., Kuenzer C. (2022): A first assessment of canopy cover loss in Germany's forests after the 2018–2020 drought years. Remote Sensing, 14: 562.

Van Stan J.T., Gutmann E., Friesen J. (2020): Precipitation Partitioning by Vegetation: A Global Synthesis. Cham, Springer: 28.

Yu X., Lamačová A., Duffy C., Krám P., Hruška J., White T., Bhatt G. (2015): Modelling long-term water yield effects of forest management in a Norway spruce forest. Hydrological Sciences Journal – Journal des Scienciés Hydrologiques, 60: 174–191.

Zahradník P., Zahradníková M. (2019): Salvage felling in the Czech Republic's forests during the last twenty years. Central European Forestry Journal, 65: 12–20.

Zelený V. (1975): Vodohospodářský význam lesů v Beskydech. Lesnictví, 21: 131–144. (in Czech)

Zhang M.K., Li J., Li N.N., Sun W., Li P.X., Zhao Y. (2024): Spatial inhomogeneity of synoptic-induced precipitation in a region of steep topographic relief: A case study. Journal of Geophysical Research-Atmospheres, 129: e2023JD039129.

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