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Design rainfall intensities in Slovakia: Historical evolution of estimation methods and challenges under a changing climate

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Design rainfall intensities are a key input for hydrological design, particularly in urban drainage planning. They also play a crucial role in flood protection, water management, and the design of sustainable and green infrastructure, making their accurate estimation essential for both economic efficiency and public safety. This paper reviews the methods used to derive rainfall design values in the territory of modern-day Slovakia over more than a century, drawing on the recent and historical contributions. It also describes the historical evolution of rainfall measuring instruments, from early mechanical ombrographs to modern automatic rain gauges, which formed the foundation for quantitative analysis of rainfall intensities. Early empirical efforts in the late 19th and early 20th centuries were closely tied to sewer-network design and relied on simplified formulas and limited observations. A major methodological shift occurred in the mid-20th century with the adoption of statistical frequency analysis, which introduced a rigorous probabilistic framework for estimating rainfall extremes. Recent progress has been enabled by digitized records, high-resolution automatic rain gauges, and advanced statistical methods, including Bayesian inference that allow explicit quantification of uncertainty. Modern methods combine regional frequency analysis with gridded products from reanalyses and climate models. There is an urgent need to adapt design methods to the ongoing climate change and an inherently non-stationary climate system. Regional climate models are increasingly used to estimate future rainfall extremes, since reliance on historical observations alone is no longer sufficient for planning and designing long-lived infrastructure. However, no universally recognized methodology has yet been endorsed, leaving national agencies and researchers to develop approaches tailored to local needs and data availability. This review provides a systematic overview that connects historical, current, and future perspectives.

KEY WORDS: design rainfall intensities; IDF curves; frequency analysis; regional frequency analysis; climate change

Introduction

Design rainfall intensities are a cornerstone of hydrological engineering, underpinning urban drainage planning, flood protection, water-resource management, and the implementation of sustainable and green infrastructure. Accurate estimation of these values is essential not only for economic efficiency and the safety of critical infrastructure but also for building resilience against increasingly frequent extreme precipitation events (IPCC, 2021). In Slovakia, systematic precipitation observations extend back to the mid-19th century, initially motivated by the needs of agriculture and the early development of urban sewer systems. Early measurements relied on mechanical and float-type ombrographs that provided the first quantitative insights into short-duration rainfall. Historically, rainfall frequency estimates in Slovakia were developed and maintained by the national weather service, today the Slovak Hydrometeorological Institute (SHMI). Pioneering studies by Dub (1947), Dzubák (1969), Šamaj and Valovič (1973), Urcikán (1980) and later Urcikán and Imriška (1986) used data from a limited number of rain-gauge sites to produce the first national design rainfall intensities and intensity–duration–frequency (IDF) relationships. These works laid the methodological groundwork for understanding spatial patterns of short-term rainfall and their implications for hydrological design in Slovakia. Similar methodological foundations were developed in parallel in the Czech Republic, where the work of Trupl (1958) played a significant role, representing one of the first comprehensive attempts to determine design rainfall values within the former Czechoslovakia. Trupl's results became an important reference point for water management hydrotechnical practice, particularly in the design of drainage systems and the assessment of extreme short-duration rainfall. Over the past decades, methods for deriving design rainfall have evolved substantially. Early empirical and envelope approaches were progressively replaced by statistical frequency analysis and extreme value theory (Coles, 2001; Katz et al., 2002). Later, regional

frequency analysis methods were introduced to make better use of sparse data, supported by high-resolution automatic rain gauges, radar measurements, and digitized historical archives. In Slovakia, significant advances were made through the application of simple scaling techniques to short-duration rainfall data (e.g. Bara et al., 2008, 2009, 2010a, 2010b; Kohnová et al., 2016, 2018), enabling more reliable estimation at ungauged sites and improving the representation of spatial variability and uncertainty. Recent studies have also explored Bayesian and non-stationary statistical frameworks for improved estimation of extremes (e.g. Onderka et al., 2024). Fusek et al. (2016) re-evaluated classical IDF relationships for the Czech Republic using POT/GP methods and confidence bands at CHMI stations in South Moravia, demonstrating that the results are highly sensitive to the chosen methodology. These updated analyses revisited and critically compared the results with traditional empirical IDFs (see Trupl, 1958), which had long served as the baseline for design rainfall estimations. Other studies have documented trends and the structure of heavy and sub-daily precipitation in the Czech Republic (e.g., Kyselý, 2009; Hanel and Máca, 2014). Hanel et al. (2016) have examined evolving patterns of rainfall events in the Czech Republic, noting increases in maximum hourly intensity alongside shorter durations, trends. Crhová et al. (2025) created a national public database with updated IDF/DDF curves for the Czech Republic, responding to observed changes, metadata homogenization needs, and the demand for consistent, uncertainty-aware nationwide design standards.

In the context of a changing climate, the traditional assumption of stationarity is no longer tenable. Observations and attribution studies have shown changes in the magnitude and frequency of heavy precipitation and flood behavior across Europe (Blöschl et al., 2019), and climate model projections indicate further increases in the intensity of extreme precipitation in many regions (IPCC, 2021). This motivates the integration of regional climate model outputs with non-stationary extreme-value methods when updating design rainfall estimates to ensure that infrastructure remains robust under plausible future climate trajectories.

This paper provides a comprehensive review of the historical evolution, current practice, and emerging approaches to design rainfall estimation in Slovakia. It synthesizes over a century of methodological development, highlights the importance of modern probabilistic and climate-informed techniques, and identifies current challenges and research gaps in adapting hydrological design to non-stationary conditions. By connecting past, present, and future perspectives, the study aims to support national and regional efforts toward climate-resilient water management and urban planning.

Understanding the rainfall regime of a given territory requires knowledge of extreme short-duration precipitation, such as convective showers or torrential rains generated within an air mass or along a cold front. Such events can reach very high intensities, producing flash floods in heatwater streams, overloading sewer networks (Sokáč et al., 2025; Onderka and Pecho, 2019; Pekárová et al., 2012), and accelerating erosion.

Because rainfall intensity is a key input to runoff estimation methods, its processing strongly influences the calculated peak runoff coefficients and, consequently, the reliability of flood hazard assessments in small catchments (Paulíková et al., 2024). For direct peak flow values calculation on small streams, methods used for the sewer systems hydraulic design in large cities is often applied (Bedient et al., 2008; Chow, 1964; Dub 1947; Pekárová et al., 2012).

History of ombrographic measurements

Precipitation, as one of the key meteorological elements, has been observed and recorded at individual meteorological stations since the very beginning of institutionalized meteorological observations in the territory of present-day Slovakia, that is, since the mid-19th century. A significant impetus for the establishment of the basic rain gauge network came with the founding of the Royal Hungarian Meteorological Institute in 1870, after which the number of stations recording precipitation steadily increased over the following decade.

The historical development of self-recording rain gauges is outlined here because these instruments, though rarely described concisely in regional literature, were fundamental for obtaining continuous records and deriving short-duration rainfall intensities essential for estimation of rainfall design values. The first recording rain gauge used in the station network on the territory of present-day Slovakia was the Hottinger weighing ombrograph of Swiss manufacture (Fig. 1). Its use is documented at the stations Stará Ďala (Ógyalla in Hungarian, today Hurbanovo) and Krásno. The Central Hungarian Observatory in Stará Ďala was equipped with this proportionally large instrument as early as 1893, when the station was elevated to observatory status.

By 1900, ten Hungarian stations including those in Stará Ďala, Kremnica, and Kežmarok were equipped with new float-type ombrographs of the Hellmann design (or, less frequently, Hellmann–Fuess), of German manufacture, with a catchment area of 200 cm² (Fig. 1). As early as 1899, however, a weighing ombrograph of domestic design, known as the Anderkó–Bogdánfy type (sometimes simply Anderkó), had been tested. This device was officially introduced into the observation network in 1902. It also had a 200 cm² catchment area, but unlike the Hellmann model, it allowed measurements during freezing periods with solid precipitation. On the other hand, it was less accurate, mainly because of its higher sensitivity to wind.

At stations where both instruments were operated (for example, Stará Ďala), the Hellmann ombrograph was used during most of the year when liquid precipitation prevailed, while during the winter period it was replaced by the Anderkó–Bogdánfy ombrograph. The oldest preserved ombrographic chart recorded by the Hellmann-type selfrecording raingauge at the Stará Ďala station is shown in Fig. 2. During the interwar period, the Polish Iszkowski float-type ombrograph with a catchment area

of 500 cm² became partly used in the Slovak part of Czechoslovakia; this type had already been employed in the Czech lands since the turn of the 19th and 20th centuries. In the second half of the 20th century, the most widespread recording instrument became the Metra IBA float-type ombrograph of Czechoslovak manufacture, with a catchment area of 250 cm². This instrument is still used at selected stations, typically during the April–October observation season. Less frequently, the monitoring network also included Gansser float-type ombrographs (250 cm²), and, on rare occasions, Sprung–Fuess weighing ombrographs were used as well (Maurer 1884; Hellmann 1897; Konkoly-Thege 1898a; Konkoly-Thege 1898b; Anderkó 1901; Anderkó 1904; Kopecký 1923; Róna 1925; Hrubeš and Kocourek 1956; Collective of authors 1960; 1966; 1968; 1969).

Foundations of Design Rainfall Estimation

The estimation of design rainfall intensities has developed over more than a century, shaped by the evolving needs of engineering practice, advances in statistical science, and changing perspectives on climate variability. What began in the 19th century as empirical assessments based on observed maxima gradually transformed into systematic methodologies for sewer design, hydrological analysis, and flood protection. The early 20th century introduced the first intensity–duration relationships, while the mid-century brought a decisive shift with the advent of extreme value theory and probabilistic frequency analysis. Later refinements, including regional frequency approaches and Bayesian frameworks, further advanced the reliability of design

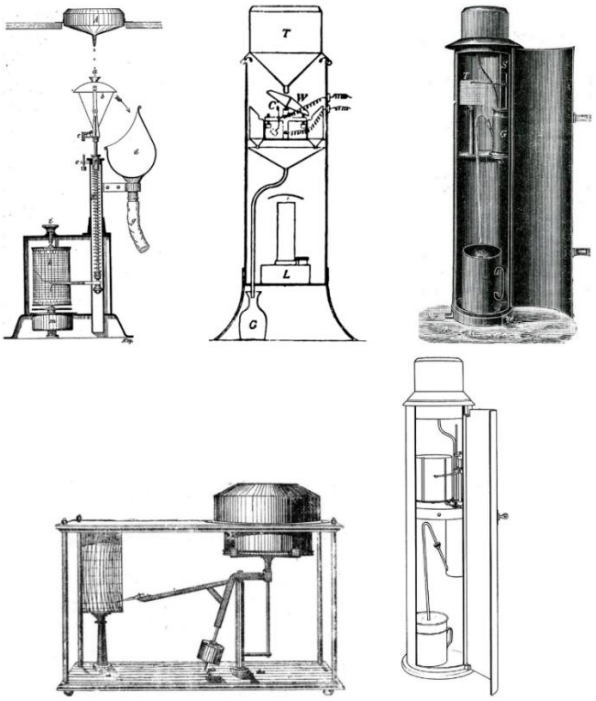


Fig. 1. The most widespread types of ombrographs used throughout the history of atmospheric precipitation measurements in Slovakia. Upper row, from left: Hottinger weighing ombrograph (Maurer, 1884), Sprung–Fuess weighing ombrograph with electric transmission (Sprung and Fuess, 1889), and Hellmann float-type ombrograph (Hellmann, 1897). Lower row, from left: Anderkó–Bogdánfy weighing ombrograph (Anderkó, 1901) and Czechoslovak Metra IBA float-type ombrograph (Slabá, 1972).

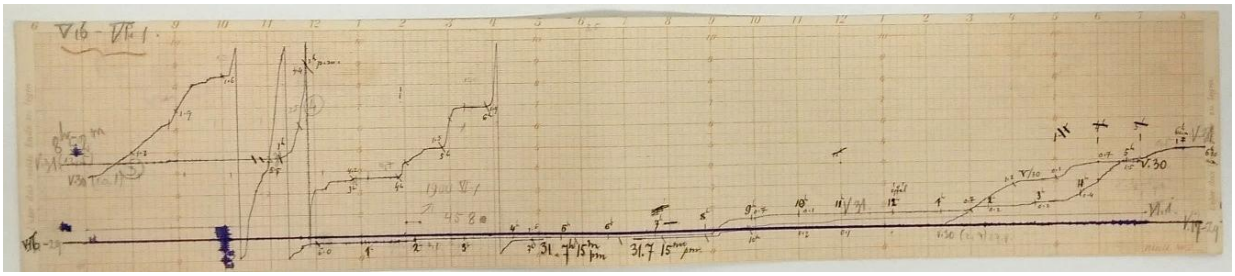


Fig. 2. The oldest preserved ombrographic chart recorded by the Hellmann-type selfrecording raingauge at the Hurbanovo station (Ógyalla), showing the rainfall record from May 16 to June 1, 1900. Two rainy days occurred on May 30–31, while a rainless period was observed between May 16–29.

estimates. Today, in the context of a non-stationary climate, design rainfall estimation increasingly integrates reanalysis data and regional climate model outputs, ensuring that methods remain relevant for infrastructure designed to operate under future conditions.

Historical Evolution of Design Rainfall Estimation Methods

The evolution of design rainfall methodologies did not take place in isolation as a purely climatological discipline, rather it was directly motivated by engineering practice, particularly the need for reliable sewer network design in European cities. A key role was played by Kuichling (1889), who first systematically applied rainfall intensity in the design of large urban drainage systems. His work represents the first quantitative relationship between rainfall intensity, catchment area, and design discharge. This approach laid the foundation of the so-called *rational method*, which in the following decades became standard in sewer network design. The rational method (Bedient et al., 2008; Chow 1964; Dub 1947) assumes that the maximum runoff from a catchment occurs when rainfall duration is at least equal to the catchment's time of concentration. In such a case, the design discharge Q_{max} can be expressed as:

$$Q_{max} = C\ i\ A, \tag{1}$$

where

Q_{max} is the design discharge [$m^3\ s^{-1}$],
C is the dimensionless runoff coefficient
i is the design rainfall intensity [mm min^{-1}],
A is the catchment area [km^2].

By the late 19th century, the first systematic attempts emerged to estimate short-duration rainfall intensities in order to provide design values for urban drainage networks. Kämptz (1831) was probably the first to highlight the need to calculate rainfall intensity for different durations in his Textbook of Meteorology I (p. 499) when analyzing rainfall extremes. Later, the problem of intense rainfall was systematically studied by Symons (1886), Lindley (1911), Hellmann (1916), and Haeuser (1919). Kaßner (1919) was the first to establish unifying criteria for assessing rainfall extremity by comparing methods developed in the United States, England, Switzerland, and Germany. These criteria later formed the basis of Wussow criterion (1922). For the Upper Danube Basin, short-duration maxima were analyzed by Bartošek (1914), who derived maximum and average intensities for this locality (Table 1).

Before the mid-20th century, design rainfall values were typically derived from simple counts of events rather than from fitted probability distributions. Engineers relied on empirical summaries of observed records, often presented in contingency or frequency tables showing how many times rainfall of a certain intensity or duration occurred within the observation period. Such methods provided a basic measure of recurrence but did not allow extrapolation beyond the length of record. As a result, design values were often defined as the highest observed rainfall total, sometimes increased by a safety margin. The major breakthrough came with the introduction of extreme value theory, especially the Gumbel distribution, which enabled the statistical modeling of tail behavior and the estimation of return periods far beyond the observed data. Later refinements by Cunnane and others standardized probability plotting positions and goodness-of-fit testing, marking the transition from empirical frequency counts to modern statistical frequency analysis.

Historical overview of sub-daily design values of rainfall

The origins of rainfall design values in Slovakia are closely tied to the early development of urban sewerage systems in Central Europe. A particularly influential figure was Sir William Heerlein Lindley (1853–1917), a British engineer and son of William Lindley, one of the most prominent urban planners of the late 19th century. Lindley specialized in sewerage and wastewater treatment projects, which required careful consideration of the frequency and intensity of extreme rainfall to properly dimension sewer profiles. His designs, including the Prague sewer system and the wastewater treatment plant at Bubeneč (1895–1906), became benchmarks for engineering practice in the region, with long-lasting influence that extended across Europe, from Frankfurt and Hamburg to Warsaw, Kyiv and Bucharest.

At the turn of the 19th and 20th centuries, systematic approaches to sewer network design began to emerge, and with them the first attempts to formalize rainfall design values. Among the early contributions, Knauff (1902) developed methods for runoff estimation in sewer systems, while Böhm (1911) and Breitung (1912) introduced early statistical concepts for analyzing rainfall intensities from the perspective of extreme events. Frühling (1910), in his extensive handbook *Wasserbau*, summarized principles of sewerage construction, including rainfall as a key design input.

These efforts also resonated in the Slovak and broader Danube basin context. Bartošek (1914) provided one of the first regionally comprehensive evaluations of maximum rainfall totals for the upper Danube, deriving generalized relationships between rainfall intensity, rainfall duration, and mean annual precipitation. His formula, applicable even to ungauged locations, can be regarded as an early precursor to modern intensity–duration–frequency (IDF) curves.

Later, the design of water management structures increasingly began to account for the rarity of rainfall intensities by introducing probabilistic concepts. Engineers and hydrologists started to evaluate the probability of exceedance of a given intensity, leading to the concept of return period, defined as the reciprocal of the frequency of rainfall of a given or greater intensity. This allowed for a quantitative assessment of the risk of extreme rainfall events and became the cornerstone of rainfall design values.

The beginnings of systematic evaluation of extreme rainfall intensities in the former Czechoslovakia date back to the period 1918–1938. Intense rainfall was also studied by Horák (1910), who analyzed maximum totals in Moravia. An important step forward for sewer network design methodology was Jůva (1928), one of the first works in Czechoslovakia to introduce innovative approaches for applying design rainfall intensities in sewer system design. One of the earliest technical handbooks was *Návod pro hydrologickou službu č. 8* (Manual for Hydrological Service No. 8), published in 1934 by the State Institute for Hydrology and Hydrotechnics of T.G. Masaryk, which at the time represented a modern approach to estimating design rainfall intensities. The first hydrological basis for sewer network design in Slovakia appeared in Dub (1940). Just as in Germany and Switzerland, *Návod pro hydrologickou službu č. 8* relied on processing ombrographic records, similar to the German technical manuals (Reinhold, 1937; 1940) prepared by the German *Abwassertechnische Arbeitsgemeinschaft* (Wastewater Technical Working Group) under the German Construction Society.

In Czechoslovakia, rainfall intensities were processed separately for Slovakia and for the Czech lands. Trupl (1958) compiled rainfall intensities for Bohemia and Moravia using data from 98 ombrographic stations. In Slovakia, the earliest study was undoubtedly Dub (1940), who processed short-duration rainfall for 10 locations. Design intensities for these locations were published in graphical and tabular form in Regime of Floods on Small Streams (Dub, 1947), which at the time served as the only available basis for estimating maximum runoff in small Slovak catchments.

In 1973, Šamaj and Valovič published *Proceedings No. 5 of the Slovak Hydrometeorological Institute – Intensities of Short-Duration Rainfall in Slovakia*, in which they processed data from 68 locations. Interestingly, the estimation method from *Návod pro hydrologickou službu č. 8* was still applied in this work, despite the availability of more advanced probabilistic methods at the time. Šamaj and Valovič later also experimented with frequency analysis (using the Gumbel distribution on annual maxima), but their results remained unpublished. Through archive research at the Slovak Hydrometeorological Institute, we were able to access these results, which form part of our ongoing comparative studies.

Moreover, alternative approaches to construct IDF relationships based on the fractal properties of rainfall, which implies scaling invariance, were developed.

The scaling of short-term rainfall refers to the analysis and modeling of precipitation patterns over relatively short time intervals, typically ranging from minutes to hours. This concept is crucial in hydrology, meteorology, and climate science for understanding the temporal variability of rainfall events and their impacts on various natural and human systems. Scaling analyses aim to characterize the statistical properties of rainfall, such as intensity, duration, frequency, and spatial distribution, at different temporal scales. Techniques like rainfall disaggregation and stochastic modeling are employed to extrapolate short-term rainfall data to longer durations or larger areas, aiding in water resource management, flood forecasting, urban planning, and climate change adaptation efforts. Understanding the scaling behavior of short-term rainfall is essential for mitigating risks associated with extreme weather events and ensuring the resilience of vulnerable communities and ecosystems.

Scaling formulas were proposed to extending the IDF relationships from (usually) daily time scale to shorter time intervals based on scaling properties of rainfall in recent studies, e.g., Gupta and Waymire (1990) studied the concepts of simple and multiple scaling to characterize the probabilistic structure of the precipitation process, Koutsoyiannis and Foulfoula-Georgiu (1993) used a scaling model to predict storm hyetographs. Menabde, et al. (1999) showed that based on the empirically observed scaling properties of rainfall and some general assumptions about the cumulative distribution function for the annual maxima of mean rainfall intensity, it is possible to derive simple IDF relationships. Hubert et al. (1998) used a multifractal point of view on rainfall IDF curves, Yu, et al. (2004) developed regional IDF formulas for non-recording sites in Taiwan, Molnar and Burlando (2008) examined the variability of scaling exponents in a mountainous region.

In Slovakia, the scaling properties of short-term rainfall were first investigated by a group of authors from the Department of Land and Water Resources Management at STU Bratislava. These authors were the pioneers in testing the scaling properties of short-term rainfall in Slovakia. They applied the simple scaling method of rainfall intensities to daily rainfall data from selected stations across the country (e.g., Bara et al., 2008; 2009, 2010a, b). Later, the seasonal variability and the influence of scaling properties on monthly short-term rainfall intensities were analyzed (e.g. Kohnová et al., 2018). Foldes et al. (2018) examined the future changes of the scaling exponent up to the year 2100, while Kohnová et al. (2016) investigated the applicability of Hardy's multiquadric method for interpolating the scaling exponent as an indirect approach to estimate IDF curves.

A qualitative step forward was made with the publication of Onderka and Pecho within the National Climate Programme of the Slovak Republic (Volume 17/22). This work represents the first comprehensive publication since the early work of Šamaj and Valovič (1973) to systematically process design intensities of short-duration rainfall across Slovakia. It builds on the latest advances in the statistical analysis of hydrometeorological data and is based on one-minute rainfall records from the state monitoring network of the Slovak Hydrometeorological Institute, covering approximately 1990–2021. Both digitized ombrograph records and automatic rain-gauge data were included. In total, 150 sites were analyzed—the largest dataset of its kind at the time of publication. The resulting design rainfall values were presented as local estimates in the form of tables and graphs. Of particular note is the application of Bayesian inference, which enabled

explicit quantification of uncertainty in both the model parameters and the estimated design rainfall values, marking a methodological departure from the traditional frequentist framework. A similar Bayesian approach has also been implemented by MeteoSwiss, which also employs posterior sampling and probabilistic quantile estimates in Swiss atlas of IDF curves (Fukutome et al., 2018).

The most important approaches of estimating design rainfall intensities are summarized in Table 1.

Modern approaches now use gridded products derived either from the interpolation of station-based design values or from frequency analysis of rainfall totals modeled by reanalyses. These allow the construction of IDF curves even in locations without long observational records. Regional frequency analysis (RFA) methods also play an important role, as they combine information from multiple locations to reduce uncertainty in design rainfall estimation. Current research,extends the use of RFA to the national scale, integrating the most recent datasets including outputs from regional climate models. This makes it possible to investigate projected changes in the statistics of extreme rainfall for future periods.

To illustrate the evolution of methodological approaches

Table 1. Overview of methods used by various authors for estimation of design values of rainfall

Author(s)	Concept	Mehodology description / fundamental equations	Explanatory notes / Deliverables
Lindley (1911)	Local estimates	IDF curves fitted with a simplified equation: $i = \frac{C}{t^{\alpha}}$ (1)	i is rainfall intensity [e.g. l s^{-1} ha^{-1}], C and α are local parameters, t denotes the duration [min] of rainfall. This equation is applicable only to single locations (i.e., location-specific). Overestimates at very short durations, especially under extrapolation.
Bartošek (1914)	Enveloping + regression	The envelope equation for maximum intensities was derived for the Upper Danube River Basin based on ombrographic data from 1876–1900. It represented one of the earliest attempts to generalize short-duration rainfall intensities across ungauged locations . $i_{max} = 1000\left(\frac{H}{100\,000}\right)^{log(10\,H)^{\left\{0.146\,t^{log[1{,}63\,t^{-0{,}021}]}\right\}}}$ (2) $i_{mean} = i_{max}\left\{0.27\,t^{(0.0014\,t\text{^}0.49)}\right\}$ (3)	$i_{max}\ and\ i_{mean}$ are the maximum and mean intensities [mm h^{-1}]; H [mm] is the mean annual precipitation total for the location under study. The mean intensities are calculated by applying a reduction factor $0.27\,t^{(0.0014\,t^{0.49})}$ to i_{max}. t is duration in hours
Reinhold (1937)	Local estimates by enveloping	IDF curves were fitted using a modified equation (1) that allows for leveling off at short durations: $i = \frac{C}{(t+a)^{\alpha}}$ (4)	$C, a,$ and α are local parameters, t is duration [min]; the exponent α controls the rate at which the intensity–duration curve levels off at shorter durations. This equation is applicable only to particular locations (i.e., location-specific).
Dub (1940; 1947)	Spatially variable estimates	Regionally specific modification of Reinhold's equation (4) using data from the period 1922–1938. $i = \frac{3200}{(t+a)^{0{,}675}(150p)^{\beta}}$ (5)	t is duration [min]; p is the probability of exceedance. Equation is valid for $p > 0.1$. $a = \begin{cases} \frac{5}{t}, & t \le 15\ \text{min}, \\ 0, & 15 < t < 60\text{min}, \\ \frac{t}{30}, & t \ge 60\text{min}. \end{cases}$ The parameter β depends on the average daily precipitation μ during months May–September with precipitation above 0.1 mm: $\beta = \begin{cases} 0.35, & \mu \le 7.5\ mm, \\ 0.30, 7.5\ mm \ge \mu < 88.3\text{mm} \\ 0.25, & \mu \ge 8.2\ mm. \end{cases}$

Šamaj and Valovič (1973)	Local estimates by enveloping + interpolation	Method A: Application of Reinhold's equation (4) to empirically determined quantiles using data from the period 1922–1944 and 1946–1965. Parameters of equation (4) were interpolated in space. Method B: Envelope curves applied to the empirically determined quantiles (local estimates for 68 stations).	Empirical parameters C, α and d have been estimated for 68 locations in Slovakia. Design rainfall for ungauged locations can computed from a map of interpolated parameter α and a map of 15-min ranfall of 1 year return period
Šamaj and Valovič (1980s)-unpublished	Local estimates from annual maxima series	Gumbel distribution function applied to annual maxima series.	Local estimates of quantiles for annual exceedance probabilities AEP=0.5 to 0.01 for durations of 30 minutes to 72 hours. 67 locations in Slovakia.
Urcikán and Imriška (1986)	Interpolation of local estimates derived by Šamaj and Valovič (1973). New nonlinear mathematical model for determining the intensity and design equivalent rainfall depth in Slovakia	$i = \frac{K}{t^a + B}$ (6) $K = i_{15}(15^{\propto} + \beta)\frac{p^{-\gamma} - D}{1 - D}$ (7) $a = \alpha\, p^{\alpha_1}$ (8) $B = \beta\, p^{-\beta_1}$ (9)	where p is probability of exceedance; i is rainfall intensity [l s^{-1} ha^{-1}]; t is duration (min); and parameters estimated for 68 locations in Slovakia i_{15}; α; α_1; β; β_1; γ and D. The empirical parameters were estimated on the same dataset as used by Šamaj and Valovič (1973). Local estimates are also possible to interpolate for ungauged locations.
Kupčo (1985; 2021)	Regional analysis (pooling)	Pooling data from raingauges within two statistically homogeneous regions. Homogeneity tested with variance analysis.	Regionalized estimates of sub-daily rainfall quantiles for two homogeneous regions.
Bara et al. (2008; 2010a; 2010b)	Statistical downscaling Local estimates of scaling exponents	$I_d \overset{dist}{=} \lambda^{-\beta} I_{\lambda d}$ (10) Scaling equation see e.g. Menabde et al., 1999; Yu et al., 2004 Testing scaling properties of short term rainfall in Slovakia Sensitivity analysis of scaling exponents	Testing scaling properties and deriving scaling exponents, estimation of design rainfall for varoius duration and periodicity. Comparison to IDF curves of Šamaj and Valovič (1973). Analysis of spatial properties and interpolation of scaling exponents.
Látečková, et al. (2011)	Statistical downscaling Local and regional approach	Sesonal analysis of short term rainfall in Slovakia, monthly derived IDF curves,	Estimation of scaling exponents IDF curves derived for the warm season (april–october) and months April to October for the duration 5 up to 1440 min and periodicity up to 0.01 for 63 raingague stations in Slovakia, period 1996–2008 or 1961–2005
Földes et al. (2018)	Statistical downscaling	Use of climate change scenarios from Community Land Model (CLM)	Output from CLM scenario used for estimation of scaling exponents in historical (1961–2020), near future (2031–2070), and far future (2071–2100) periods. Comaprison of changes in scaling exponents, IDF curves and design values of rainfall durations were 60, 120, 180, 240, and 1440 minutes in 31 stations
Kohnová et.al. (2016)	Regional estimates of IDF curves	Regionalisation of scaling exponents on the whole territory of Slovakia	Regionalison of scaling exponents using radial basic function
Onderka and Pecho (2022)	Local estimates	Annual maxima series were extracted from rain gauges located at 150 loctions in Slovakia (1995–2022). Generalized Extreme Value distribution was used with parameters and quantile uncertainties estimated by Bayesian inference in conjunction with Markov Chain Monte Carlo (MCMC) sampling.	Quantiles of rainfall with durations from 5–240 minutes and annual exceedance probabilities AEP = 0.5 – 0.001 with 90% credibility intervals are available.

Onderka (2024) – unpublished	Local estimates	The Langbein formula (Lnagbein 1949; Chow, 1964) was applied to the results obtained by Onderka and Pecho (2022) in order to derive probabilities of exceedance p.	Quantiles of rainfall with durations from 5–240 minutes with exceedance probabilities p = 0,639 – 0.001 (i.e. return periodes T=1–1000 years) are available.
Onderka et al. (2023)	Gridding (spline with tension + elevation as a covariate	To incorporate the effects of orography on the spatial pattern of rainfall intensities we applied the regularized spline with tension approach (Hofierka et al., 2002; Mitasová and Mitas, 1993). A DEM model was used as a covariate to interpolate the locally estimated design values of rainfall intensities derived by Onderka and Pecho (2022).	224 *GeoTiff* raster layers with rainfall intensities corresponding to return periods 2, 5, 10, 20, 30, 50 and 100 years, and rainfall durations lasting 5, 10, 15, 20, 30, 40, 50 and 60 minutes; 90 minutes, and 2, 3, 6, … up to 24 hours.
Onderka et al. (2025)	Reginal analysis (pooling)	Regional analysis of sub-daily rainfall intensities by the method described in Kupčo (1985) and Onderka et al. 2025). The Fuzzy C-Means (FCM) clustering was deployed to classify rainfall durations and determine the optimal number of clusters. The Generalized Extreme Value (GEV) distribution was fitted to module coefficients, and Bayesian inference was used to estimate 90% credible intervals, improving the reliability of frequency estimates.	Regional curves of 5-240 minute rainfall quantiles for 2 homogeneous regions and probabiolities of exceedance p = 0,639 – 0.001
Onderka et al. (2024)	Adjustment for climate change	A non-stationary Generalized Extreme Value (GEV) model was applied to bias-corrected EURO-CORDEX regional climate simulations (RCP8.5) to estimate future sub-hourly rainfall intensities at 75 Slovak stations, using scaling relationships between 5- and 180-minute quantiles derived from high-resolution observations.	Preliminary projections of sub-daily rainfall quantiles for Slovakia by 2080, indicating a 10–20 % increase in 2-year and about 5 % increase in 100-year rainfall intensities, forming the first national-scale, climate-adjusted IDF estimates aligned with emerging non-stationary design standards.

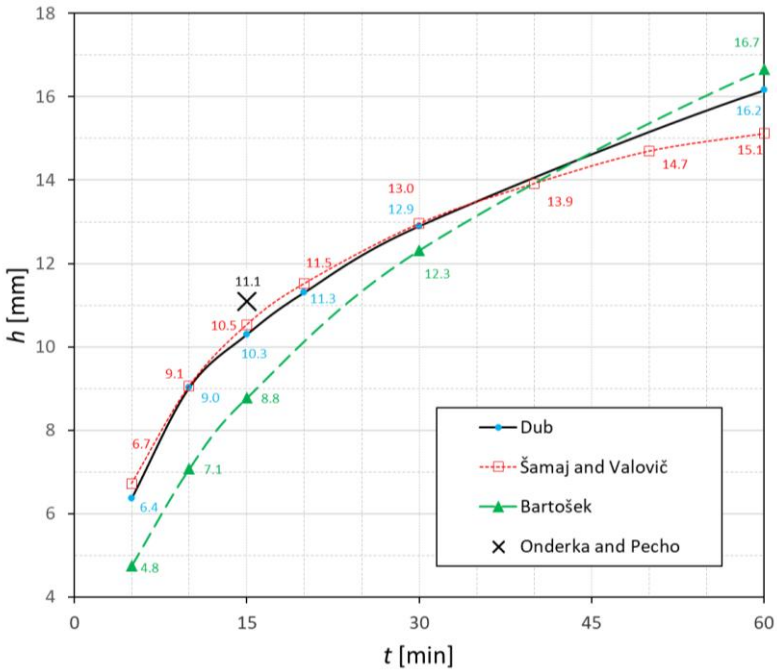


Fig. 3. Comparison of design rainfall values (1-year return period) estimated for Bratislava by various authors (for detailed description of the various approaches refer to Table 1: a) Dub (1940; 1947); b) Šamaj and Valovič (1973) – Method B; (c) mean values i_{mean} estimated by the equation of Bartošek (1914); Note that i_{mean} derived from Bartošek's equation represents the 1-year return period (Jůva, 1928, page 33), and it serves here only as a historical reference. Fifteen-minute intensities are also shown for the recent results of Onderka and Pecho (2022) who applied the GEV distribution to annual maxima series. The 15-minute intensity of Onderka and Pecho (2022) was further adjusted using the Langbein formula (Chow, 1964).

to estimating short-duration design rainfall in Slovakia, Fig. 3 compares results obtained for Bratislava by several key authors representing different periods and analytical frameworks. From Fig. 3 it can be seen that for the 1-year 15-minute rainfall depth at Bratislava-Koliba, the simulation based on Bartošek's equation yields 8.8 mm, while Šamaj and Valovič (1973) indicate 10.5 mm, Dub (1940; 1947) 10.3 mm, and Onderka and Pecho (2022) 11.1 mm. Although a detailed comparison is beyond the scope of this paper, the observed differences reflect both the varying observational periods and the distinct methodological principles, from empirical and enveloping techniques to modern probabilistic and Bayesian inference frameworks.

Design values under the changing climate

Global warming is strongly linked to cumulative greenhouse gas emissions, with recent data showing CO_2 concentrations reaching 417 ppm, which is about 50% higher than pre-industrial levels. This persistent increase reflects both anthropogenic emissions and feedback mechanisms in the climate system (Schwalm et al., 2020). Among the IPCC Representative Concentration Pathways, RCP8.5 best matches recent emission trends, corresponding to an additional 8.5 W m^{-2} of radiative forcing by 2100 and closely aligning with observed cumulative emissions from 2005–2020 (Friedling et al., 2022). In response to the growing need for climate-informed design guidance, NOAA has recently launched the Atlas 15 (https://water.noaa.gov/about/atlas15), which aims to incorporate non-stationarity and climate-model information into the next generation of rainfall-frequency estimates (Perica et al., 2025). This reflects a broader global effort to bridge the gap between climate science and hydrological design practice. Using the RCP8.5 scenario and an ensemble of bias-corrected EURO-CORDEX regional climate model simulations (RACMO22E, REMO2015, CCLM4-8-17, and RCA4), Onderka et al (2024) applied a non-stationary Generalized Extreme Value (GEV) model to estimate sub-hourly rainfall intensities at 75 stations in Slovakia. The analysis relied on high-resolution rainfall records, from which scaling relationships between 5- and 180-minute quantiles were derived to extend design-scale estimates. Their projections indicate that by 2080, rainfall intensities with a 2-year return period may increase by 10–20%, while 100-year return levels could rise by about 5% relative to 1991–2021. These projected changes are physically consistent with the Clausius–Clapeyron scaling of precipitation with temperature (Ban et al., 2015; Blenkinsop et al., 2015; Lenderink et al., 2017; Onderka and Pecho, 2021). Although moderate in magnitude, such increases may be sufficient to challenge the capacity of existing stormwater and drainage systems, particularly in rapidly urbanizing regions. The findings of Onderka et al. (2024) complement earlier pan-European analyses (Poschlod et al., 2021; Berg et al., 2019), which often underestimated short-duration extremes or lacked regional coverage for Slovakia. By filling this spatial gap, the results presented by Onderka et al. (2024) provide the first regionally consistent projections of sub-daily rainfall quantiles for Slovakia based on high-resolution climate model ensembles. They also demonstrate the importance of integrating non-stationary methods into future IDF curve development, in line with emerging international practices such as *NOAA Atlas 15*.

In Slovakia, there is an equally strong need for initiatives similar in scope and ambition to *NOAA Atlas 15*, designed to provide spatially consistent and climate-informed precipitation frequency estimates. Establishing such a framework would represent a major step toward integrating non-stationarity and climate-model information into hydrological design practice, supporting the development of resilient cities and critical infrastructure under future climatic conditions. Beyond national benefits, a coordinated European effort could harmonize design rainfall standards across borders, improve climate adaptation planning, and ensure that infrastructure investments remain robust in the face of intensifying precipitation extremes.

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