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Refinement of design precipitation by combining estimates from adjusted radar data and ombrographic measurements

(Zpřesnění návrhových srážek kombinací odhadů z adjustovaných radarových dat a ombrografických měření)

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Abstract: Design precipitation estimates are essential for hydrological modelling, flood risk assessment, and water management planning. They traditionally rely on long-term but often sparse rain-gauge measurements with limited spatial representativeness. This study introduces a synergistic approach that refines these estimates by merging design precipitation fields obtained from radar-derived precipitation intensities adjusted using 1-day rain-gauge precipitation totals and ombrographic measurements. The output provides design precipitation totals for Czechia at 1-km spatial resolution for selected return periods and precipitation durations of 1, 6, and 24 h. Based on cross-validation, empirical Bayesian kriging of ratios between the two design precipitation fields was identified as the most effective merging method. The resulting estimates better capture spatial gradients of extreme precipitation. While the highest 24-h design totals are concentrated in mountainous regions, consistent with circulation patterns driving prolonged stratiform precipitation, shorter durations exhibit pronounced spatial variability associated with intensive convective precipitation. Compared with estimates derived solely from adjusted radar data, the proposed approach yields higher and more realistic design totals for short durations. Comparison with previously developed datasets confirms the reliability of the new estimates and highlights the importance of radar adjustment and robust regional frequency analysis. The proposed approach is applicable to regions with contrasting precipitation regimes similar to those found in Central Europe.

Keywords: ombrographic measurements – adjusted radar data – regional frequency analysis – design precipitation – geostatistical merging

Abstrakt: Odhady návrhových úhrnů srážek jsou klíčové pro hydrologické modelování, hodnocení povodňového rizika a dimenzování vodohospodářských staveb. Odhady se tradičně opírají o dlouhodobá, avšak často řídká staniční srážkoměrná měření s omezenou prostorovou reprezentativností. Předkládaná studie představuje synergický přístup ke zpřesnění těchto odhadů založený na sloučení polí návrhových úhrnů odvozených z radarových intenzit srážek adjustovaných denními úhrny srážek ze stanic a z ombrografických měření. Výsledkem jsou návrhové úhrny pro území Česka s prostorovým rozlišením 1 km pro vybrané doby opakování a délky trvání srážek 1, 6 a 24 hodin. Pomocí křížové validace byla jako nejúčinnější metoda slučování vybrána metoda empirického

bayesovského krigingu poměrů mezi oběma poli návrhových úhrnů. Výsledné odhady lépe zachycují prostorové gradienty extrémních úhrnů srážek. Zatímco nejvyšší návrhové 24hod. úhrny jsou soustředěny do horských oblastí v souladu s cirkulačními příčinami trvalých vrstevnatých srážek, kratší délky trvání vykazují výraznou prostorovou variabilitu související s intenzivními konvektivními srážkami. Ve srovnání s odhady založenými pouze na adjustovaných radarových datech poskytuje navržený přístup vyšší a realističtější návrhové úhrny pro krátké délky trvání. Porovnání s dříve vytvořenými datovými sadami potvrzuje spolehlivost nových odhadů a zdůrazňuje význam adjustace radarových dat a robustní regionální frekvenční analýzy. Navržený přístup je využitelný i v dalších oblastech s rozdílnými srážkovými režimy podobnými těm ve střední Evropě.

Klíčová slova: ombrografická měření – adjustovaná radarová data – regionální frekvenční analýza – návrhové srážky – geostatistické slučování

Introduction

Extreme precipitation events significantly affect both the natural environment and human society (e.g., Dunkerley 2021; Mahapatra et al. 2018). Effective risk management therefore requires an understanding of the meteorological causes of these events and their statistical characteristics.

Extreme precipitation statistics are commonly described using design precipitation (Overeem et al. 2008). Design precipitation is the precipitation total (depth) associated with a specified return period, accumulation duration, and location. Originally developed for the design of urban drainage systems, design precipitation remains a key tool in hydrological engineering with ongoing efforts focused on improving its estimation by applying more robust methods (Hulec et al. 2024). Estimation of design precipitation typically relies on time series of block maxima or threshold exceedances, which are fitted with extreme value distributions such as the Generalized Extreme Value or Generalized Pareto distribution (Koutsoyiannis et al. 1998).

Traditionally, design precipitation estimates have been based on rain-gauge measurements (Moccia and Mineo 2020). However, reliable estimates require long records and dense station networks, while sparse coverage often fails to capture localized extreme events (Lengfeld et al. 2020). More recently, the development of weather radar measurements has provided a complementary source of precipitation data, initially for studying precipitation depth–area relationships (Durrans et al. 2002) and subsequently for design precipitation estimation (Overeem et al. 2009).

Radar measurements provide continuous high-resolution spatial coverage and capture the spatiotemporal variability of precipitation more effectively than rain gauges (Marra and Morin 2015). However, precipitation intensities derived from radar reflectivity are affected by several sources of uncertainty (Berne and Krajewski 2013). To reduce these uncertainties, radar-derived precipitation intensities are commonly adjusted using rain-gauge measurements (e.g., Hasan et al. 2016; Bližňák et al. 2018). Gauge-adjusted radar-derived intensities (hereinafter adjusted radar data) provide a promising basis for design precipitation estimation. In addition, their high spatial resolution enables the application of regional frequency analysis methods, which improve the robustness of estimates derived from relatively short radar records by incorporating information from statistically similar neighbouring locations (Hosking and Wallis 1997).

The aim of this study is to introduce and evaluate an innovative method for improving design precipitation estimates by combining information from (i) adjusted radar data and (ii) ombrographic records and automatic rain-gauge measurements (hereinafter ombrographic measurements) in the territory of Czechia. The method merges design precipitation fields derived independently from both datasets using a geostatistical approach, thereby exploiting their complementary strengths while reducing their individual limitations.

The paper is organized as follows. Section 2 describes the two input datasets, Section 3 summarizes the regional frequency analysis applied to derive design precipitation estimates and introduces the proposed merging approach, Section 4 discusses the results for Czechia, and Section 5 concludes the paper.

Data

Adjusted radar data

The dataset includes 20-year series of 10-min precipitation intensities calculated in fixed 10-min intervals on a 1×1 km grid covering the territory of Czechia during the frost-free seasons (April–October) of 2002–2021.

The adjustment procedure, originally proposed by (Sokol 2003), is described and validated in (Bližňák et al. 2018). Input radar data comprised pseudo-CAPPI reflectivity products at 2 km above sea level from the two C-band Doppler radars (Fig. 1) operated by the Czech Hydrometeorological Institute (CHMI). Input ground-based precipitation measurements used for the adjustment comprised quality-controlled series of 1day precipitation totals from approximately 700 evenly distributed rain gauges (Fig. 1) operated by CHMI. Radar-derived 1day precipitation totals were first adjusted by a domain-wide multiplicative factor that corrected the overall bias relative to rain-gauge measurements. Subsequently, local residual biases were corrected using inverse-distance-weighted differences between measured and radar-derived totals at nearby rain gauges. The resulting adjusted 1day totals were then disaggregated into 10-min intensities according to the temporal distribution of radar reflectivity.

Ombrographic measurements

The dataset includes 20- to 70-year series of precipitation intensities accumulated over durations from 2 min to 96 h, based on quality-controlled 1min ombrographic records and automatic rain-gauge measurements from 164 CHMI stations across Czechia during 1951–2022 (Fig. 1). It was developed as part of the PERUN project by Crhová et al. (2024). Quality control comprised verification of suspicious extreme values, assessment of potential inhomogeneities, and evaluation of the impact of missing data. The dataset preparation is also described in (Kašpar et al. 2026).

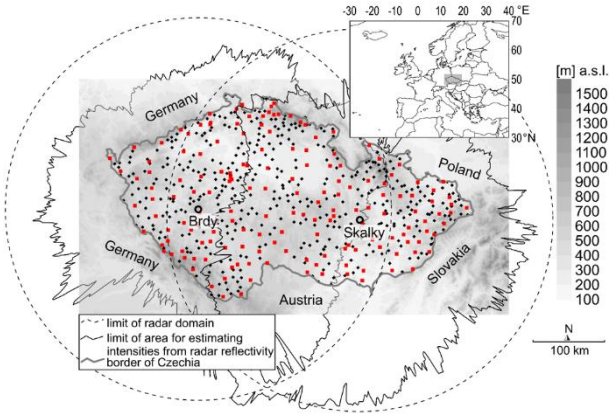


Fig. 1. Elevation in Czechia with the positions (small circles) and domains (large circles) of the Brdy and Skalky weather radars, along with the positions of rain gauges used to adjust precipitation intensities estimated from radar reflectivity (small markers) and with ombrographic measurements (red small markers). The inner curves delineate the recommended area for radar-based precipitation intensity estimation according to the COST 73 project.

Method

Estimation of adjusted radar and ombrographic design precipitation

Design precipitation estimates were derived independently for both input datasets by applying the same methodology described in detail by Kašpar et al. (2021). The three-parameter Generalized Extreme Value distribution (GEV) was employed to fit the annual maxima of precipitation totals. Kyselý and Picek (2007) identified GEV as a suitable model for precipitation extremes in most regions of Czechia.

Hosking (1990) showed that using sample L-moments for parameter estimation was usually more efficient with small to moderate samples than other approaches such as the conventional maximum likelihood approach. The GEV parameters were therefore estimated by applying the L-moment-based index storm procedure combined with the region-of-influence method (ROI: Hosking and Wallis 1997). ROI improves the robustness of local estimates by adjusting the sample L-moments at a site using standardized L-moments from neighbouring statistically homogeneous locations while preserving a site-specific scaling factor represented by the mean annual maximum. The ombrographic design precipitation estimates were further fitted with Depth–Duration–Frequency curves constructed by applying a recently developed parameterization method described in a companion study by Müller et al. published in this volume.

Merging of adjusted radar and ombrographic design precipitation fields

Here, we summarize a geostatistical approach for combining design precipitation fields derived independently from adjusted radar data and ombrographic measurements. More details, including the selection of the most suitable geostatistical interpolation method and its performance evaluation, can be found in Kašpar et al. (2026).

The objective of the approach is to preserve the ombrographic design precipitation estimates at gauge locations as closely as possible while maintaining the spatial gradients in the adjusted radar design precipitation field. This allows the advantages of both datasets, namely the high spatial resolution of adjusted radar data and the long observational records of ombrographic measurements to be exploited while reducing their limitations associated with the relatively uncertain point estimates of precipitation intensities derived from radar reflectivity and the limited spatial representativeness of ombrographic measurements.

Based on leave-one-out cross-validation, Empirical Bayesian Kriging (EBK: Krivoruchko 2012) applied to ratios between ombrographic and adjusted radar design precipitation totals provided the best performance and was therefore selected for the merging procedure. Unlike conventional kriging methods, which treat the fitted semivariogram as fixed, EBK accounts for uncertainty in semivariogram estimation by generating multiple plausible semivariogram models and incorporating their distribution into the interpolation process.

The merging procedure can be summarized as follows:

- Estimate design precipitation totals from the input adjusted radar and ombrographic datasets.
- Calculate ratios between ombrographic and adjusted radar design precipitation totals at gauge locations.
- Interpolate the ratios onto the radar grid using EBK.
- Multiply the adjusted radar design precipitation field by the interpolated ratio field.

Due to computational constraints, only selected accumulation durations (1, 6, and 24 h) and return periods (2, 5, 10, 20, 50, and 100 yr) were evaluated. The selected durations represent different rainfall regimes, ranging from short-term convective precipitation to prolonged stratiform rainfall, while the selected return periods are statistically justifiable given the length of the input time series.

Discussion

Comparison between adjusted radar and ombrographic design precipitation totals

A comparison of adjusted radar and ombrographic design precipitation totals at gauge locations (Fig. 2) shows that adjusted radar estimates tend to be lower for short accumulation durations and long return periods. This highlights an important advantage of the proposed merging procedure, which increases short-duration adjusted radar design precipitation totals and thus provides safer estimates, reducing the risk of underestimation.

This underestimation is most pronounced for the 1h duration and is mainly attributable to the temporal and spatial aggregation inherent in radar reflectivity measurements. Precipitation intensity peaks during short-lived localized convective events may be attenuated by the use of the fixed sampling interval (Wen et al. 2021) and by spatial averaging within radar pixels (Peleg et al. 2018).

In contrast, the mean bias is negligible for the 24h duration, while the relative spread is comparable to that for the 1h duration. The largest differences occur mainly in mountainous regions, where radar measurements are affected by terrain shielding, partial beam blockage, and the greater height of the radar beam above the ground caused by the relatively large distance of the main mountain ranges from the radar sites (see also Fig. 1).

On average, adjusted radar 1h design precipitation totals correspond to 90.6% and 86.5% of the ombrographic estimates for the 2year and 100year return periods, respectively. For the 24h duration, the mean difference decreases to only 1.3% for the 100-year return period. Local contrasts may reflect spatial variations in radar performance and differences in the length and temporal coverage of ombrographic records, which affect the fitted extreme-value statistics (Fig. 3).

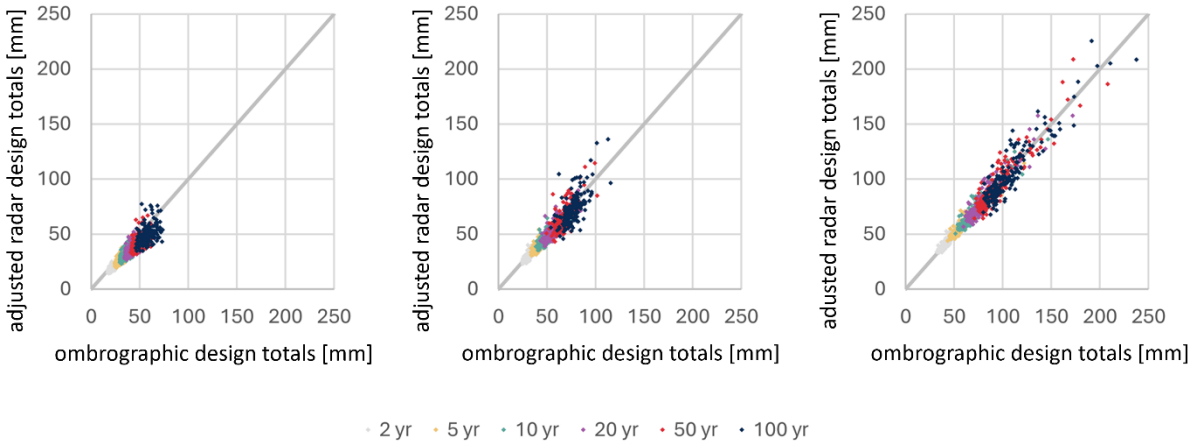


Fig. 2. Comparison of adjusted radar and ombrographic design precipitation totals at gauge locations for 1h, 6h, and 24h accumulation durations (left to right) and individual return periods according to the legend.

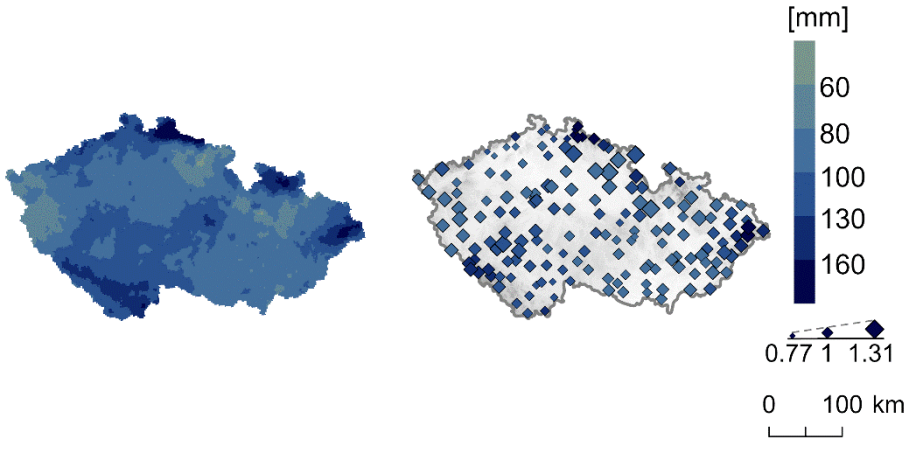


Fig. 3. Adjusted radar (left) and ombrographic (right) 24h design precipitation totals for a 100year return period. Marker size represents the ratio of ombrographic to adjusted radar design totals.

Final combined design precipitation totals and their distribution

Fig. 4 shows the final fields of design precipitation totals in the territory of Czechia and Tab. 1 summarizes the corresponding ranges of values for individual accumulation durations and return

periods. The spatial patterns differ substantially among durations. While the 1h and 6h design precipitation fields exhibit pronounced local variability, the 24h fields are smoother and more structured with the highest values concentrated in mountainous regions. This pattern becomes increasingly apparent with increasing return period and becomes evident also for the 6h duration. Similar spatial patterns were reported for radar-based design precipitation in neighbouring Germany (Lengfeld et al. 2019).

The aforementioned differences reflect the distinct nature of the precipitation events responsible for the annual maxima used in the extreme-value statistics. The highest short-duration precipitation totals are predominantly associated with localized convective storms, whereas the highest long-duration totals are mainly related to widespread stratiform precipitation accompanied by orographic enhancement, particularly on the northern and northeastern windward slopes of the mountains, consistent with the prevailing circulation conditions (Kašpar and Müller 2010). Consequently, the spatial variability decreases with increasing accumulation duration.

The changing spatial pattern is also reflected in the statistical distribution of design precipitation totals (Fig. 5). The distribution is nearly symmetric for the 1-h duration and short return periods, but becomes increasingly right-skewed for longer durations and return periods in agreement with the increasing influence of strong orographic enhancement.

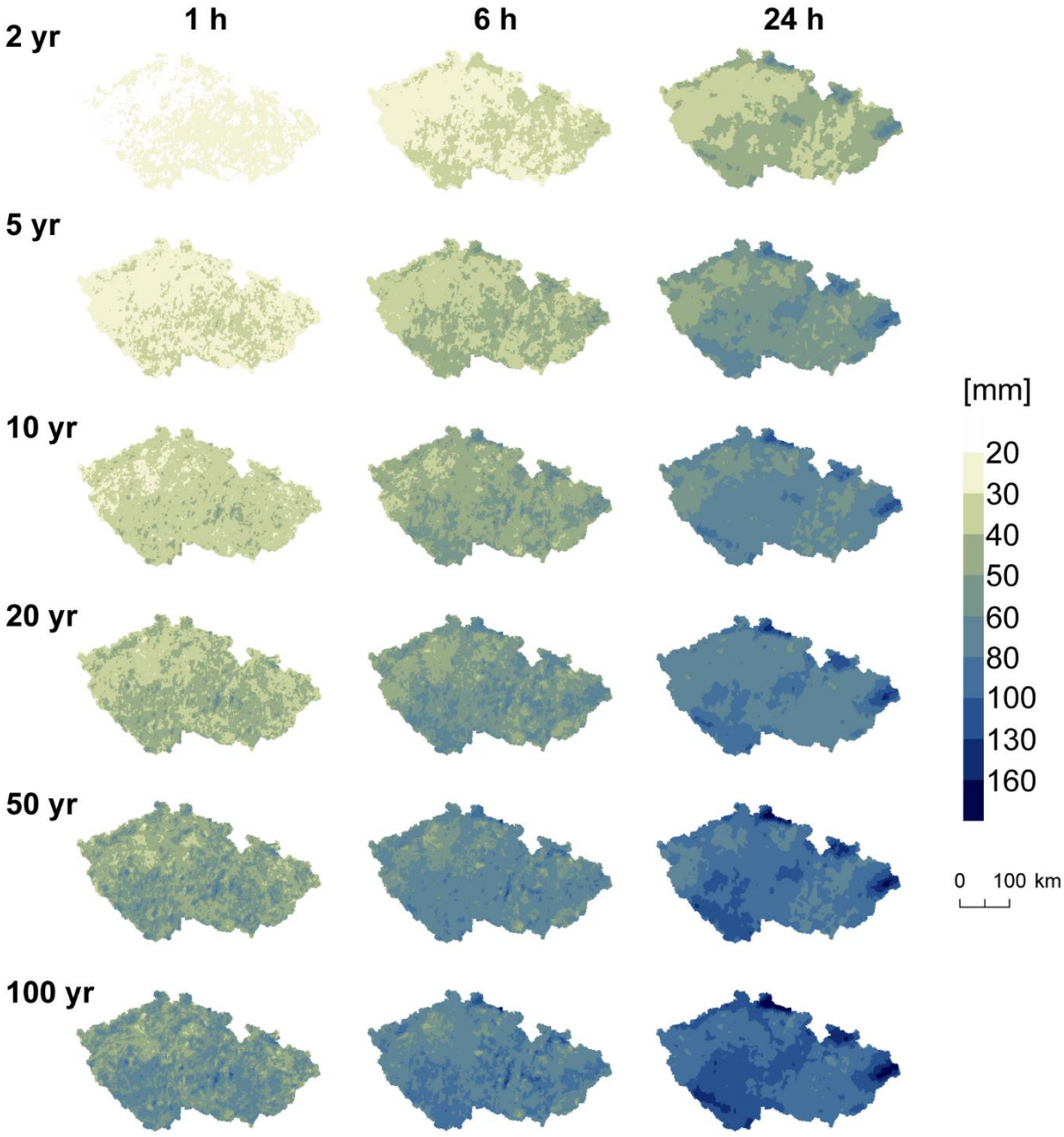


Fig. 4. Spatial distribution of combined design precipitation totals, arranged from top to bottom by increasing return period and from left to right by increasing accumulation duration.

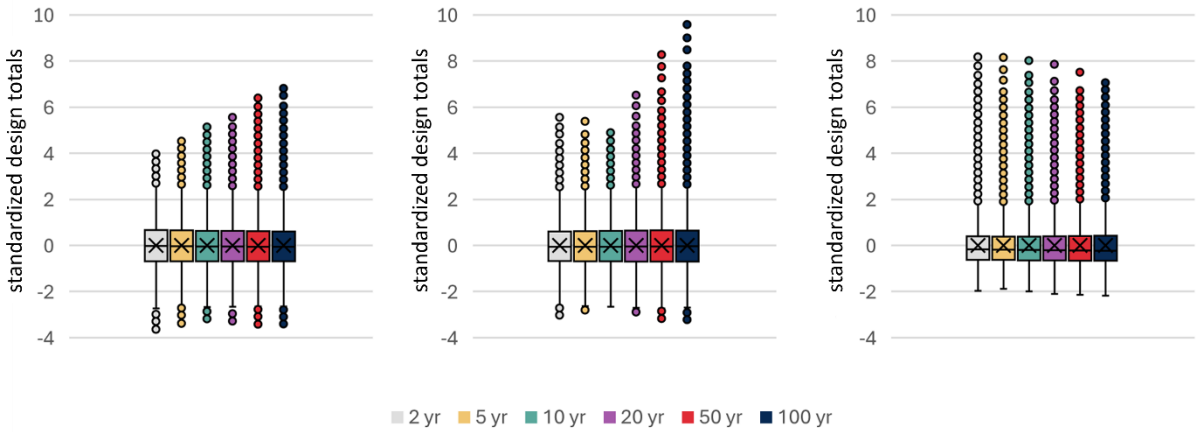


Fig. 5. Box plots of standardized combined design precipitation totals (mean = 0, standard deviation = 1) for 1-h, 6-h, and 24-h accumulation durations (left to right) and return periods according to the legend. Boxes indicate the interquartile range (IQR), with the median shown as a horizontal line and the mean as a cross. Whiskers extend to 1.5 times the IQR, and outliers are shown as individual points.

Table 1. Ranges of combined design precipitation totals for selected accumulation durations and return periods.

Duration [h]	Return period [yr]	Minimum design total [mm]	Maximum design total [mm]
1	2	12.5	28.9
	100	27.7	117.6
6	2	19.8	47.1
	100	38.7	180.1
24	2	30.7	87.5
	100	62.4	235.6

Comparison with other data sources

Hulec et al. (2024) provide an overview of previously developed datasets of design precipitation totals for present-day Czechia. The authors subsequently analysed four datasets developed employing different methodologies, including empirically (Trupl 1958) and statistically (Crhová et al. 2022) derived ombrographic design totals, the DES_RAIN dataset (Vaššová and Kovář 2011) derived by reducing 1day design totals to shorter durations using empirical reduction coefficients, and adjusted radar design totals derived by applying regional frequency analysis based on the L-moment-based index storm procedure and ROI (Kašpar et al. 2021). These datasets are further briefly compared with the presented combined dataset at four sites representing different regions and elevations in Czechia.

Fig. 6 shows a comparison of -h design precipitation totals, for which differences among datasets are typically the largest (Hulec et al. 2024). The DES_RAIN dataset tends to substantially overestimate 1h design totals at higher elevations because the empirical reduction coefficients do not account for the weaker influence of orographic enhancement on short-duration precipitation (Kavka et al. 2016). The other datasets are in reasonable agreement. The combined dataset yields generally higher 1h design totals, with the average difference increasing from approximately 7% for the 2year return period to 22% for the 100year return period. This again highlights an important advantage of the proposed merging procedure, which provides more conservative estimates while remaining consistent with the other datasets. The higher estimates are likely related to the application of regional frequency analysis and the use of high-resolution adjusted radar data, which together improve the representation of short-duration and local precipitation extremes associated mainly with convective storms. Compared to the adjusted radar 1h design precipitation totals of Kašpar et al. (2021), the higher combined estimates are attributable to the correction of the radar-based underestimation discussed above by means of ombrographic measurements.

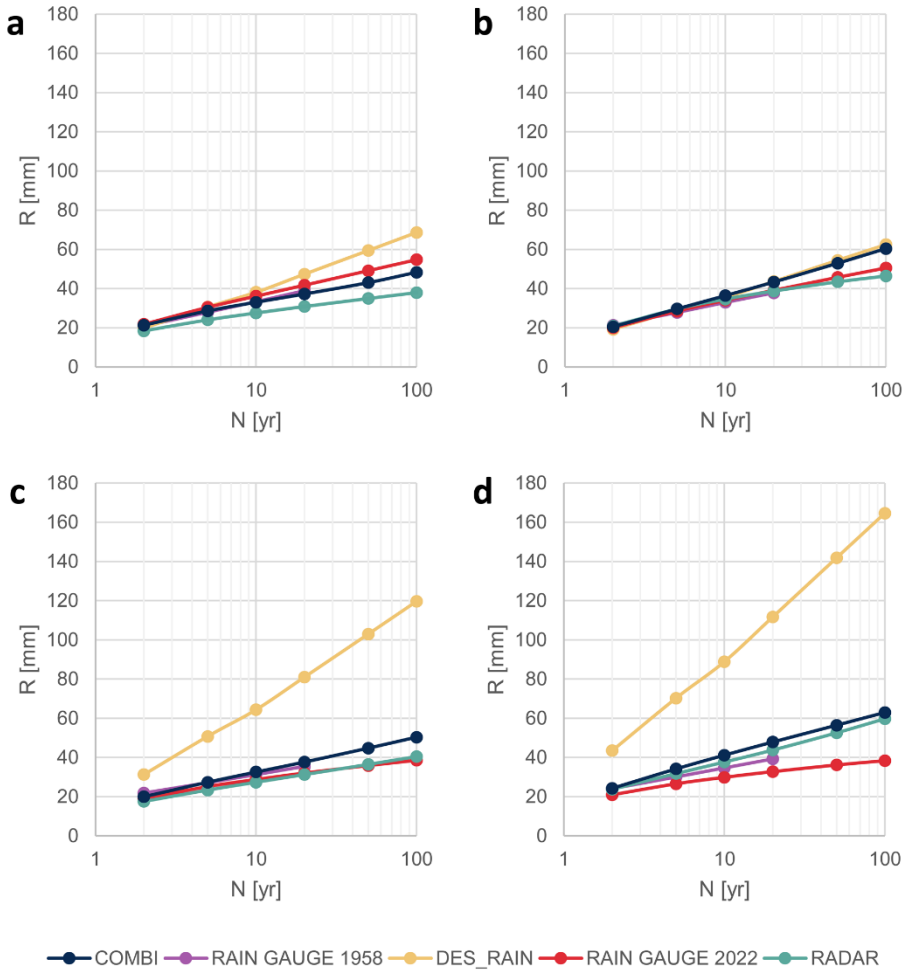


Fig. 6. Comparison of 1h design precipitation totals R for different return periods N presented in this paper (COMBI) with four other previously developed datasets of 1h design totals at the following stations in Czechia: (a) Olomouc, Klášterní Hradisko / Holice (210 m a.s.l.), (b) Telč / Kostelní Myslová (569 m a.s.l.), (c) Desná, Souš (778 m a.s.l.), and (d) Lysá Hora (1322 m a.s.l.). Other datasets are (see also Section 4): RAIN GAUGE 1958 (Trupl 1958), DES_RAIN (Vaššová and Kovář 2011), RAIN GAUGE 2022 (Crhová et al. 2022), and RADAR (Kašpar et al. 2021).

Conclusion

This study presents a geostatistical approach for combining design precipitation fields estimated independently from gauge-adjusted radar reflectivity-derived precipitation intensities and ombrographic measurements for the territory of Czechia. The proposed methodology preserves the spatial variability of extreme precipitation captured by high-resolution radar data while incorporating reliable long-term ombrographic measurements, thereby enhancing the spatial consistency and robustness of design precipitation estimates. At the same time, it mitigates the uncertainty associated with the conversion of radar reflectivity to precipitation intensity and the limited spatial representativeness of rain-gauge measurements. The robustness of the final combined design precipitation estimates is further enhanced by employing advanced regional frequency analysis using the L-moment-based index storm procedure and ROI, followed by geostatistical merging with EBK interpolation of the ratios between ombrographic and adjusted radar design precipitation totals.

Application to Czechia demonstrates that the proposed methodology corrects the underestimation of short-duration adjusted radar design precipitation totals, thereby providing more conservative estimates while remaining consistent with other design precipitation datasets available for Czechia. The resulting spatial distribution of design precipitation is also physically plausible, reflecting precipitation formation mechanisms, causal circulation patterns, and orographic enhancement.

Despite the advanced methodology applied, uncertainty remains, particularly for short accumulation durations and long return periods owing to the localized nature of extreme convective precipitation and the limited length of available observations. The proposed approach is applicable to regions with contrasting precipitation regimes similar to those found in Central Europe, although its performance depends on radar coverage, gauge-network density, and terrain complexity.

Future improvements may include incorporating meteorological causes of heavy precipitation and topographic effects into local design precipitation estimates, together with the development of spatial uncertainty maps.

Acknowledgments

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