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Intensity–Duration–Frequency (IDF) Design Rainfall Framework for Türkiye: A Practical Tool for Engineering Applications

Fatih TOSUNOGLU[1*]
Thomas Rodding KJELDSEN[2]

ABSTRACT

This study presents a new nationwide intensity–duration–frequency (IDF) framework for estimating extreme rainfall events for Türkiye. The IDF model is based on sub-daily rainfall records from 193 meteorological stations. Standard-duration annual maximum series (30 minutes to 24 hours) were analysed. Data homogeneity was evaluated using the Standard Normal Homogeneity Test, Buishand Test, and Pettitt Test and the results indicate that the maximum series are homogeneous with no significant anthropogenic influence. Trend analyses using the Mann–Kendall test reveal pronounced spatial and duration-dependent variability. Short-duration extremes (30 min–5 h) show statistically significant increasing trends, especially in western and southwestern coastal regions, whereas longer durations (6–24 h) display more heterogeneous and regionally balanced patterns. Four candidate two-parameter probability distributions (Lognormal, Gamma, Weibull, and Logistic) were assessed using the Akaike and the Bayesian Information Criterion. Results indicate a clear dominance of the Lognormal distribution across nearly all durations and regions, with the Gamma distribution serving as a secondary alternative, particularly at longer durations. Beyond statistical evaluation, the study introduces a unified and practitioner-oriented national IDF tool that enables direct extraction of design rainfall intensities for selected durations and return periods. This standardised framework enhances consistency in hydraulic design and supports climate-resilient infrastructure planning. The findings provide a robust foundation for national-scale rainfall frequency analysis while highlighting the need for future integration of non-stationary modelling approaches.

Keywords: Intensity–Duration–Frequency (IDF), extreme rainfall, lognormal distribution, Mann–Kendall trend test, practitioner-oriented national IDF tool, Türkiye.

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1 Erzurum Technical University, Department of Civil Engineering, Erzurum, Türkiye
ftosunoglu@erzurum.edu.tr - https://orcid.org/0000-0002-8423-1089

2 University of Bath, Department of Architecture and Civil Engineering, Bath, UK
trk23@bath.ac.uk - https://orcid.org/0000-0001-9423-5203

* Corresponding author

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1. INTRODUCTION

Extreme rainfall events is a critical driver of hydrological hazards, including urban flooding, flash floods, landslides, and infrastructure failure. Thus, estimating the frequency and intensity of such events under climate variability and change is a key challenge to develop mitigation strategies. Among the most widely used approaches in hydrologic design and water resources engineering are Intensity–Duration–Frequency (IDF) relationships, which provide a statistical representation of the relationship between rainfall intensity, storm duration, and return period. IDF relationships are typically derived from long-term precipitation records using frequency analysis of annual maximum rainfalls for selected durations. Examples of statistical distributions used in the construction of IDF curves include: the Gumbel, the Log-Normal, Generalised Extreme Value, Pearson III and Weibull distributions. For instance, Minh et al. [1] developed the IDF curves for Can Tho City in Vietnam using Pearson III, Log-Pearson III, and Log-Normal distributions, compared them with commonly used empirical formulas, and found that the revised Vietnamese standard with newly calibrated parameters provided the best performance based on efficiency index and root mean square error (RMSE) criteria. Kawara and Elsebaie [2] developed new IDF curves for the Yalamlam area in Saudi Arabia using 30 years of daily rainfall data, applied the Log-Pearson type III and Gumbel distributions, averaged their results, and proposed conversion ratios to estimate sub-daily rainfall for various durations when short-interval data are unavailable. Escobar-González et al. [3] developed IDF curves for a sub-basin in high-altitude Quito, Ecuador, using data from 12 meteorological stations, applying the Log-Pearson type III and Gumbel distributions.

Türkiye presents a unique hydro-climatic setting characterised by strong spatial variability driven by Mediterranean, continental, and Black Sea climatic influences. Orographic effects, seasonal precipitation contrasts, and localised convective storms all contribute to highly heterogeneous rainfall patterns across the country [4, 5, 6]. Consequently, a unified and national-scale IDF framework needs to consider these regional differences in extreme rainfall behaviour. Previous studies in Türkiye have investigated different aspects of extreme rainfall characteristics, IDF relationships, and frequency analysis using both stationary and non-stationary approaches. For example, Aksu et al. [7] analysed the spatial and temporal variability of standard-duration maximum precipitation over the Black Sea Region, while Aksu et al. [8] developed non-stationary IDF curves under changing climatic conditions. Similarly, Haktanir et al. [9] performed regional frequency analyses of annual maximum rainfall series using the L-moments method. Recent studies have also focused on non-stationary modelling of annual maximum rainfall data across Türkiye [10], probabilistic characteristics of maximum rainfall [11]. In addition, regression-based estimation methods for standard-duration maximum rainfall have been proposed by Yerdelen et al. [12], while several local and regional IDF investigations have been conducted for different cities and climatic regions of Türkiye. For instance, Şenocak and Acar [13] modelled short-duration rainfall intensity equations for the Aegean Region, whereas Yüksek et al. [14] investigated rainfall IDF relationships with particular emphasis on the Eastern Black Sea Basin. Alramlawi and Fıstıkoğlu [15] estimated IDF curves using large-scale atmospheric datasets through statistical downscaling techniques. Moreover, the potential impacts of climate change on IDF/ frequency–intensity–duration (FID) relationships have been examined for different regions of Türkiye, including Istanbul [16] and Rize [17].

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Despite these important contributions, previous studies in Türkiye have generally focused on specific regions, selected station groups, or individual methodological approaches. Therefore, a unified, standardized, and practitioner-oriented national IDF framework applicable across the country's diverse climatic regions is still lacking. In particular, limited attention has been given to integrating spatial variability, probability distribution selection, and practical user-interface-based applications within a single comprehensive framework. Many countries worldwide have already developed and published national IDF frameworks to ensure consistency and reliability in hydrological and engineering design applications. Examples include the Australian Rainfall–Runoff methodology [18], the UK Flood Estimation Handbook [19], the national IDF model for Greece developed by Koutsoyiannis et al. [20], and the national IDF framework for Canada proposed by Simonović et al. [21]. These examples demonstrate the importance of national-scale and standardized approaches for supporting consistent design rainfall estimation.

Although numerous academic studies in Türkiye provide statistically rigorous IDF analyses, their outputs are often not directly accessible or easily applicable for operational and engineering practices. Engineers and practitioners require simple and efficient tools capable of rapidly providing design rainfall intensities for different durations and return periods without the need for complex statistical analyses or recalculations. Therefore, this study aims to address these gaps by developing a national-scale IDF framework together with a user-friendly interface/tool for the rapid estimation of design rainfall intensities and IDF relationships at both gauged and ungauged locations across Türkiye. By doing so, the study seeks to bridge the gap between academic research and practical implementation through an accessible and operational decision-support system

Specifically, the objectives of the study are to:

1. Collect, compile, and quality-control long-term daily and sub-daily maximum rainfall records obtained from meteorological stations across Türkiye;
2. Investigate the spatial and temporal variability of daily and sub-daily maximum rainfall extremes;
3. Determine the most appropriate probability distribution functions for modelling daily and sub-daily maximum rainfall records;
4. Develop IDF curves applicable to different climatic regions;
5. Create a practitioner-oriented tool for the rapid estimation of design rainfall intensities and IDF relationships for selected durations and return periods at both gauged and ungauged locations.

By integrating statistical rigor with practical applicability, the proposed framework seeks to bridge the gap between academic research and engineering implementation. The resulting IDF model is expected to support resilient infrastructure planning, improve flood risk mitigation strategies, and contribute to sustainable water resources management in Türkiye.

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2. STUDY AREA AND DATASETS

In this study, a total of 193 meteorological stations across Türkiye were utilised to develop a nationwide IDF framework. Among these, 171 stations provide continuous observations spanning from 1970 to 2020, while the remaining 22 stations have varying start and end periods. All stations included in the analysis possess sufficiently long record, which is at least 30 years, to ensure statistical significance for frequency analysis. For each station, the annual maximum rainfall series were extracted for 11 standard durations, including 30 minutes, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours, 6 hours, 8 hours, 12 hours, 18 hours, and 24 hours, providing the basis for consistent derivation of IDF relationships across different temporal scales. During the preliminary analysis of the data series, homogeneity tests commonly employed in the literature, including the Standard Normal Homogeneity Test [22], Buishand Test [23], and Pettitt Test [24], were applied. Based on the results of these tests at a 99% confidence level, it was concluded that the observed abrupt changes in the records are natural in origin, and there is no evidence of human-induced effects on the rainfall series. Due to limitations in the overall length of the manuscript, the detailed descriptions and mathematical formulations of these tests are not provided here. Detailed explanations can be found in the following studies [25, 26, 27]. The locations of the meteorological stations used in this study are shown in Figure 1.

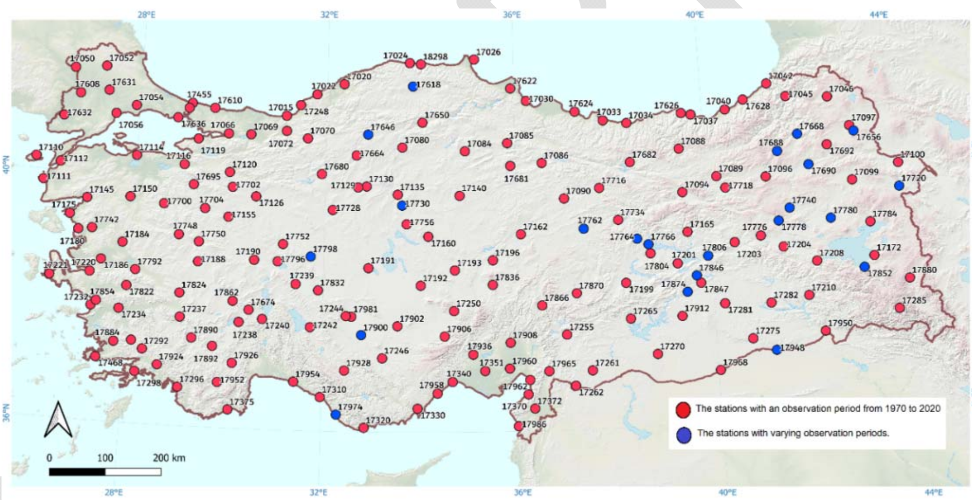

Figure 1 - Map showing the locations of the meteorological stations used in the study

3. METHODOLOGY

3.1. Temporal evaluation of annual maximum series

The temporal behaviour of the Annual Maximum (AMAX) series at each station was evaluated using the Mann–Kendall (MK) trend test, a widely applied non-parametric method for detecting monotonic trends in hydro-meteorological time series [28, 29]. The MK test is particularly suitable for extreme value series because it does not require normality, is resistant to outliers, and performs well with skewed distributions characteristics commonly observed in AMAX data. The mathematical formulation of the MK tests is given as follows;

Consider a time series $x_1, x_2, ..., x_n$ representing annual maxima observed over n years. The MK statistic S is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \tag{1}$$

where the sign function is defined as:

$$sign(x_j - x_i) = \begin{cases} 1; & if\ x_j > x_i \\ 0; & if\ x_j = x_i \\ -1; & if\ x_j < x_i \end{cases} \tag{2}$$

For large samples (n>10), the Variance of S approximately follows a normal distribution with mean and it is calculated by:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p - 1)(2t_p + 5)}{18} \tag{3}$$

where t_p is number of data points in the p-th tied group and g represents the number of tied groups. The standardised Z-statistic is then calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}; & if\ S > 0 \\ 0\ ; & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}; & if\ S < 0 \end{cases} \tag{4}$$

The null hypothesis H_0 assumes no trend, while the alternative hypothesis H_1 indicates a monotonic trend [30]. The trend is considered statistically significant if $|Z| > Z_{\alpha/2}$. $Z_{\alpha/2}$ corresponds to the selected significance level (e.g., 1.96 for α=0.05).

3.2. Probability Distributions for Modelling Annual Maximum Series

In frequency analysis of hydrological extremes, the AMAX series is commonly modelled using continuous probability distributions capable of representing positively skewed behaviour and heavy upper tails. In this study, four widely used two-parameter distributions, namely Weibull, Gamma, Lognormal, and Logistic, were considered as candidate models for each station. To identify the most appropriate distribution for each station, the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) were employed. Both criteria are likelihood-based measures that balance model fit and complexity. These criteria are given by

$$AIC = -2\ln(L) + 2k \tag{5}$$

$$BIC = -2\ln(L) + k\ln(n) \tag{6}$$

where L is represents the maximum likelihood value of the fitted probability distribution function, k is the number of estimated parameters, and n is the sample size. AIC emphasises predictive accuracy and applies a moderate penalty for additional parameters while BIC imposes a stronger penalty for model complexity, especially for larger sample sizes. For each station's AMAX series, the distribution with the lowest AIC and BIC values was selected as the best-fitting model. Using both criteria ensures robustness in model selection by accounting for both goodness-of-fit and parsimony, thereby reducing the risk of overfitting.

Although three-parameter distributions such as GEV, LN3, LP3, and other three-parameter distributions are commonly employed in hydrological frequency analysis and are also recommended in the practices of the Turkish State Meteorological Service (MGM), this study focused on two-parameter probability distributions (Weibull, Gamma, Lognormal, and Logistic). The primary motivation behind this preference was to achieve a more robust, parsimonious, and stable modelling framework for a large-scale national application involving 193 stations and multiple rainfall durations. In general, three-parameter distributions introduce additional uncertainty in parameter estimation and may lead to instability, particularly for relatively short or highly variable AMAX series. The inclusion of extra shape or location parameters can increase sensitivity to outliers and sampling variability, thereby affecting parameter reliability across stations. Since one of the principal objectives of this study was to develop a standardized and practitioner-oriented national IDF framework, reducing uncertainty and ensuring parameter consistency were considered critical priorities. Preliminary analyses additionally demonstrated that the selected two-parameter distributions provided sufficiently accurate representations of rainfall extremes according to AIC- and BIC-based evaluations. Therefore, considering the balance between model complexity, uncertainty, and robustness, two-parameter distributions were preferred in the present study.

4. RESULTS

4.1. Spatial and Temporal Evaluation of The Annual Maximum Series

The Mann–Kendall trend test results for standard-duration maximum precipitation (30 minutes to 24 hours) reveal spatial and temporal variability across Türkiye; see Figure 2 where dark red triangles denote statistically significant positive trends ($Z \geq 1.64$, $\alpha = 0.10$), while dark blue inverted triangles indicate statistically significant negative trends ($Z \leq -1.64$). Light-coloured symbols represent non-significant trends. For the shortest durations (30 minutes and 1 hour), of the existence of positive trends is evident, particularly in western and southwestern Türkiye, including the Aegean and Mediterranean coastal regions. Positive trends signify an increase in the AMAX data over time. Significant positive trends can also be found in parts of the Marmara region and along sections of the Black Sea coast. Negative trends at these short durations are comparatively sparse and geographically scattered, with a few localised clusters in central and eastern Anatolia. This pattern suggests an increase of short-duration extreme rainfall, especially in coastal and densely populated western regions. At intermediate durations (2, 3, 4, and 5 hours), the spatial distribution of trends remains similar, though the number of statistically significant stations slightly decreases compared to the 30-minute and 1-hour durations. Positive trends

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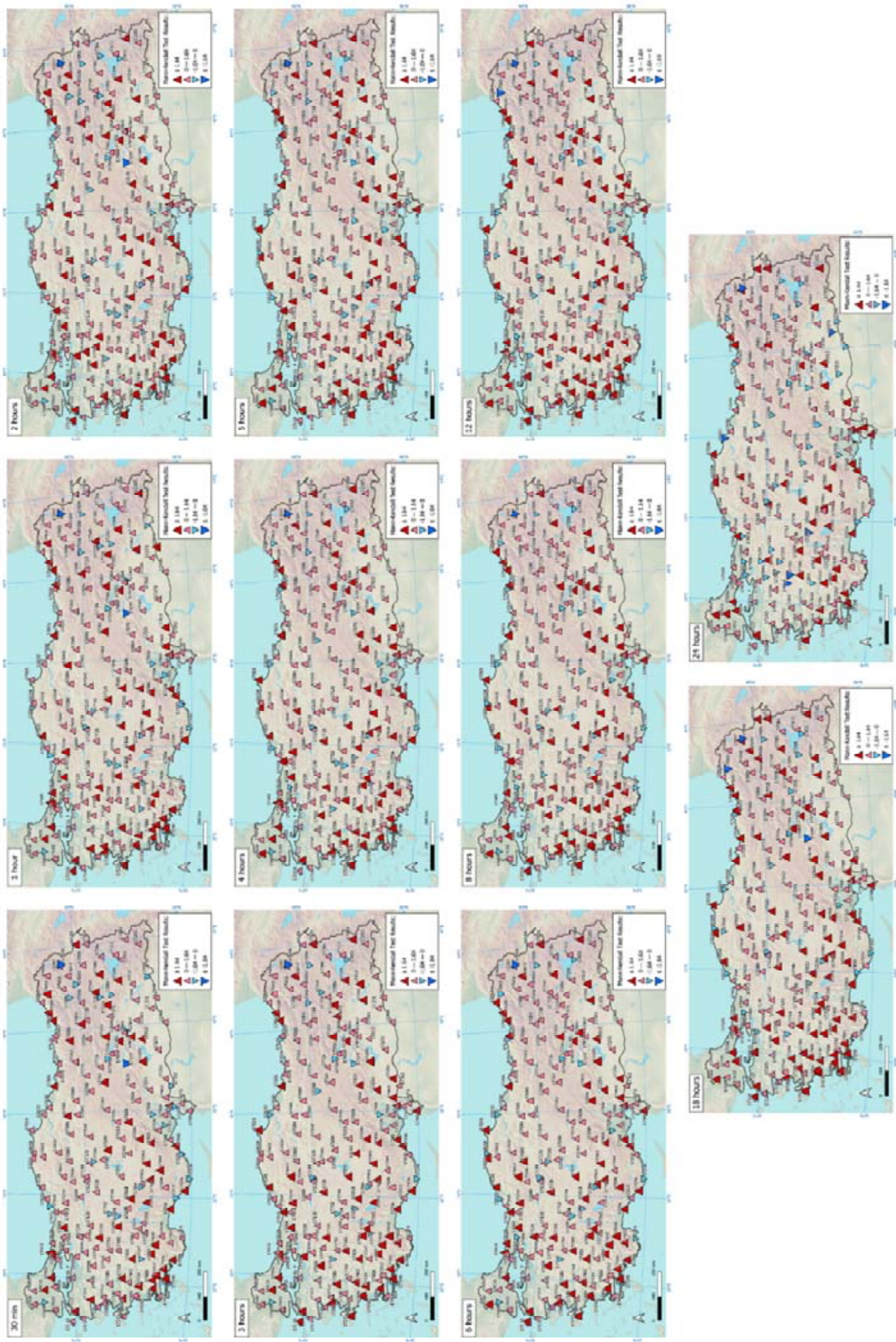

Figure 2 - Spatial distribution of Mann–Kendall trend test results for AMAX rainfall series at different standard durations across Türkiye

continue to dominate western, southwestern, and some northern coastal areas. However, negative trends become more noticeable in central Anatolia and parts of eastern Türkiye, forming more coherent regional patterns rather than isolated points. This indicates that while sub-daily extremes are generally increasing over time in many regions, some interior areas are experiencing either no change or slight decreases in maximum rainfall at these durations.

For longer durations (6, 8, 12, 18, and 24 hours), the pattern becomes more spatially heterogeneous. Although significant positive trends are still prominent in southwestern Türkiye and along parts of the Mediterranean coast, negative trends appear more frequently in eastern and southeastern Anatolia. In the Black Sea region, trends are mixed, with both positive and negative significant stations located relatively close to each other, reflecting complex regional hydroclimatic influences. By 24 hours, the number of significant trends (both positive and negative) appears more balanced compared to shorter durations, suggesting that long-duration extreme precipitation changes are less spatially uniform.

Overall, the results suggest a spatially coherent increase in short-duration extreme rainfall across western and coastal Türkiye, while longer-duration extremes exhibit greater regional variability and a more mixed signal. The concentration of significant positive trends in urbanised and coastal zones is particularly noteworthy, as it implies increasing flash flood potential. These findings highlight the importance of considering rainfall duration as well as spatial dimensions when assessing climate change impacts on extreme precipitation across Türkiye.

4.2. Best-Fitting Probability Distributions for The Annual Maximum Series

The results presented in Figure 3 shows the frequency of preferred distributions across durations at the 193 AMAX series. The results demonstrate that among the four candidate probability distributions (Lognormal, Weibull, Gamma, and Logistic) evaluated for modelling standard-duration (30 min–24 h) AMAX series, the Lognormal (LN) distribution clearly exhibits dominant performance across almost all durations according to both AIC and BIC criteria. For short durations (30 min–3 h), the LN distribution overwhelmingly outperforms the other models, indicating that short-term extreme rainfall intensities are highly positively skewed and well represented by a multiplicative stochastic structure. Although a slight decrease in LN dominance is observed toward longer durations (12–24 h), it remains by far the most frequently selected model, confirming its robustness across temporal scales. The Gamma (GA) distribution emerges as the second most suitable alternative, particularly at intermediate and longer durations, where aggregation effects tend to moderate extreme skewness and produce distributional characteristics that align well with the flexible shape properties of the Gamma model. In contrast, the Weibull (WEI) and Logistic (LOGIS) distributions show consistently low selection frequencies, suggesting limited capability in capturing the heavy-tailed and asymmetric behaviour typical of extreme rainfall data in Türkiye. The agreement between AIC and BIC-based model rankings further strengthens the reliability of these findings, indicating that the superiority of the LN distribution is not driven by model complexity but by its genuine statistical compatibility with the empirical AMAX rainfall series. Overall, the analysis highlights the LN distribution as the most appropriate and stable model for IDF development and extreme

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rainfall frequency analysis across Türkiye, with the GA distribution serving as a secondary alternative for longer durations.

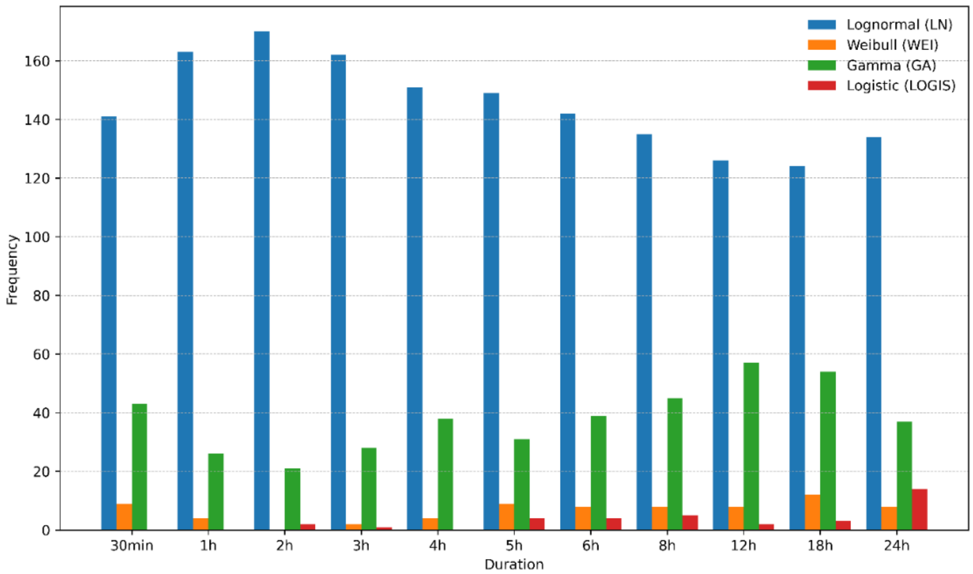

Figure 3. Frequency of Best-Fitting Probability Distributions for Standard-Duration Maximum Rainfall Series in Türkiye

Figure 4 - Spatial distribution of dominant probability models for standard-duration maximum rainfall series across Türkiye (overall evaluation)

Additionally, Figure 4 shows the spatial distribution of the best-performing probability distributions for standard-duration (30 min–24 h) maximum rainfall (AMAX) series across Türkiye. In the Figure 4, the dominant distribution type at each station was determined as the model that most frequently provided the best fit across all durations, and this overall representative distribution was mapped spatially. The results indicate that the LN distribution dominates over most of Türkiye, particularly in central, northern, and eastern regions, highlighting the generally skewed nature of extreme rainfall. The GA distribution appears as the second most common dominant model, mainly in certain coastal and transitional climatic zones. The WEI distribution is dominant at only a limited number of stations, while the LOGIS distribution shows negligible spatial dominance. Overall, the map confirms the widespread robustness of the LN model for extreme rainfall analysis in Türkiye.

4.3. IDF Curves Using Two-Parameter Log-Normal Distribution and IDF Tool Implementation

After identifying the lognormal (LN) distribution as the dominant model for the AMAX series at each station, it was subsequently employed to estimate rainfall quantiles and construct a methodology for creating IDF curves applicable at any location in Türkiye. The mathematical models and algorithms assist in the IDF fitting and updating IDF tool process, as described below:

Firstly, X_d denotes the annual maximum rainfall for duration d, and is assumed log-normal distributed with two parameters as:

$$X_d \sim LN(\alpha_d, \beta_d^2) \tag{7}$$

where α_d and β_d^2 are estimated from the real mean and standard deviation as [31]

$$\alpha_d = \ln \bar{x}_d - \tfrac{1}{2}\ln(CV_d^2 + 1) \tag{8}$$

$$\beta_d^2 = \ln(CV_d^2 + 1) \tag{9}$$

The quantile of the distribution is given as:

$$\begin{aligned} X_{T,d} &= exp(\alpha_d + \beta_d z_T) \\ &= exp\left(\ln \bar{x}_d - \frac{1}{2}\ln(CV_d^2 + 1) + \sqrt{\ln(CV_d^2 + 1)}\, z_T\right) \\ &= \bar{x}_d (CV_d^2 + 1)^{-\frac{1}{2}} exp\left(\sqrt{\ln(CV_d^2 + 1)}\, z_T\right) \end{aligned} \tag{10}$$

where z_T is the $\left(1 - \frac{1}{T}\right)$ quantile of the standard normal distribution. If values of $CV_d$are assumed constant across durations (i.e. $CV_d = CV$ for all values of d), then the only parameter required is the mean at the desired duration $\bar{x}_d$. The mean corresponding to a selected duration can be expressed as a linear function of that duration, as follows:

$$\ln \bar{x}_d = \ln a + b \ln d \quad \leftrightarrow \quad \bar{x}_d = a d^b \tag{11}$$

By combining Eqs. (10) and (11) the design intensity at each site can be estimated as:

$$\frac{X_{T,d}}{d} = \frac{\bar{x}_d}{d}(CV^2 + a)^{-\frac{1}{2}} exp\left(\sqrt{\ln(CV^2 + 1)}\, z_T\right)$$

$$= a d^{b-1} \ln(CV^2 + 1)^{-\frac{1}{2}} exp\left(\sqrt{\ln(CV^2 + 1)}\, z_T\right) \tag{12}$$

Equations (7)–(12) describing the LN2 distribution parameters and quantile estimation were adopted from the standard formulations given by Chow et al. [32], Stedinger et al.[33] and Kite [34].

A key outcome of this study is the development of a user-friendly IDF interface for rapid estimation of rainfall intensities and IDF relationships at gauged and ungauged locations. Using Equation (7–12), the design intensity for each site was computed, and disseminated via an online IDF tool for Türkiye. The online IDF tool allows users to pick any location (site) in Türkiye and derive the IDF-curve for this site, using the model in Eq. (12) in combination with regional frequency analysis. The estimate is derived using weighted average (inverse distance weighting) of the three model parameters a, and b as well as CV_d in Eq. (12) derived from geographically nearby sites where long-term data are available (and thus Eq. (12) has been specified). The tool will enable design rainfall intensity to be derived for rainfall event from 1hr – 48hrs and for return periods between 2 – 1000 years at any geographical location in Türkiye.

User interface: Figure 5 presents the main interface of the developed online IDF framework. The interface was designed to provide a standardized and practical environment for estimating rainfall intensity values and generating IDF relationships for both gauged and ungauged locations across Türkiye. The system allows users to define the location of interest together with key hydrological design parameters, including rainfall duration and return period. Based on the selected inputs, the framework automatically computes the corresponding rainfall intensity estimates using the statistically derived IDF relationships developed in this study. The interface therefore serves as an operational decision-support component that facilitates the practical implementation and accessibility of the proposed national-scale IDF methodology for engineering and hydrological applications.

To calculate design rainfall for any location, one can follow the steps, as follows;

Step 1 Select location: The map in Figure 6 allows the user to navigate and select (left click on mouse) any location in continental Türkiye. One selected, a red pin will be added to the map, indicating the exact location (see Figure 6). The location can easily be adjusted through by repeating this process as many times as required.

Step 2 Select return period: Enter the desired return period in box. The maximum allowed return period is 1000 years.

Step 3 Select rainfall duration: Enter the desired rainfall duration. The duration can be set between 1 to 48 hours.

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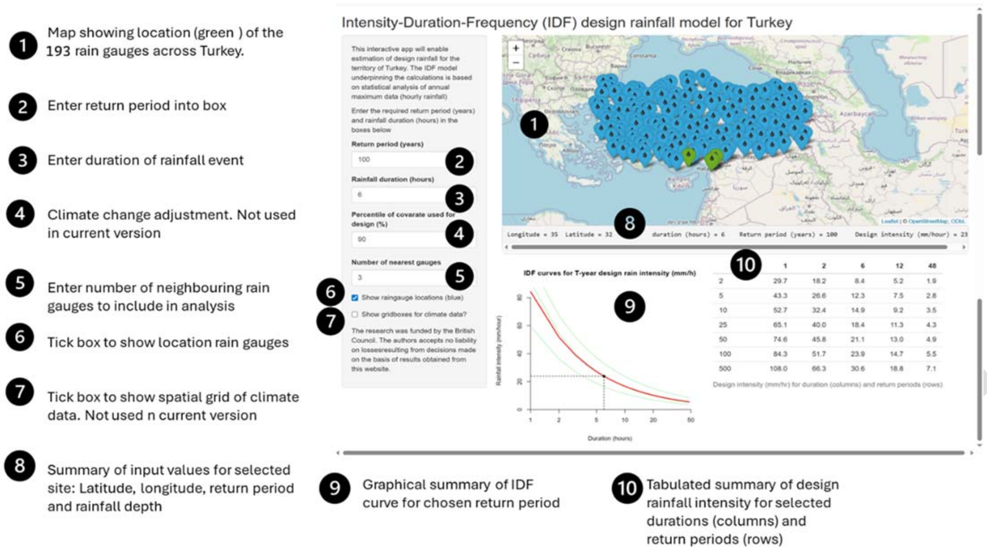


Figure 5 - IDF tool user interface

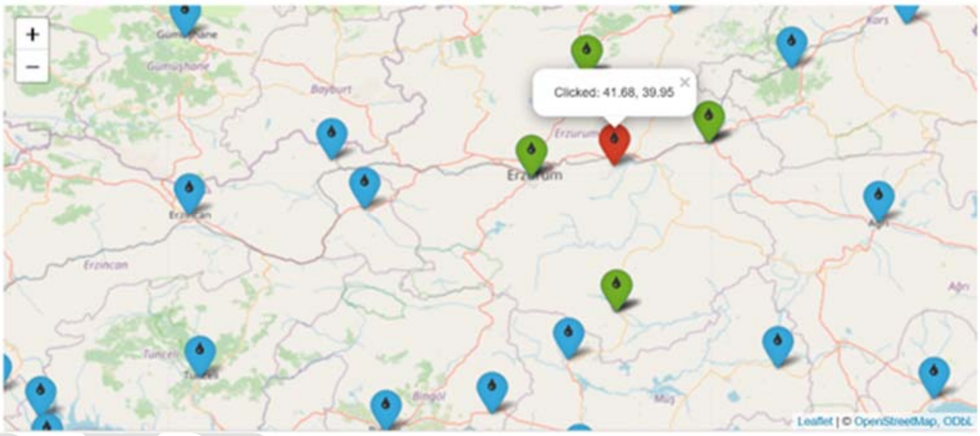
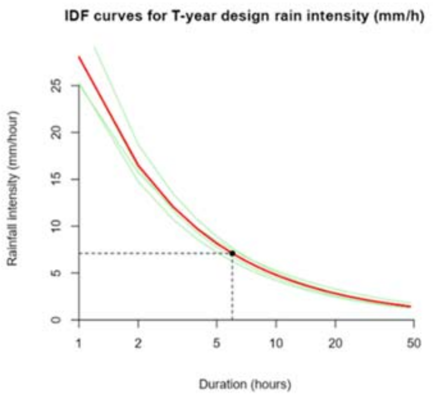


Figure 6 - Example of selecting location near the city of Erzurum (in red colour sign), including the four geographically closest rain gauges (in green colour signs).

Step 4 Select number of neighbouring rain gauges: Enter the desired number of nearby gauges. The number of gauges can vary between 1 and 10. Once a number has been entered, the tool will automatically select the geographically closest sites to be included in the analysis. The selected sites will be indicated by changing the colour of the rain gauge markers from blue to green where green indicate that a site has been selected. An example of selecting a location near the city of Erzurum (shown in red) and identifying the four geographically closest rain gauges (shown in green) is presented in Figure 6.

Once step 4 is completed, the tool will provide a summary of the input variable (latitude and longitude of site, return period and duration of event as well as the resulting design rainfall intensity (mm/hours). The output of the frequency analysis is reported in two locations. The graph shows the relationship between duration (hours, horizontal axis) and design rainfall intensity (mm/hours, vertical axis) for the selected return period. The dashed horizontal and vertical lines indicate the chosen duration. An example of the output graph is shown in Figure 7 (left) corresponding to the location selected in Figure 6. The graph shows four thin green lines, each representing the IDF relationships at each of the four selected nearby sites. The thick red line is the main result and is derived as the average of each of the four green lines. Details of the methodology are provided in the next section. The table in Figure 7 provides a summary of the calculated design rainfall intensity (mm/hr) for typical durations (hours, columns of table) and return periods (years, rows of table).



	1	2	6	12	48
2	11.6	6.8	2.9	1.7	0.6
5	16.0	9.4	4.1	2.4	0.8
10	18.9	11.1	4.8	2.8	1.0
25	22.6	13.3	5.7	3.4	1.2
50	25.3	14.9	6.4	3.8	1.3
100	28.1	16.5	7.1	4.2	1.4
500	34.6	20.3	8.8	5.1	1.8

Design intensity (mm/hr) for duration (columns) and return periods (rows)

Figure 7 - Graphical (left) and tabulated (right) summary of design rainfall calculations for site selected in Figure 6 using 4 nearby rain gauges, and target return period of 100 years and a duration of 6 hours.

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5. DISCUSSION

The development of a nationwide IDF framework based on 193 meteorological stations provides one of the most spatially comprehensive assessments of extreme rainfall behaviour in Türkiye to date. Unlike previous basin or city-scale investigations [16, 27, etc.] this study adopts a spatially consistent methodology covering diverse climatic regimes influenced by Mediterranean, continental, and Black Sea systems. This broader spatial coverage enhances the representativeness and transferability of the derived IDF relationships, particularly for national-scale infrastructure planning and regulatory standardisation. The homogeneity assessment results indicate that detected shifts in rainfall extremes are primarily of natural climatic origin rather than anthropogenic measurement inconsistencies.

Recent national and regional studies conducted in Türkiye have provided valuable insights into the spatial and temporal characteristics of extreme precipitation. For example, Aksu et al. [7] reported considerable spatial variability in standard-duration maximum precipitation across the Black Sea Region, highlighting the influence of complex topography and regional climatic conditions on extreme rainfall behaviour. More recently, Aksu et al. [8] developed non-stationary rainfall intensity–duration–frequency relationships for selected regions of Türkiye and demonstrated that the magnitude and frequency characteristics of extreme precipitation can vary substantially between climatic zones. Similar conclusions have also been reported by several regional IDF studies conducted in western, central, and coastal parts of the country. The findings of the present study are generally consistent with these observations, confirming the strong spatial heterogeneity of rainfall extremes across Türkiye. However, unlike previous studies that were typically limited to specific regions, river basins, or subsets of stations, the proposed framework adopts a unified methodology applied to 193 meteorological stations covering the entire country. This nationwide consistency enables direct comparison of rainfall characteristics across different climatic regions and provides a common basis for engineering design applications at the national scale.

From a practical perspective, the proposed framework also addresses an important operational need. In Türkiye, design rainfall estimates used in hydraulic infrastructure projects are often derived from station-specific analyses, regional studies, or locally developed IDF relationships. Although these approaches provide valuable information, differences in methodologies, probability distributions, record lengths, and update periods may lead to inconsistencies among engineering applications. The nationwide framework developed in this study contributes towards a more standardised approach by providing a common methodological basis applicable across the country. Such a framework can support engineering practice, infrastructure planning, urban drainage design, and future updates of national rainfall design standards. Furthermore, the integration of the framework into a user-oriented interface increases the accessibility of scientifically derived design rainfall information for practitioners, consultants, and public institutions.

The use of AMAX for 11 sub-daily durations (30 minutes, 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 8 h, 12 h, 18 h, and 24 h) ensures methodological consistency across stations and allows direct comparison of intensity–duration scaling behaviour across climatic regions. However, while the AMAX approach is widely adopted in IDF studies, it may neglect secondary extreme events occurring within the same year, which can be incorporated using a peaks-over-threshold (POT) framework. Unlike the AMAX method, POT utilizes all events exceeding a predefined threshold and therefore can provide a larger sample of extremes for frequency analysis [35]. Future studies could explore POT-based regional frequency analysis to assess whether additional information on extreme rainfall behaviour can be extracted, particularly in convective-dominated regions along the Mediterranean and Black Sea coasts.

A key contribution of this study lies not only in statistical modelling but also in practical applicability. The IDF studies discussed in the previous sections of this paper have provided important methodological developments and statistical results; however, they have lacked practitioner-oriented implementation tools for practical engineering applications. By aiming to develop a unified, accessible framework, this study addresses an important gap between academic research and engineering practice. A standardised national IDF tool can reduce inconsistencies in hydraulic design across institutions, improve

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comparability between projects, and support climate-resilient infrastructure planning. Despite its strengths, several limitations should be acknowledged. First, although the majority of stations cover the 1970–2020 period, differences in record lengths among 22 stations may introduce some spatial inconsistency in return level estimates. Second, the analysis assumes stationarity in rainfall extremes, which may not fully reflect ongoing climate change impacts. Incorporating non-stationary frequency analysis frameworks that account for temporal trends or large-scale climate indices could enhance future IDF updates.

In recent decades, increasing evidence has challenged the assumption of stationarity in extreme rainfall analysis, leading to the development of non-stationary IDF modelling frameworks. Several studies have incorporated time and climate indices as covariates to account for changing precipitation extremes [36, 37]. These studies generally report that non-stationary models can outperform stationary approaches at locations where significant trends or climate-driven variability are detected, while stationary models may remain adequate in regions without clear evidence of change.

Despite these advances, selecting physically meaningful covariates remains a major challenge. Many non-stationary models rely primarily on time as an explanatory variable, which limits physical interpretability and does not explicitly represent underlying climatic drivers [38]. Therefore, although non-stationary IDF modelling represents an important direction for future research, particularly under climate change, its application requires careful justification based on observed trends and climatic context. Future developments may also integrate scenario-based climate projections to support more resilient infrastructure design. We plan to continue this work in future research, focusing on identifying the most suitable covariates and developing the optimal model type for non-stationary modelling of extreme rainfall in Türkiye and develop new IDF curves under changing environment.

6. CONCLUSION

This study develops a nationwide, statistically consistent, and practitioner-oriented IDF framework for Türkiye based on 193 meteorological stations. Beyond rigorous frequency analysis, a key contribution of the research is the provision of a unified and user-friendly national IDF tool that enables practitioners to directly obtain design rainfall intensities for selected durations and return periods without repeated statistical recalculations. This tool helps bridge the gap between academic research and engineering practice and supports standardised hydraulic design across institutions. Moreover, trend analyses indicate evidence of increases in short-duration extremes (30 min–5 h), particularly in western and south-western coastal regions, while longer durations (6–24 h) show more spatially heterogeneous patterns. Model selection results confirm the clear dominance of the Lognormal distribution across most durations and regions, with the Gamma distribution serving as a secondary alternative among the candidate pdfs; which were Weibull, Gamma, Lognormal, and Logistic.

Overall, the proposed national IDF framework and accompanying practical tool provide a robust foundation for consistent, transparent, and climate-informed infrastructure planning in Türkiye, while highlighting the importance of future non-stationary analyses.

PRE-PRINT

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Data availability: The online tool can be accessed at: Intensity-Duration-Frequency (IDF) design rainfall model for Turkey

PRE-PRINT

References

[1] Minh, H. V. T., Lavane, K., Lanh, L. T., Thinh, L. V., Cong, N. P., Ty, T. V., Downes, N. K., & Kumar, P., Developing intensity–duration–frequency (IDF) curves based on rainfall cumulative distribution frequency (CDF) for Can Tho City, Vietnam. Earth, 3(3), 866–880, 2022.

[2] Kawara, A. Q., & Elsebaie, I. H., Development of rainfall intensity, duration and frequency relationship on a daily and sub-daily basis: Case study Yalamlam Area, Saudi Arabia. Water, 14(6), 897, 2022.

[3] Escobar-González, D., Singaña-Chasi, M. S., González-Vergara, J., Erazo, B., Zambrano, M., Acosta, D., … Peluffo-Ordóñez, D., Intensity–duration–frequency curve for extreme rainfall event characterization in the High Tropical Andes. Water, 14(19), 2998, 2022.

[4] Sahin, S., & Cigizoglu, H. K., Homogeneity analysis of Turkish meteorological data set. Hydrological Processes, 24(8), 981–992, 2010.

[5] Türkeş, M., Koç, T., & Sariş, F., Spatiotemporal variability of precipitation total series over Turkey. Int. J. Climatol., 29(8), 1056–1074, 2008.

[6] Kömüşcü, A. Ü., & Aksoy, M., Characterizing variability of spatial patterns of annual and seasonal precipitation of Turkey and identifying the probable driving factors including teleconnection patterns. J. Water Clim. Change, 15(3), 1392–1416, 2024.

[7] Aksu, H., Cetin, M., Aksoy, H. et al., Spatial and temporal characterization of standard duration-maximum precipitation over Black Sea Region in Turkey. Nat Hazards, 111, 2379–2405, 2022.

[8] Aksu, H., Aksoy, H., Çetin, M., et al., Development of rainfall intensity–duration–frequency curves under nonstationary conditions. Sustain. Water Resour. Manag., 11(4), 2025.

[9] Haktanir, T., Citakoglu, H., & Seckin, N., Regional frequency analyses of successive-duration annual maximum rainfalls by L-moments method. Hydrol. Sci. J., 61(4), 647–668, 2016.

[10] Şahin, N., Şan, M. & Kankal, M., Stationarity or nonlinear nonstationarity? Assessing standard duration extreme rainfall under Türkiye's complex topography and climate variability. Stoch Environ Res Risk Assess 40, 26, 2026.

[11] Temel, I., Asikoglu, O. L., & Alp, H., Examining the Probabilistic Characteristics of Maximum Rainfall in Türkiye. Atmosphere, 16(10), 1177, 2025.

[12] Yerdelen, C. Asikoglu, L. Ö., Abdelkader, M. Eris, E. Estimation of standard duration maximum rainfall by using regression models, J. Water Land Dev., 50:28-288, 2021.

[13] Şenocak, S., & Acar, R., Modelling of short-duration rainfall intensity equations for the Aegean region of Turkey. Fresenius Environ. Bull., 16(9b), 1220–1226, 2007.

[14] Yüksek, Ö., Anılan, T., Saka, F., & Orgun, E., Rainfall Intensity-Duration-Frequency Analysis in Turkey, with the Emphasis of Eastern Black Sea Basin. Teknik Dergi, 33(4), 12087-12103, 2022.

[15] Alramlawi, K., & Fıstıkoğlu, O., Estimation of intensity–duration–frequency (IDF) curves from large scale atmospheric dataset by statistical downscaling. Teknik Dergi, 33(1), 11591–11615, 2022.

[16] Güçlü, Y. S., Şişman, E., & Yeleğen, M. Ö., Climate change and frequency–intensity–duration (FID) curves for Florya station, Istanbul. J. Flood Risk Manag., S403-S418, 2016.

[17] Şen, O., & Kahya, E., Impacts of climate change on intensity–duration–frequency curves in the rainiest city (Rize) of Turkey. Theor. Appl. Climatol., 144, 1017–1030, 2021.

[18] Ball, J.E., Babister, M.K., Nathan, R., Weinmann, P.E., Weeks, W., Retallick, M. and Testoni, I., Australian Rainfall and Runoff-A guide to flood estimation, 2016.

[19] Prosdocimi, I., Stewart, E.J. and Vesuviano, G., A depth–duration–frequency analysis for short-duration rainfall events in England and Wales. Hydrol. Res., 48(6), 1624-1638, 2017.

[20] Koutsoyiannis, D., Iliopoulou, T., Koukouvinos, A., Malamos, N., Mamassis, N., Dimitriadis, P., Tepetidis, N., Markantonis, D. (2023) Τεχνική Έκθεση [Technical Report; in Greek]. Production of Maps with Updated Parameters of the Ombrian Curves at Country Level (Implementation of the EU Directive 2007/60/EC in Greece); Department of Water Resources and Environmental Engineering—National Technical University of Athens: Athens, Greece.

[21] Simonovic, S.P., A. Schardong, D. Sandink, and Srivastav, R., A Web-based Tool for the Development of Intensity Duration Frequency Curves under Changing Climate, Environ. Model. Softw., 81, 136-153, 2016.

[22] Alexandersson, H., A homogeneity test applied to precipitation data. Int. J. Climatol., 6(6), 661–675, 1986.

[23] Buishand, T. A., Some methods for testing the homogeneity of rainfall records. J. Hydrol., 58, 11–27, 1982.

PRE-PRINT

[24] Pettitt, A. N., A non-parametric approach to the change-point problem. Appl. Stat., 28(2), 126–135, 1979.

[25] Bickici Arikan, B., & Kahya, E., Homogeneity revisited: Analysis of updated precipitation series in Turkey. Theor. Appl. Climatol., 135, 211–220, 2019.

[26] Khaliq, M. N., & Ouarda, T. B. M. J., A note on the critical values of the standard normal homogeneity test (SNHT). Int. J. Climatol., 27, 681–687, 2007.

[27] Tosunoglu, F., Can, I., & Kahya, E., Evaluation of spatial and temporal relationships between large-scale atmospheric oscillations and meteorological drought indexes in Turkey. Int. J. Climatol., 38, 4579–4596, 2018.

[28] Kendall, M.G., Rank correlation methods. London: Charless Griffin, 1975.

[29] Mann, H. B., Nonparametric tests against trend. Econometrica, 13(3), 245–259, 1945.

[30] Yilmaz, M., & Tosunoglu, F., Trend assessment of annual instantaneous maximum flows in Turkey. Hydrol. Sci. J., 64(7), 820–834, 2019.

[31] Kjeldsen, T.R., Risk and Uncertainty for Civil Engineering. CRC Press, London, 220 pages, 2025.

[32] Chow, V.T., Maidment, D.R., & Mays, L.W., Applied Hydrology. McGraw-Hill, New York, 1988.

[33] Stedinger, J.R., Vogel, R.M. and Foufoula-Georgia, E., Frequency Analysis of Extreme Events. Chapter 18. In Maidment, D.R., Ed., Handbook of Hydrology, McGraw Hill, New York, 1993.

[34] Kite, G.W., Frequency and Risk Analyses in Hydrology. Water Resources Publications, Fort Collins, Colorado, 2019.

[35] Beguería, S., Tomas-Burguera, M., Serrano-Notivoli, R. et al., Evolution of extreme precipitation in Spain: contribution of atmospheric dynamics and long-term trends. Stoch Environ Res Risk Assess 39, 2137–2157, 2025.

[36] Cheng, L. Y., & AghaKouchak, A., Nonstationary precipitation intensity–duration–frequency curves for infrastructure design in a changing climate. Sci. Rep., 4, 7093, 2014.

[37] Ouarda, T. B. M. J., Yousef, L. A., & Charron, C., Non-stationary intensity–duration–frequency curves integrating information concerning teleconnections and climate change. Int. J. Climatol., 39(4), 2306–2323, 2019.

[38] Silva, D. F., Simonovic, S. P., Schardong, A., & Avruch Goldenfum, J., Assessment of non-stationary IDF curves under a changing climate: Case study of different climatic zones in Canada. J. Hydrol. Reg. Stud., 36, 100870, 2021.

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