Review of historical and recent estimates of design precipitation totals and intensities in Czechia

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ABSTRACT The estimation of design precipitation totals and intensities is an approach for characterising the statistics of precipitation extremes and is widely used in water management practice. In nearly the past 100 years, more than 20 studies have been published on this topic. The aim of this paper is a complex comparison of these studies in terms of both methods applied and the results obtained. We present a chronological review of papers addressing design one-day and multiday precipitation totals as well as sub-daily intensities and compare eight available datasets in terms of the values obtained. Although there is reasonable agreement between the estimates of design one-day precipitation totals, more significant differences exist between the estimates of design sub-daily precipitation intensities, mainly due to the wider range of methods applied and the shorter time series. To further improve the estimates, the authors propose a combination of station-based and radar-based design precipitation intensities.

KEY WORDS design precipitation – precipitation intensities – precipitation extremes – return period – Czechia

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1. Introduction

Heavy precipitation is a dangerous natural phenomenon that deserves special attention and can be classified using various criteria (e.g., Breugem et al. 2020). In terms of its origin, we distinguish between convective and stratiform precipitation. In Czechia, the highest short-term rainfall intensities usually occur in convective storms lasting only tens of minutes to a few hours, while the highest rainfall totals with durations ranging from one day to a few days occur in stratiform precipitation on the windward sides of the mountains (Bližňák, Kašpar, Müller 2018).

Gao et al. (2014) presented three main groups of methods for evaluating heavy precipitation. The first group is based on precipitation totals that characterize a heavy precipitation event, while the other two groups use statistical methods. One method is thresholding, which uses certain percentiles of the frequency distribution of rainfall totals to define heavy precipitation events; the second method uses design precipitation totals, i.e., precipitation totals of a given duration with a certain probability of exceedance, which is expressed as the return period. This paper focuses on design precipitation totals, as estimating design precipitation totals is essential for proper water management in the landscape.

The direct effect caused by heavy precipitation is the formation of surface runoff from the affected area. If there is sufficient rainfall, the watercourses fill up, and if the discharge increases further, flooding occurs. The risk of flooding is increased globally by human activity, the impact of which is manifested by stress on the natural system and a decrease in its resistance (Kundzewicz, Pińskwar, Brakenridge 2018). This forces a response from hydrological or water management practitioners, for whom heavy rainfall data are a crucial input for hydrological modeling (Adamowski, Adamowski, Bougadis 2010; Johnson et al. 2016). It is used especially for designing water management structures and measures, which include, for example, small reservoirs, bridges, or flood and erosion control measures, usually in small catchments (of one to hundreds of km^2) that are typically not hydrologically monitored (Gaume et al. 2009). To size such measures correctly, it is necessary to model the runoff response to a rainfall event of a magnitude corresponding to the relevant design precipitation totals.

The return period of a precipitation total means that the reaching or exceeding of the given precipitation total occurs once in this period on average. It can be expressed in mm (design precipitation total) or $mm.h^{-1}$ (design intensity). In engineering practice, the unit can also be $l.s^{-1}.ha^{-1}$ (e.g., Rosík 1939, Trupl 1958).

The beginning of research on precipitation extremes in the Czech territory dates back to the first years of the 20th century. At that time, the network of rain gauges already comprised hundreds of stations, and the first recording rain gauges (ombrographs) had already appeared. One of the first studies of precipitation extremes in this territory was carried out in Moravia by Horák (1910). He evaluated absolute precipitation maxima for up to 225 stations with data series lengths between 5 and 25 years for different rainfall durations ranging from five minutes to 24 hours. The motivation for studying rainfall extremes was mainly continuing urbanization and the associated need to construct sewer networks with sufficient capacity to drain rainwater from impervious street and roof surfaces. Therefore, since the 1930s, many studies directly addressing design precipitation intensities have appeared in the Czech literature. To date, no comprehensive studies summarizing these studies have been published. Thus, the aim of our paper is to review them and compare available estimates of design precipitation totals and intensities with different durations in Czechia. This review covers the whole time period from the initial studies, which introduced this research issue, to the most recent studies using modern methods of precipitation monitoring. This paper is divided into Chapters 2 and 3, which are devoted to estimates of design precipitation totals at the daily scale and design subdaily precipitation intensities, respectively. Apart from presenting individual studies and their methodologies, we also compare the available design precipitation estimates for selected stations and discuss their possible differences.

2. Design 1-day and multiday precipitation totals

2.1. Overview of the studies and methods used

In this chapter, we present 11 studies that differ in the methods used for data processing as well as in the format and availability of the results. The details of all the studies are summarized in Table 1.

2.1.1. Work before 2000

The first one-day design precipitation totals were most likely prepared at the Hydrometeorological Institute in 1973 (Kotrnec 1976). Thirty-nine stations with the longest series of precipitation measurements were evaluated. The determined empirical exceedance curves for each station were extrapolated using the Pearson type III distribution and lognormal distribution. Based on these data, general formulas based on average annual rainfall totals for return periods ranging from 1 to 100 years were derived.

This work was followed up by Polišenský in 1976 when he analyzed 12 stations from the Morava River basin, which were selected to cover the entire basin evenly in elevation. With one exception, the data were processed for the same period. The length of the series, 45 years, was not considered by the author to be sufficient for reliable determination of design precipitation totals (Polišenský 1987).

Table 1 – Overview of the described datasets of design one-day and multi-day precipitation totals in Czechia

Author	Year of publication	Period	Duration (days)	Return period (years)	Data source (stations)	Time series length (years)
Kotrnec	1976	1931–1970	1	1–100	39	—
Polišenský	1976	1900–1945	1	—	12	45
Kulasová et al.	1983–1985	—	1–3	—	1,055	min 10
Šamaj, Valovič, Brázdil	1985	1900–1980	1	2–200	579	min 50
Johanovský	1985	1900–1980	1	1–100	28	avg 64.9
Polišenský	1987	1896–1970	1–3	1–1,000	3	min 50
Kašpárek, Krejčová	1993	—	1	0.2–250	37	min 20
Kulasová, Šercl, Boháč	2004	1890, 1895–2002	1–3	100; 1,000	700–1,000	ones to tens
Brázdil et al.	2005	1890, 1895–2003	1–7	100	700–1,000	ones to tens
Kyselý, Picek	2007	1961–2000	1–7	—	78	40
Kozlovská, Šácha, Toman	2019	1961–2013	1	2–100	8	52

Source: authors' elaboration according mentioned studies
[a] The dataset was mentioned in Polišenský (1987)

In the 1980s, the elaboration of design precipitation totals was carried out several times. In three research reports, Kulasová et al. (1983, 1984, 1985) evaluated the design of one-day to three-day precipitation totals successively for the main Bohemian catchments based on data from a total of 1,055 rain gauge stations that had been obtaining measurements for at least 10 years. A three-parameter lognormal distribution was chosen to estimate the design precipitation totals, the statistical characteristics of which were calculated using the method of moments. Ten-year observations were used only to calculate the mean of the annual maxima, and only observations exceeding 30 years were used for the coefficient of variance and asymmetry. Isoline maps were created for these characteristics, from which the parameters of the statistical distribution can be determined for each location.

In contrast to the abovementioned studies, Šamaj, Valovič and Brázdil (1985) studied the entire territory of the former Czechoslovakia. They processed a considerable number of rain gauge stations, 579 in the Czech part of the country and 334 in the Slovak part of the country, which were measured for at least 50 years

Area	Method/Distribution (estimation of parameters; data)	Format of result	Availability
Morava river basin	Pearson Type III, Three-parameter lognormal (block maxima)	discrete values, formulas	literature
Morava river basin	—	—	not available [a]
Bohemia	Three-parameter Lognormal (moments; block maxima)	maps of distribution parameters	literature
Czechia	Pearson Type III, Gumbel	discrete values	literature
Bohemia	Three-parameter Lognormal (moments)	graphic comparison with formulas	literature
Moravia	Pearson Type III, Three-parameter Lognormal, Logarithmic Pearson Type III (moments), empirical curves of exceedance	discrete values	literature
Prague	Type III Extreme Value with upper bound	aggregate values	literature
Czechia	Combination of Gumbel (maximum likelihood) and empirical approach	map	literature
Czechia	Combination of Gumbel and empirical approach	map	literature
Czechia	GEV (L-moments, regionalization, block maxima)	discrete values – return periods for totals greater than 80 and 150 mm	literature
South Moravia	Gumbel (weighted moments), GEV (weighted moments, maximum likelihood; block maxima)	discrete values	literature

(except for some stations in mountainous areas). The length of the 50-year series was determined experimentally as the shortest suitable one by comparing design precipitation totals for 12 stations over the whole observation period and the corresponding shortened series. Two statistical distributions – Gumbel and Pearson Type III –were used to calculate the design precipitation totals. The results obtained were quite different, with the largest differences occurring for both the shortest and the longest return periods. The values obtained using the Gumbel distribution were usually higher, with the exception of the longest return periods for some stations. In addition to calculating design precipitation totals, the authors also considered the meteorological causes of rainfall maxima and their spatial distribution.

In the same year, Johanovský (1985) published his work, which is particularly valuable because he compared direct calculations of design one-day precipitation totals with indirect calculations using previously published formulas (see Chapter 3.1.2). He worked with 28 selected stations with data series mostly longer than 50 years. The method of moments was used to derive the parameters of the three-parameter lognormal distribution that was applied to determine the design precipitation totals.

Polišenský (1987) continued his research on design one-day precipitation totals. He processed data from three stations for design one-, two-, and three-day precipitation totals. The derivation of design precipitation totals was approached using three statistical distributions: the Pearson Type III distribution, three-parameter lognormal distribution, and logarithmic Pearson distribution. The parameters of these distributions were estimated using the method of moments. Furthermore, design precipitation totals were also extracted from the empirical exceedance curve. It was not possible to determine which method is the most reliable for determining design precipitation totals; in the case of long series, simply extracting values from the empirical exceedance curve appears to be sufficiently reliable.

Based on the results obtained, Polišenský (1987) believed it was inappropriate to create generally valid formulas for the calculation of design precipitation totals based only on the long-term normal precipitation and elevation of the site, as these parameters do not have sufficient influence on design precipitation totals.

For the Prague area, Kašpárek and Krejčová (1993) also addressed design one-day precipitation totals. They used data from 37 stations with a time series longer than 20 years, using the annual maxima from Kulasová et al. (1983, 1984, 1985). The Type III extreme value distribution with an upper bound was used to derive the design precipitation totals. The distribution parameters were estimated via nonlinear regression from the empirical values determined for a one-year return period, the envelope curves of the highest precipitation totals of a given duration, and a comparison of the empirically and theoretically determined totals. Only the calculated mean values were published.

2.1.2. Revisions after the 1997 and 2002 floods

Extreme precipitation totals recorded during the 1997 and 2002 flood events motivated further studies on designing precipitation totals on a daily scale. Thus, Kulasová, Šercl and Boháč (2004) revisited their estimation using extended time series including the significant floods in 1890 and 2002. Modern geographic information system methods were used for data processing. The annual station maxima of one-day to three-day rainfall totals were interpolated using inverse distance weighted and kriging methods with the inclusion of the influence of orography. For each pixel, the higher value obtained from both interpolations was used.

The three-parameter lognormal distribution, the Gumbel distribution, and the generalized extreme value (GEV) distribution with three methods for deriving its parameters were used to calculate the design precipitation totals. None of the methods completely respected the extreme value distribution. Therefore, a solution combining statistical and empirical approaches was proposed, comparing the 100-year design precipitation values obtained via Gumbel distribution with highest measured totals in the time series. The authors further proceeded to reduce the values to the catchment area and to refine the floating time interval.

The same methodological procedure was used to derive design precipitation total maps in a monograph by Brázdil et al. (2005), where the time series was extended to 2003. In addition, four- to seven-day precipitation totals were also determined. However, for their evaluation, interpolated maxima from the 1,000 series were used only for 1961–2002.

2.1.3. Introduction of regional frequency analysis and the GEV distribution

Kyselý and Picek (2007) introduced the method of regional frequency analysis based on the L-moment values of the distribution of block maxima (see Hosking, Wallis 1997) in statistically homogeneous regions containing the station under consideration (Burn 1990). This method improves the estimation of design precipitation totals, especially for higher return periods with relatively short time series of annual block maxima. The data thus obtained are both more reliable and climatologically consistent than in the case of local analysis at individual stations. Spatial variability in homogeneous regions, which results from random fluctuations, is significantly reduced in the case of the regional approach. The return periods derived by the local approach were found to be unrealistically high compared to the climatology of heavy precipitation in Central Europe (e.g., for a rainfall of 80 mm at 10% of the stations exceeding 1,000 years). This was due to the uncertainty in the tails of the statistical distribution due to the asymmetry of the distribution, while the regional approach remained more stable.

Kyselý and Picek (2007) evaluated the most appropriate of four statistical distributions applied to the data: the GEV, the generalized logistic distribution, the three-parameter lognormal distribution, and the Pearson Type III distribution. Testing these approaches, it was found that the GEV was the most appropriate distribution for most durations and most regions, with only the generalized logistic distribution proving more appropriate for the northeastern region of Czechia, where the influence of orographic intensification and more frequent precipitation associated with Mediterranean cyclones meet. In contrast, the Pearson Type III distribution, used in some previous studies (e.g., Šamaj, Valovič, Brázdil 1985), was found to be inappropriate. Overall, however, the differences due to the use of different types of distributions were smaller than the differences between the regional and local approaches. The approach thus tested was subsequently applied to data from all available rainfall gauging stations, but one-day design precipitation totals have not been published.

Recently, the issue of one-day design precipitation totals was also addressed by Kozlovská, Šácha and Toman (2019). In their research, they used only a small number of stations in the South Moravia region but with long time series and the same measurement period, which made the results more comparable. The Gumbel and GEV statistical distributions were applied to the annual maxima of one-day precipitation totals; the parameters of the Gumbel distribution were derived using the weighted moments method, while the parameters of the GEV distribution were derived using both the weighted moments method and the maximum likelihood method. Two nonparametric statistical tests (Kolmogorov–Smirnov and Anderson–Darling tests) were used to test the fit of the model distributions to the real data. The results for both distributions were very similar since the shape parameter of the GEV distribution was close to zero and the distributions essentially converged. For most of the stations evaluated, at least for some of the criteria tested, the GEV distribution was better; therefore, it was also recommended by the authors. Even for the stations where testing revealed that the Gumbel distribution was more appropriate, the difference in the resulting 100-year design precipitation totals was no more than 3 mm.

2.2. Comparison of available sources of one-day design precipitation totals

2.2.1. The presented data

From the presented datasets of one-day design precipitation totals, we selected those for which design precipitation totals for specific stations were available in the relevant literature or which were obtained directly from their authors. Thus, the data obtained came from both the oldest studies (Kotrnec 1976) and recent research (Kyselý, Picek 2007; Kozlovská, Šácha, Toman 2019). Moreover, these studies were supplemented with data from Šamaj, Valovič and Brázdil (1985). As the authors of these papers focused on different areas at different times, there was not a complete overlap among the stations used for our analyses. The stations used for comparison are listed in Table 2. The only station for which results from all the abovementioned datasets were available was Strážnice (Fig. 1a). In addition, five other stations with data available in most of the datasets were selected (Fig. 1b–1f). These stations are located at different elevations. The selected datasets cover different periods; therefore, changes in the station's location or overlap of individual stations over time could occur; in two cases, data series compiled from two nearby stations were selected for comparison. However, the distance between these stations is no more than 4 km, and the elevation difference is less than 50 m.

When comparing the data, note that the authors used different methodological procedures (e.g. different statistical distributions and the way of deriving their parameters) and that the lengths and periods of the time series used were not the same. This may explain some differences among these datasets. For example, even

Table 2 – Summary of stations used to compare various estimates of design one-day precipitation totals and sub-daily precipitation intensities. The sources were denoted by following abbreviations: KOT (Kotrnec 1976), ŠAM (Šamaj, Valovič, Brázdil 1985), KYS (Kyselý, Picek 2007), KOZ (Kozlovská, Šácha, Toman 2019), TRU (Trupl 1958), D_R (DES_RAIN software by Vaššová and Kovář 2011), CRH (Crhová, Kliegrová, Valeriánová 2022), RAD (design precipitation totals derived from radar data by Kašpar et al. 2021). The cross indicates available data.

					Design one-day precipitation totals				Design sub-daily precipitation intensities			
Station	ID	Elevation	Latitude	Longitude	KOT	ŠAM	KYS	KOZ	TRU	D_R	CRH	RAD
Strážnice	B1STRZ01	176	48.9	17.3	×	×	×	×				
Olomouc, Klášterní Hradisko	O2OLKL01	215	49.6	17.3	×	×	×		×	×		
Olomouc, Holice	O2OLOM01	210	49.6	17.3							×	×
Rožnov pod Radhoštěm	O3ROZN01	375	49.5	18.1	×	×	×					
Telč	—	527	49.2	15.5		×			×	×		
Kostelní Myslová	B2KMYS01	569	49.2	15.4			×	×			×	×
Desná, Souš	P2DESN01	772	50.8	15.3		×	×		×	×	×	×
Lysá hora	O1LYSA01	1,322	49.5	18.4		×	×		×	×	×	×

Source: authors' elaboration.

long series may not capture any extreme rainfall that would correspond to a true 100-year return period event at a given location; in this case, design precipitation totals with long return periods are underestimated. Conversely, if such rainfall is captured in a short series, then a shorter return period than the true one may be assigned to the event, resulting in an overestimation of the design precipitation total.

2.2.2. Data analysis

The values of the one-day design precipitation totals at the compared stations (Fig. 1) ranged between 33 and 53 mm for the two-year return period, except for the mountain station Lysá hora (Fig. 1f), where the design total already exceeded 70 mm for such a short return period. For stations at lower altitudes (Fig. 1a, 1b, 1d), the design precipitation totals increased more slowly with the return period than for the mountain stations (Fig. 1e, 1f); the increase was also rather high at the Rožnov pod Radhoštěm station (Fig. 1c), which is located at a low elevation and at the foot of the mountains. For the 100-year return period at low-elevation stations, the design precipitation totals did not usually exceed 100 mm, while under mountainous conditions, they reached values of approximately 150 mm

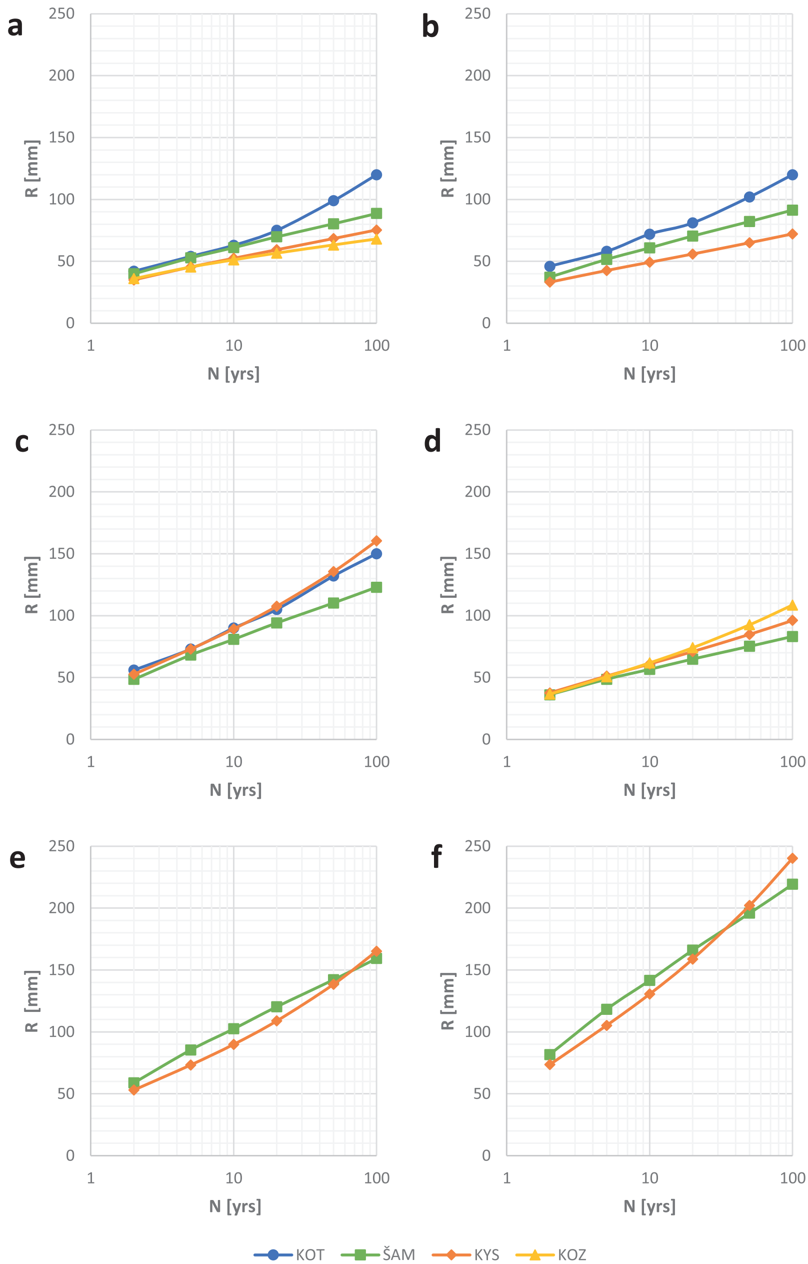

Fig. 1 – Comparison of design one-day precipitation totals R for different return periods N for the stations (a) Strážnice, (b) Olomouc, Klášterní Hradisko, (c) Rožnov pod Radhoštěm, (d) Telč / Kostelní Myslová, (e) Desná, Souš, and (f) Lysá hora according to different authors. For abbreviations see Table 2. Source: authors' elaboration of original data by Kotrnec (1976); Šamaj, Valovič, Brázdil (1985); Kyselý, Picek (2007); and Kozlovská, Šácha, Toman (2019).

and eventually reached more than 200 mm at the exposed summit station at Lysá hora Mountain.

A comparison of the data showed that the design precipitation totals from the different datasets were in good agreement for short return periods, with deviations of less than 10%. The agreement was significantly worse for return periods of 20 years or more, with the highest estimate of the design precipitation total being almost double the lowest estimate at some stations. This was particularly pronounced in the estimates of Kotrnec (1976). This overestimation was already noted by Johanovský (1985). In addition to the different data-processing methodologies, the relatively short time series used was also a likely cause.

A pair of datasets with high numbers of involved stations and long time series (Šamaj, Valovič, Brázdil 1985; Kyselý, Picek 2007) achieved relatively good agreement at most stations, with a maximum bias of up to 30%. Both datasets also consistently captured the nature of the increase in the design precipitation total with the return period. At lower elevations, the regional approach systematically lowered the estimates (Fig. 1a, 1b), as it reduced the estimation uncertainty due to the large representation of spatially heterogeneous convective precipitation in these regions. In the case of the mountain stations (Fig. 1e, 1f), these datasets achieved even better agreement, with a maximum bias of less than 15%. However, they differed in the nature of the increase: for long return periods, the design precipitation estimates obtained by the regional approach increased noticeably faster. The largest difference between these datasets was observed at the Rožnov pod Radhoštěm station (Fig. 1c), where the design precipitation estimates obtained by Kyselý and Picek (2007) were even greater than those obtained by Kotrnec (1976). This may be due to the strong influence of nearby mountain stations belonging to the homogeneous pool of stations used for regionalization; therefore, the estimates by Kyselý and Picek (2007) showed similar behavior as those from the mountain stations.

3. Design subdaily precipitation intensities

3.1 Overview of the studies and methods used

We identified and analyzed 11 sources of subdaily design precipitation intensities from the 1930s to the present. These sources differed in the methodological approaches used and the format and availability of results. Details of all the sources are given in Table 3.

Table 3 – Overview of the described datasets of design subdaily precipitation intensities in Czechia

Author	Year of publication	Period	Duration (min)	Return period (years)	Data source (stations)	Time series length (years)
Halámek	1939	1912–1935	5 to 60	0.33 to 10	8	avg 10.75
Rosík	1939	-	10 to 120	0.5 to 10	18	avg 17.6
Trupl	1958	1898–1956	5 to 120	0.2 to 20	98	avg 17.5
Němec	1964	1899–1956	max 600	max 100	39	-
Jírovský	1986	1961–1986	5 to 180	0.2 to 25	43	avg 25.6
Kašpárek & Krejčová	1993	1961–1986	10 to 1440	0.2 to 250	5	avg 32
Vaššová & Kovář (DES_RAIN)	2011	1901–1980	10 to 1200	2 to 100	579	min 50
Kavka et al.	2016	1901–1980	360	2 to 100	579	min 50
Fusek, Hellebrand, Michálek	2016	1959–2003	5 to 360	5 to 100	6	avg 27.2
Kašpar et al.	2021	2002–2021	30 to 1440	2 to 100	radar, res. 1 km	20
Crhová, Kliegrová, Valeriánová	2022	1951–2020	30 to 1440	2 to 100	60	min 32

Source: authors' elaboration according mentioned studies.

3.1.1. Pioneer studies in the 1930s

Halámek's study (1939) was one of the earliest studies on subdaily precipitation intensities and served as the basis for the design and construction of the sewer network in Brno. Until then, too low values of design precipitation intensities were used, including those adopted from the German area (e.g., Imhoff 1906, Wussow 1922).

Halámek (1939) took advantage of the dense station network in Brno, where 11 ombrographic stations had been put into operation step by step since 1912. The longest series had a record duration of 23 years, and the shortest series had a duration of only four years. The data from the eight stations with the longest series were processed.

The periodicity of the precipitation intensities was evaluated based on a table of independent rainfall intensities.

In the same year, Rosík (1939) published his results. He followed up on his previous attempts to quantify subdaily design precipitation intensities made in 1930. However, the results were underestimated, especially for short durations

Area	Method/Distribution (estimation of parameters; data)	Format of result	Availability
Brno	empirical	IDF curves, aggregate values	literature
Province Moravia-Silesia	empirical (thresholds)	aggregate IDF curve, formula	literature
Czechia	empirical (thresholds)	discrete values, formula, maps of distribution parameters	literature
Labe river basin	Goodrich	parameters, formula	literature
Czechia	empirical (thresholds)	discrete values	literature
Prague	Type III Extreme Value with upper bound	aggregate values	literature
Czechia	reduction of daily values	discrete values	software
Czechia	reduction of daily values	map	web app (unavailable)
South Moravian region	Generalized Pareto (maximum likelihood; partial duration series)	IDF curves	literature
Czechia	GEV (L-moments; block maxima)	map, discrete values	author
Czechia	GEV (L-moments; block maxima)	discrete values	author

(up to 30 minutes), because of insufficient ombrographic observations available at that time.

The author processed longer than 10 years of measurements from ombrographs in the territory of the Moravian-Silesian province, with the longest series reaching 38 years. In total, approximately 4,000 rainfall episodes were reported and evaluated. The data were tabulated using the peaks-over threshold method. The threshold was set by the State Hydrological Institute's guidelines from 1934. Each value found was then reassigned to its periodicity. The results were presented as average intensity curves for the four periods based on Reinhold's formula (Reinhold 1935):

$$i = \frac{C}{(T+b)^a} \quad (1)$$

where i is the design precipitation intensity in l.s^{-1}.ha^{-1}, T is the duration of the precipitation in minutes, a is the tangent of the intensity curve, and C and b are constants.

The author focused in detail on the town of Moravská Ostrava, where seven ombrographic stations with the same measurement period were located in an area of 10 km². He found that even in such a small area, there were significant differences in the values of the intensity curves. Specifically, in the area of Moravská Ostrava, the intensity of precipitation increased from west to east, where the intensity with the same periodicity was up to 20% greater. Among all stations, the differences in intensity curves could reach up to 100% for short-term intensities with even a short return period. The author explained this by the small spatial extent and randomness of the occurrence of convective precipitation. The author also documented the inconsistency between the spatial distribution of annual precipitation totals and the spatial distribution of their maximum intensities, which also differed for different return periods. Like Halámek (1939), Rosík (1939) also concluded that the values valid for Germany (Imhoff 1906; Reinhold 1935) were lower than those calculated for the Moravian-Silesian country. Only the data from Bavaria were similar.

3.1.2. The classic work of Trupl and subsequent studies

Trupl (1958) followed up on the abovementioned studies with the same purpose in the 1950s with his classic work. He analyzed data from the whole territory of Czechia and had at his disposal a larger number of ombrographic records from a total of 109 stations, 11 of which were excluded from further processing due to unreliable results. The longest data series was 48 years long, and the shortest was only 9 years. In the ombrographic records, all sections of a given duration of up to 120 min were found to exceed a predetermined threshold (2 to 7 mm depending on duration). Only those episodes that involved only a short interruption of rain (e.g., a maximum of 10 min during 90 to 120 min of rainfall) were evaluated.

Each precipitation event was processed from the highest precipitation intensity to find all independent maxima for that event. Subsequently, the occurrence frequencies of the maximum intensities in millimeter intervals were used to construct an upper envelope curve indicating the relationship between rainfall and exceedance frequency, from which design values for specific periodicities could be read.

In contrast to his predecessors (see Table 3), Trupl also provided tables of design subdaily precipitation totals calculated for individual stations. He also established parameters for the classic Reinhold's formula (Eq. 3) for estimating design precipitation intensities of different durations and return periods valid for the main river basins of Czechia. The design precipitation intensities could also be estimated at any location by using the formula parameter maps (expressing the tangent of the intensity curve) and the 15-minute rainfall intensity map with a return period of one year. For the location under investigation, a nearby station whose parameter value corresponded to the interpolated value at the location under investigation was identified. Thus, a modification ratio of the 15-minute intensities from the map to the 15-minute intensities for the nearby station was constructed. This ratio was then used to modify the values for all rainfall durations and return periods. Although the author considered a standard return period of up to 20 years, summary intensity curves for longer return periods (up to 500 years) were also derived.

Čerkašin (1964) and Němec (1964) built on Trupl's work, establishing relationships that are also valid for longer durations and return periods. Čerkašin (1964) derived his formula from Trupl's summary curves for longer return periods. The formula is

$$h = 14.5\sqrt[3]{t} \tag{2}$$

where h is the design precipitation total in mm and t is the duration of precipitation for 100-year design precipitation totals. Němec (1964) derived the parameters of his formula from Trupl's data for 39 stations in the Elbe River basin using the Goodrich distribution. The formula is

$$i = \frac{(a \log t + b)N^n}{t} \tag{3}$$

where i is the rainfall intensity in mm/min, t is the duration of the precipitation in min, N is the return period in years and a, b, and n are individual parameters for each station. This formula is valid for return periods up to 100 years and durations up to 600 minutes, tentatively also up to 24 hours. For short return periods (up to 5 years), this formula slightly overestimated the design precipitation intensities compared to Trupl (1958).

A comparison of selected formulas was performed for one-day precipitation by Johanovský (1985). He compared the formulas of Němec (1964), Čerkašin (1964), and Kotrnec (1976) with his own calculations (see Chapter 2.1.1). For all pairs of direct and indirect calculations, their ratios were calculated, histograms of their frequencies were produced, and the means and standard deviations were calculated. While the distributions of the indirect calculation proportions according to Němec's formula and design one-day precipitation totals were relatively symmetric and the average ratios for all evaluated return periods were only slightly different from one, the Kotrnec's formula overestimated the values compared to the direct calculation; an even greater overestimation and standard deviation were achieved with Čerkašin's formula. For the five selected mountain stations, Kotrnec's formula achieved better results, while the values obtained by Němec's formula were lower than those obtained via direct calculation.

Trupl's work was followed up in the 1980s at the Czech Hydrometeorological Institute by Jírovský (1986), who applied Trupl's methodology and evaluated ombrographic records from 43 stations for a relatively short period from 1961 to 1986. For a few selected stations, a longer period was used with a maximum interruption of three years. The data were already being processed by a computer.

Jírovský's data were used by Kašpárek and Krejčová (1993). In addition to the abovementioned design one-day precipitation totals (see Chapter 2.1.1.), they also addressed subdaily intensities for the Prague area. They used data from a total of five ombrographic stations. However, these data suffered from an inconsistent dependence between the rainfall duration and the design precipitation intensity, with a decrease in the intensity with increasing duration (especially between 40 and 60 minutes and between 120 and 180 minutes). Therefore, weighted averages from these stations were used, where the weight was the ratio of the observation period of a particular station to the sum of the observation periods of all stations. As in the case of the design one-day precipitation totals, the parameters of the Type III extreme value distribution with an upper bound were empirically estimated, and the average values of the design subdaily precipitation intensities were calculated for Prague.

3.1.3. Design subdaily intensities by reducing 1-day totals

Ombrographic records were also taken in the following years, but they were not evaluated or published; therefore, further research on the design subdaily precipitation intensities focused on the method of reducing design one-day precipitation totals, which were compiled in the 1980s (Šamaj, Valovič, Brázdil 1985; see Chapter 2.1.1.). They had the advantage of a denser station network but introduced uncertainty into the results because of the need to determine reduction factors. This was the approach taken at the Czech University of Agriculture in Prague in the development of DES_RAIN software (Vaššová, Kovář 2011), which is still used in practice due to its user-friendliness.

DES_RAIN works in Microsoft Office Excel; the user simply selects the station of interest from the list, and the program calculates design precipitation totals and graphically processes the results. Šamaj's daily values were reduced using reduction coefficients derived according to the methodology of Hrádek and Kovář (1994) using average values of design subdaily precipitation intensity for the Czech Labe basin derived by Trupl (1958) and one-day maximum precipitation totals (Kulasová et al. 1983). The values of the reduction coefficients derived in this way were determined for rainfall durations from 10 to 120 minutes. For durations from 120 to 1440 minutes, the values of the coefficients were extrapolated.

Later, the program was modified to the DES_RAIN_VARIABLE version (ČZU, FŽP, KBÚK 2014), which accounts for the variable design precipitation intensity. The values of the design precipitation totals are the same as in the previous software DES_RAIN, only the intensities within the rainfall are distributed according to a synthetic hyetograph with asymmetric shape (Kalvová, Metelka 2010).

The same input data were used by Kavka et al. (2016) to prepare maps of 6-hour design precipitation. The correction of the station position data was performed, and then design precipitation totals were interpolated to the raster with a resolution of 1 km. The interpolation was performed by a regression analysis followed by residual correction. The parameters of the regression analysis were the geographic location and maximum elevation of six 45° transects with different radii. The residuals were interpolated via the empirical Bayesian kriging method. The data were made available through WMS and a web application.

3.1.4. Most recent studies

Fusek, Hellebrand and Michálek (2016) reported newly processed ombrographic data for six South Moravian stations. The time series, with lengths ranging from 11 to 41 years, were processed in one-minute steps. For rainfall durations longer than one hour, independent precipitation events were considered independent of those events for which the time window between peak intensities was longer than the considered duration.

The parameters of the generalized Pareto distribution were determined by the maximum likelihood method using all maxima exceeding a specified threshold. This was determined by two graphical methods. The first method was based on a mean residual life plot, which visualizes the dependence of the threshold on the mean of all observations exceeding the threshold. It should be linear above the threshold. The second method was based on the fact that for a correctly determined threshold, the shape parameter varies linearly with an increasing threshold. The observed thresholds varied from 1.0 to 2.0 mm for a 5-minute rainfall event or from 8.2 to 9.4 mm for a 360-minute rainfall event. The design precipitation intensities estimated in this way were compared with those of Trupl (1958). The differences found were no more than 30% and were even smaller for stations with long series of measurements. These differences were also partly due to the various methodologies used.

The complex processing of ombrographic data for the whole territory of Czechia was approached by Crhová, Kliegrová and Valeriánová (2022). Sixty stations were processed with at least 32 years of ombrographic and automatic rainfall data for 1951–2020. The models of the two-parameter Gumbel distribution and the three-parameter generalized extreme value (GEV) distribution were tested, and their parameters were derived using L-moments and the maximum likelihood method. The results obtained by the two approaches were quite different. In 46% of the cases, the higher estimate of the design precipitation intensity with a return period of 100 years differed by more than 20% of the value of the lower estimate. The design precipitation intensities estimated using the GEV parametric model with parameters derived from L-moments were selected as the best fit. The same procedure was applied to the monthly maxima in the warm half of the year. Recently, this product is being expanded to include data from

164 stations (Crhová et al. 2024). This dataset is publicly available at www.perun-klima.cz.

With the development of remote sensing methods in meteorology, especially ground-based radar measurements, the potential for improving design precipitation intensity estimates is increasing because of the major disadvantage of direct measurements – the sparse network of ombrographs and automatic rain gauges. Globally, radar data were first used to derive reduction factors applied to precipitation data (Stewart 1989); only later did they begin to be used to directly derive design precipitation intensities (e.g., Overeem, Buishand, Holleman 2009).

In Czechia, design precipitation intensities from radar data were derived by Kašpar et al. (2021). Radar precipitation intensities were first adjusted by daily precipitation totals from the rain gauge network using the method of Sokol (2003). Statistical analysis of extreme values was performed based on the three-parameter GEV distribution, and L-moments were used to estimate their parameters. To increase the robustness of the estimation, the L-moments were determined by the region of influence (ROI) method (Kyselý, Gaál, Picek 2011). The radar data can be considered spatially continuous. Thus, design precipitation estimates are available for any location with a horizontal resolution of 1 km.

3.2. Comparison of available sources of design subdaily precipitation intensities

3.2.1. The presented data

Recently, two sources of design subdaily precipitation intensities in Czechia have been publicly available, namely, tabelated values in Trupl (1958) and downloadable values from the DES_RAIN application (Vaššová, Kovář, 2011). In addition, the values from the most recent processing based on ombrographic and radar data were obtained from the Czech Hydrometeorological Institute (Crhová, Kliegrová, Valeriánová 2022) and from the authors of a study (Kašpar et al. 2021), respectively. These four sources were included in the comparison. For a more detailed comparison, the following stations (or pairs of nearby stations, see Chapter 2.2.) were selected from a total of twelve stations processed in all four datasets: Lysá hora and Desná, Souš, representing mountain locations; Telč / Kostelní Myslová, representing mid-elevations; and Olomouc, Klášterní Hradisko / Holice, representing lowlands. These stations were also used for the comparison of design one-day precipitation totals (see Table 2). A comparison of design one-hour precipitation totals for different return periods for the same stations is shown in Figure 2. Figure 3 shows the estimates for a return period of 20 years, which is the longest standard return period used by Trupl (1958).

3.2.2. Analysis of the data

The estimates of the design one-hour precipitation intensities typically ranged from 14 to 24 mm and from 29 to 60 mm for the 2-year and 20-year return periods, respectively (Fig. 2). For the two datasets based on subdaily station data, there was no significant difference in the design precipitation estimates among the stations. This indicates that design precipitation estimates in Czechia were not dependent on elevation for such a short duration.

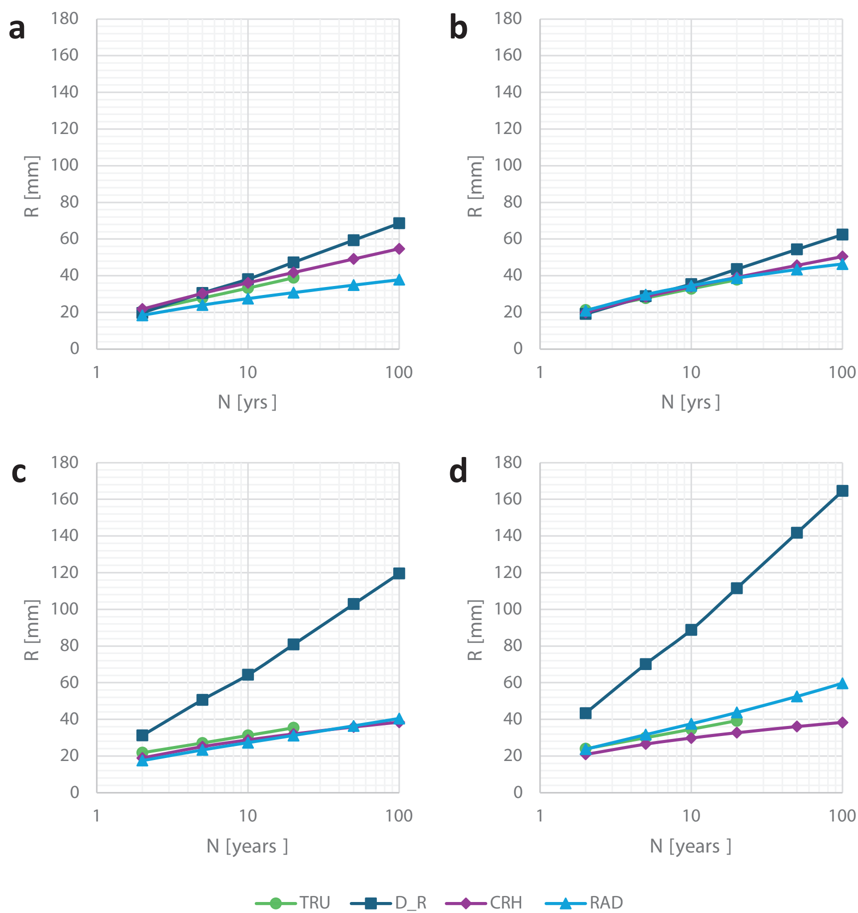

Fig. 2 – Comparison of design one-hour precipitation totals R for different return periods N for the stations (a) Olomouc, Klášterní Hradisko / Holice, (b) Telč / Kostelní Myslová, (c) Desná, Souš, and (d) Lysá hora according to different authors. For abbreviations see Table 2. Source: authors' elaboration of original data by Trupl (1958); Vaššová and Kovář (2011); Crhová, Kliegrová, Valeriánová (2022); and Kašpar et al. (2021).

In contrast, the DES_RAIN dataset was significantly different from the other datasets. Across all 12 stations, the values of the design precipitation intensities for the same durations were on average 50% greater than those for the other datasets. At the individual stations, the largest difference was observed at the mountain stations (Fig. 2c, 2d), where the design one-hour precipitation intensities exceeded those of the other datasets by more than 100%. This difference increased with the return period: for one-hour of precipitation at the Lysá hora station (Fig. 2d), the estimated value for the 100-year return period was four times greater than

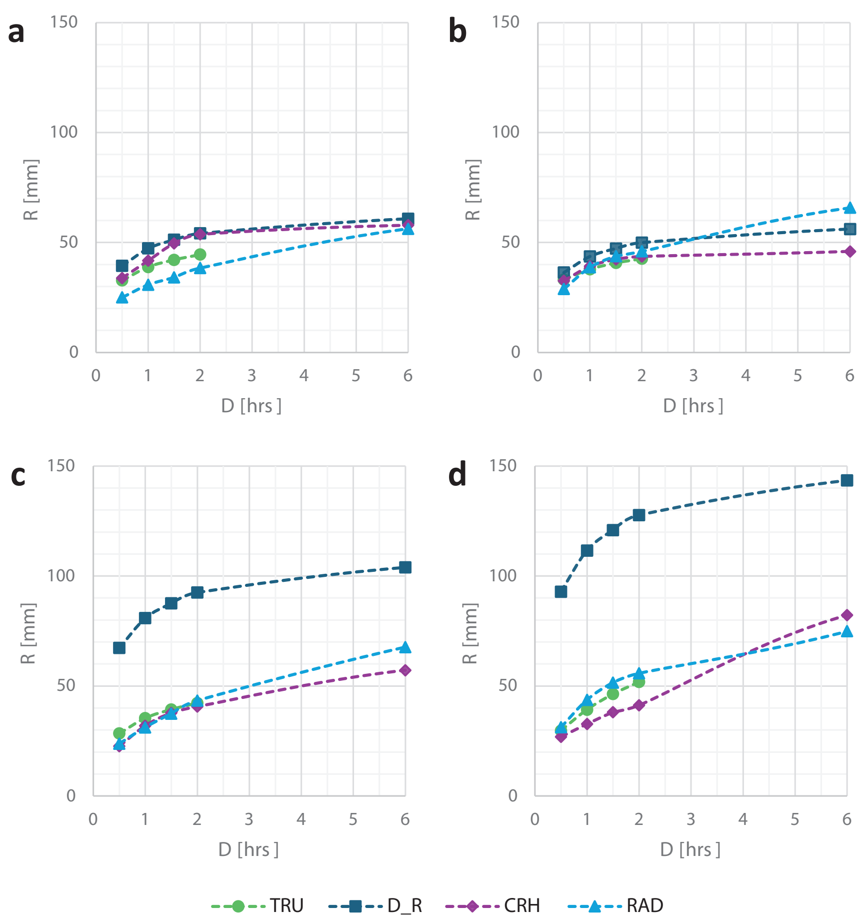

Fig. 3 – Comparison of design subdaily precipitation totals R with a return period of 20 years for different durations D for the stations (a) Olomouc, Klášterní Hradisko and Holice, (b) Telč and Kostelní Myslová, (c) Desná, Souš, and (d) Lysá hora according to different authors. For abbreviations see Table 2. Source: authors' elaboration of original data by Trupl (1958); Vaššová and Kovář (2011); Crhová, Kliegrová, Valeriánová (2022); and Kašpar et al. (2021).

the station-based estimate. Stations at lower elevations did not show such large differences, yet even in their case, the design precipitation intensities from the DES_RAIN dataset were among the highest. The reason seems to be the significant methodological difference in deriving design subdaily precipitation intensities by the application of a reduction factor to one-day precipitation totals. Kavka et al. (2016) pointed to the possible overestimation of such reduced design precipitation under mountain and foothill conditions, where the orographic precipitation enhancement is not reflected so much in the case of short-term precipitation; the authors also mentioned that the reduction coefficients used were derived only for the Labe basin, i.e., only in two-thirds of the area of Czechia. However, even these comments do not fully explain why the values from the DES_RAIN dataset were so much higher than those from the other datasets.

With increasing duration, estimates of design precipitation also increased (Fig. 3). For the 20-year return period, for example, one-hour design precipitation estimates typically ranged from 29 to 60 mm, followed by six-hour precipitation estimates ranging from 45 to 80 mm (Fig. 3). Low-lying stations showed a substantial slowing increase in estimates for durations longer than two hours (Fig. 3a, 3b), while the increase remained rather large for mountain stations (Fig. 3c, 3d). For the DES_RAIN dataset, the overestimation relatively decreased for longer durations, but the absolute differences remained unacceptably high for the mountain stations.

The two datasets based on ombrographic data, the classic dataset by Trupl (1958) and the current dataset by Crhová, Kliegrová and Valeriánová (2022), showed very good agreement on average. Trupl's design precipitation intensities were usually slightly lower, with a maximum deviation of 6%, and the best agreement was achieved for the 2-year return period. The design precipitation intensities derived from radar data appeared to be slightly underestimated compared to those derived from these two datasets at all 12 stations for short rainfall durations (one hour or less) and return periods (10 years or less), while they were overestimated for longer durations and return periods. Nevertheless, radar-derived design precipitation intensities showed a significantly different dependence on duration and return period at specific stations (e.g., at the Lysá hora station in Figs. 2d and 3d). This may be due to the different lengths of the time series used in the analysis.

4. Discussion and conclusion

Research on design precipitation intensities has been conducted in Czechia for almost one hundred years. It includes both studies that aimed to provide a comprehensive climatology of design precipitation totals and intensities for the whole territory of Czechia (e.g., Trupl 1958; Šamaj, Valovič, Brázdil 1985; Kulasová, Šercl, Boháč 2004) and studies locally focused on the territory of one city only (Halámek 1939; Kašpárek, Krejčová 1993). The catastrophic floods of 1997 and 2002 provided a new impulse to study design precipitation totals in recent decades (Kulasová, Šercl, Boháč 2004). Time series extensions have allowed modern studies to improve the precision of design precipitation estimates, particularly in the case of design one-day precipitation totals. Moreover, regionalization methods have been adopted for further refinement of estimates (Kyselý, Picek 2007). Therefore, there is fairly good agreement for the estimates of daily design precipitation totals, except for the oldest dataset (Kotrnec 1976). The increase in estimates for long return periods for the dataset by Kyselý and Picek (2007) compared to the one by Šamaj, Valovič and Brázdil (1985) at mountain stations is probably due to including totals from flood-rich years.

The methodological approaches used by the authors to process the data have changed over time. In the earliest papers, the authors worked mostly with Pearson Type III and three-parameter lognormal statistical distributions. Later, the Gumbel distribution was adopted. The most recent papers also addressed the generalized extreme value distribution (GEV). Some studies (e.g., Kotrnec 1976; Polišenský 1987; Kyselý, Picek 2007; Kozlovská, Šácha, Toman. 2019) processed data using more statistical distributions, which enabled a comparison of these approaches. According to these studies, the GEV distribution seems to be the most suitable for estimating design precipitation totals and intensities in Czechia.

Compared to design one-day precipitation totals, there is noticeably less agreement among design subdaily precipitation intensity datasets, especially because shorter time series were used. The first work based on long time series of subdaily precipitation intensities was that of Crhová, Kliegrová and Valeriánová (2022). Studies focusing on subdaily precipitation intensities differ more in terms of the methodology used. The oldest studies did not work with statistical distributions at all but were based only on empirically found exceedance curves, while other studies attempted to overcome the lack of ombrographic measurements by using reduction coefficients applied to daily totals (DES_RAIN in Vaššová, Kovář 2011). However, this approach proved to be inappropriate in mountainous areas, overestimating design precipitation intensities by more than four times. Unfortunately, the DES_RAIN dataset is still widely used in water management practice because it is easily available and even implemented in some hydrological models (Hrádek, Kuřík 2001).

Another possible source of uncertainty in the design precipitation estimates may be the inappropriate methodological approach applied in processing the precipitation data. In particular, it is necessary to maintain the statistical independence of their selection so that multiple data from a single precipitation event are not used (eg. Koutsoyianis, Kozonis, Manetas 1998). The independence of selection has to be tested statistically. In a few cases (Polišenský 1987; Kašpárek, Krejčová

1993; Kulasová, Šercl, Boháč 2004), design values for return periods longer than 100 years were also investigated. With available time series lengths of decades at most, such estimates are unrealistic and the width of their confidence interval increases considerably (Koutsoyiannis, Baloutsos 2000; Moccia, Mineo 2020).

Data from approximately ten times fewer stations were used to derive design subdaily precipitation intensities than for design one-day precipitation totals in datasets covering the entire Czechia region. This is due to the abovementioned sparse network of ombrographic measurements compared to those of conventional rain gauges. The time series of automatic rain gauges is still insufficiently long to derive design precipitation intensities. The latest dataset by Crhová, Kliegrová and Valeriánová (2022) contains one station per area of 1,315 km² on average. This is a significantly lower spatial representation than in the latest processing of design subdaily precipitation intensities in the frame of the Slovak National Climate Programme (Onderka, Pecho 2022). The authors processed data at 150 stations in Slovakia, corresponding to one station per area of 327 km² on average. An even denser network of 1,410 stations (one station per area of 254 km²) was used in the German KOSTRA-DWD 2020 dataset (Junghänel et al. 2022). However, shorter time series were used for derivation in both countries – a minimum of 10 years in Germany and data from 2005 to 2021 in Slovakia. If only stations with a time series length of at least 30 years were considered, then 270 stations were used in Germany (one station per area of 1,324 km²). Thus, with comparable time series lengths, the density of the network of stations used in Czechia and Germany is almost identical.

One of the most recent studies also used remote sensing methods to derive design precipitation intensities (Kašpar et al. 2021). The innovative approach of using radar data to derive design precipitation intensities overcomes the disadvantage of a low-density ombrographic measurement network and provides detailed information on the spatial variability of design precipitation intensities. However, mainly due to the short time series of radar data, the estimates could be quite different from the station-based estimates. Therefore, we propose a suitable way to improve the estimates of design precipitation: to combine radar-based estimates synergistically with station-based estimates using suitable spatial interpolation methods while preserving the advantages of the high spatial resolution of radar data and long ombrographic time series. The first attempts at this approach have already been made in the water management methodology by Kavka et al. (2023).

The authors also recommend establishing a national dataset of design precipitation totals and intensities. The lack of data is a significant difference compared to, e.g., neighboring Germany, where the national dataset of design precipitation totals, KOSTRA-DWD, is regularly updated and publicly available as open data (Junghänel et al. 2022).

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