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Analysis of Extreme Precipitation Trends and Probability Distributions Across Return Periods in Northwest Iran

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A b s t r a c t

Understanding the frequency and intensity of such events is crucial for infrastructure design, flood risk assessment, and water resource management, particularly in light of climate change. This study analyzes maximum daily precipitation trends and probability distributions across return periods in Ardabil Province, northwest Iran, aiming to identify suitable distributions for estimating extreme 24-hour precipitation, calculate maximum values for different return periods, and assess temporal trends in these events. Daily precipitation data from synoptic stations in Ardabil Province were analyzed using the CumFreq software for distribution fitting and the Mann-Kendall test to detect trends in the data. Various probability distributions were fitted to the data, with the "Dagum gen." and "Frechet" (Fisher-Tippet T2) distributions providing the best fits for several stations. Maximum daily precipitation values for return periods of 2, 5, 10, 25, 50, and 100 years were calculated, showing significant regional variability. Stations such as Nir and Parsabad exhibited much higher precipitation values compared to stations like Ardabil Airport and Namin, with notable differences in precipitation intensities across return periods. The Mann-Kendall trend test revealed mixed results, with some stations showing increasing precipitation trends, such as Sareyn (p<0.05), while others showed no significant change. These results indicate that regional climatic and topographic factors strongly influence precipitation patterns in different return periods, indicating the need for localized risk assessments and water management strategies. These results are vital for intense flood estimation, hydrological modelling, and infrastructure design, providing key indications for climate change adaptation and extreme event preparedness in Ardabil province.

Key words:
probability distributions, extreme precipitation events, trend analysis, climatic variability, statistical distribution

1 INTRODUCTION

Background

Extreme precipitation events, as a critical component of the hydrological cycle, are often associated with floods and droughts (Wang et al., 2022). Intense precipitation can lead to significant damage and loss, such as landslides, flooding, damage to agricultural crops, livestock, and even human lives (Batista et al., 2019). Prolonged heavy precipitation events, lasting several hours or days, can cause river overflow or coastal flooding as a primary trigger, or act as a contributing factor in compound flood events, such as rain-on-snow events or floods caused by river runoff combined with runoff from intense precipitation. Thus, the frequency and intensity of heavy precipitation events, as triggers of severe floods, mass movements, and erosion, are particularly important (Poschlod et al., 2021). Therefore, to manage water resources and other related objectives to minimize the associated damage, studying and predicting the frequency of extreme precipitation events is essential (Batista et al., 2019). Information on the frequency and intensity of heavy precipitation is typically needed by government authorities, disaster management agencies, and engineers for designing runoff control structures in water engineering projects (Poschlod et al., 2021). Accurate estimation of daily precipitation return periods is required for hydrological purposes such as designing flood protection infrastructure, dams, and runoff retention ponds (Rivoire et al., 2022). Quantifying and understanding the frequency of heavy precipitation events is key to planning, designing, and managing water-related infrastructure (Gründemann et al., 2023). Information on extreme precipitation and the runoff it generates has become increasingly important in the context of climate change (Oliveira et al., 2021).

Literature review

Several studies have been conducted regarding estimating daily precipitation values across different return periods. Schaefer (1990) examined a regional analysis of annual maximum precipitation using the Flood Index method and generalized extreme value distributions in Washington state, concluding that this method was applicable in the Nahgumon region. Desa and Rakhecha (2007), investigating the probability of maximum 24-hour precipitation in the tropical Johor region of Malaysia, found that point estimates of PMP (propable maximum precipitation) for 24 hours, calculated using frequency factors, were appropriately estimated. PMP 24-hour maps revealed spatial variations ranging from 400 mm to over 1000 mm, which can assist in improving the design of water storage structures and water resource management. Casas et al. (2008), in estimating the maximum possible precipitation in Catalonia, noted that their results could improve water resource management and reduce the risks of intense precipitation. DeGaetano (2009) assessed the temporal changes in the return periods of extreme precipitation in the United States, finding that nearly two-thirds of the precipitation return period trends for 2-, 5-, and 10- years were increasing, with more noticeable trends in the 1960 – 2007 period compared to 1950 – 2007, resulting in a 20% decrease in the expected return period median. Casas et al. (2011) studied the maximum possible precipitation for various return periods in Barcelona, Spain, using both real storm maximization and statistical methods, noting similarities between computed PMP values and finding that expected PMP increased over time, especially for moderate-duration precipitation (2 to 9 hours), which could aid in better understanding precipitation patterns and water management in Barcelona. Mailhot et al. (2010), analyzing seasonal return periods of maximum daily precipitation in the Amazon of Brazil, concluded that future daily and multi-day events would become more intense and frequent across all regions. Saidi et al. (2015), evaluating trends in extreme precipitation changes in the Piedmont (northwest Italy), found that heavy precipitation, particularly over short durations, had increased over the past 20 years. Their statistical analysis (parametric and non-parametric tests) showed that in most cases, the hypothesis of trend stationarity could not be rejected, indicating the importance of a detailed, local study of climate changes and their impact on extreme precipitation events. Santos et al. (2015), analyzing seasonal return periods of maximum daily precipitation in the Amazon, concluded that heavier precipitation would be expected during the rainy seasons. Malehinezhad et al. (2015) introduced appropriate statistical distributions for the studied stations by comparing extreme and partial daily maximum precipitation series to determine the best probability distribution for Tehran province. Najafi and Moazami (2016) studied precipitation trends in Iran (1969 – 2009) using 187 stations. They observed declining annual precipitation driven by winter reductions, especially in the north, west, and northwest. While extreme precipitation magnitudes remained stable, their frequency decreased significantly, particularly in winter and spring in the northwest. Santos et al. (2016), after modelling extreme daily precipitation events and estimating their return periods using extreme value theory and KS (Kolmogorov–Smirnov) tests, found that the GEV (generalized extreme value) and GPD (generalized Pareto distribution) distributions fit well in all subregions of the Amazon and are suitable for studying extreme daily precipitation events. They also noted that more intense precipitation is expected to occur in the southern and coastal subregions of the Brazilian Amazon for all return periods studied. Gründemann et al. (2023), examining the temporal and spatial behaviour of extreme precipitation on a global scale, found that GEV distributions and the POT (peak-over-threshold) method, which only uses the largest events for estimating extreme precipitation, do not provide consistent spatial results. They developed the MEV (metastatistical extreme value) method, which considers all precipitation events, resulting in better spatial patterns for local precipitation.

Despite advancements in analyzing maximum precipitation events, gaps remain in understanding spatial variability and long-term trends across regions. While various methods and distributions have been useful, few studies have fully explored their fit across different climates and geographic settings. Further research is needed to assess the temporal trends and dynamics of heavy precipitation events in diverse climatic regions.

Scope and Objective

Estimation of design rainfall is essential for assessing the probability of extreme floods in the design of hydraulic structures and quantifying the risk of failure of these structures (Johnson & Smithers, 2019). The return period of an event is the average time between occurrences of the event (Rivoire et al., 2022). Risk and failure calculations are widely used to assess the potential risk of extreme events on water infrastructure. Due to climate variations and hydrological components, it is expected that extreme events (such as heavy rainfall and droughts) will increase in frequency and intensity in the future. However, this requires local-scale estimations of these changes to assess and understand the shifting risks in different regions (Milojevic et al., 2023; Sato & Shuin, 2023). Analysis of extreme precipitation events is typically conducted using statistical approaches and models like probability distributions and generalized extreme value distributions (Giarno et al., 2023). Extreme value theory provides an accurate method for extrapolating and interpolating distribution characteristics based on appropriate assumptions (Wehner et al., 2024), offering efficient techniques for estimating the probabilities of extreme events based on historical data (Mélice & Reason, 2007). This study was conducted at synoptic stations in various climatic regions of Ardabil Province, with the following objectives: a) to identify suitable probability distributions for estimating 24-hour extreme precipitation at synoptic stations in different climates; b) to calculate maximum daily (24-hour) precipitation values across various return periods; c) to analyze and compare precipitation values across different return periods; and d) to assess the significance of trends in the temporal changes of maximum daily precipitation in the study area.

2 MATERIAL AND METHODS

Description of the data

The data used in this study consists of daily (24-hour) precipitation records collected at synoptic stations in accordance with the standards of the Meteorological Organization. The data were obtained from the Iran Meteorological Organization (IRIMO). The protocol for measuring daily precipitation at synoptic stations follows standardized methods set by WMO, ensuring accurate and uniform global data collection. Daily precipitation is measured using standard rain gauges over a 24-hour period (00:00 to 24:00). Data has been recorded manually and automatically, with quality control checks to verify reliability. The statistical period varies based on the establishment year of each station and has been analyzed over a 43-year period (from 1976 to 2019, with shorter records at some stations). Prior to analysis, the data were checked and confirmed for homogeneity and the absence of statistical gaps.

In the present study, daily precipitation data from synoptic stations located in Ardabil Province were used for analysis, with their key characteristics provided in Tab. 1. The studied stations are located across various climatic and topographical conditions. At higher elevations, such as MeshginShahr, the climate is cold semiarid, characterized by cold winters and mild summers. In contrast, lower-elevation areas like Parsabad, Bilesavar, and Germi experience a temperate semiarid climate, with most precipitation occurring during the winter months (Ghafari et al., 2020). Some stations are situated in plain areas, while others are located in mountainous regions of the study area (such as Sareyn, Nir, and MeshginShahr stations), which are adjacent to the Sablan Mountain and characterized by a cold climate (Mostafazadeh & Talebi Khiavi, 2024). The warmest areas, including Parsabad, Bilesavar, and parts of Germi, have temperatures of 13 – 15°C, while southwestern lowlands range from 11 – 12°C, and Khalkhal highlands range from 6 – 8°C. Northern regions receive low rainfall (282 mm annually), Sabalan highlands (e.g., Sareyn, Nir, MeshginShahr) get around 522 mm, Khalkhal receives 442 mm, and central areas (e.g., Ardabil, Namin) range from 282 – 342 mm. Average wind speeds are 3.8, 2.0, 1.9, and 2.1 m/s at Ardabil, Parsabad, MeshginShahr, and Khalkhal, respectively. The geographical locations of the stations in the study area are presented in Fig. 1. Regarding the grouping of the studied stations based on their location and climatic conditions, the stations are classified into different climate types according to the Emberger climate classification. Their characteristics are presented in Tab. 2. The key statistical characteristics of the maximum daily precipitation data for the studied stations are presented in Tab. 3.

Tab. 3 presents key statistical characteristics of the maximum daily precipitation data across various stations in Ardabil province from 1976 to 2019, with shorter records at some stations. The mean precipitation varies significantly, ranging from 21.0 mm at Nir to 34.1 mm at Bilesavar, a difference of 13.1 mm. Ardabil shows the highest maximum value (63.0 mm) and range (49.4 mm), while Nir has the smallest range (19.0 mm), indicating regional climatic differences. Variability also differs widely, with Ardabil having the highest standard deviation (10.2 mm) and Nir the lowest (6.6 mm), reflecting greater consistency in precipitation at Nir. The range values further emphasize these differences, with Ardabil's range being much larger than Nir's. Skewness and kurtosis values indicate different distribution shapes. Stations like Ardabil and Sareyn show high positive skewness (1.9 and 2.2), suggesting a longer right tail, while others like Ardabil Airport and Namin have more symmetric distributions. Sareyn also shows high kurtosis (5.5), indicating a distribution with more extreme values compared to a normal distribution.

Research methodology

Probability distribution fitting

In line with the research objective, daily precipitation data for the study period were collected from synoptic stations in Ardabil Province, and the maximum 24-hour precipitation values during the study period were extracted. Regarding the normality of the data, it should be noted that the recorded data are verified by technicians from the Meteorological Organization before being made available to users. It is also worth mentioning that preliminary data processing was conducted before calculating the statistical distributions. The numerical values of the

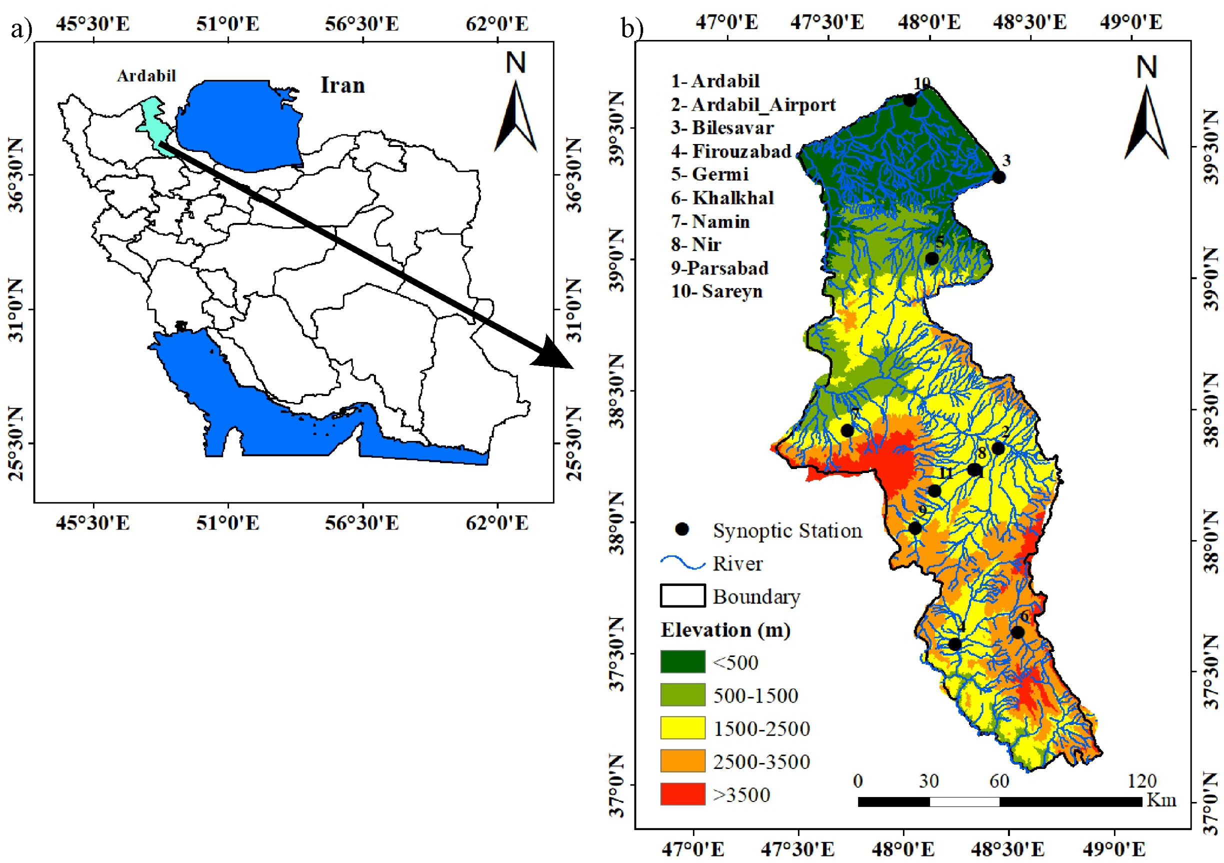

Fig. 1. Geographical locations of the stations in the study area.

Tab. 1. Characteristics of synoptic stations in Ardabil Province for analyzing maximum daily precipitation

Station	Longitude			Latitude			
	DD°	MM'	SS"	DD°	MM'	SS"	Elevation (m)
Ardabil	48	19	43	38	13	05	1335
Ardabil Airport	48	24	57	38	19	50	1317
Bilesavar	48	19	09	39	21	54	101
Firouzabad	48	13	00	38	35	00	1050
Germi	48	03	26	39	03	03	746
Khalkhal	48	32	18	37	36	32	1797
MeshginShahr	48	40	40	38	22	30	1560
Namin	48	29	28	38	25	13	1480
Nir	48	01	32	38	02	15	1593
Parsabad	48	52	38	39	36	27	82
Sareyn	48	04	50	38	08	49	1658

Tab. 2. Classification of Studied Stations Based on Topography and Emberger Climate Classification

Station	Topography	Climate Type
Ardabil	Mountainous	Cold Semi-Arid
Firouzabad	Mountainous	
Ardabil Airport	Plain	
MeshginShahr	Mountainous	Moderate Semi-Arid
Nir	Mountainous	
Parsabad	Plain	
Bilesavar	Plain	
Germi	Semi-Mountainous	
Khalkhal	Mountainous	Cold Semi-Humid
Namin	Foothills	
Sareyn	Mountainous	

Tab. 3. Key statistical characteristics of the maximum daily precipitation data (1976 to 2019 with shorter records at some stations) used in the frequency analysis

Station Statistics	Ardabil	Ardabil Airport	Bilesavar	Firouzabad	Germi	Khalkhal	MeshginShahr	Namin	Nir	Parsabad	Sareyn
Mean (mm)	25.4	22.3	34.1	24.3	31.4	28.6	29.9	21.0	32.2	28.5	29.8
Median (mm)	23.0	22.0	32.0	23.0	29.0	28.6	29.9	18.8	30.1	24.2	27.9
Mode (mm)	28.0	21.0	36.0	28.0	36.0	36.0	28.0	18.0	25.0	24.0	25.0
Std.Dev. (mm)	10.2	7.3	11.2	8.7	11.6	6.0	9.1	8.8	6.6	11.2	10.6
Sample Variance (mm^2)	104.3	53.4	124.5	76.0	134.0	46.8	83.0	77.7	43.3	124.9	111.4
Kurtosis (-)	4.4	-0.2	1.3	3.1	-0.4	0.5	-0.7	0.1	-0.7	2.4	5.5
Skewness (-)	1.9	0.3	1.3	1.4	0.6	0.0	0.2	0.4	0.9	1.5	2.2
Range (mm)	49.4	25.5	37.0	34.4	39.0	32.0	32.4	29.6	19.0	51.3	43.0
Minimum (mm)	13.6	11.0	22.0	12.6	16.0	14.0	14.6	6.4	25.0	14.1	19.0
Maximum (mm)	63.0	36.5	59.0	47.0	55.0	46.0	47.0	36.0	44.0	65.4	62.0

data used in the study were manually entered into the CumFreq software. In the CumFreq software, the cumulative frequency of the observed values was calculated, and various probability distributions were fitted to the data series. The comparison between calculated and observed values was conducted by computing the cumulative frequency of observed precipitation data and fitting various probability distributions to the data series using the CumFreq software. The observed cumulative frequency will be derived directly from the recorded maximum daily precipitation values by the CumFreq software. The mean absolute differences between the calculated (modelled) and observed cumulative frequencies were used to evaluate the goodness-of-fit for each distribution. In the CumFreq software, the Mean Absolute Differences (mean of absolute deviations) measure the difference between observed values and those fitted by a probability distribution model. It is defined as the average of absolute differences between actual data and model-predicted values. The process involves fitting a probability distribution (e.g., normal, log-normal, Gumbel) to the data, calculating predicted values for each data point, determining the absolute differences between observed and predicted values, and then averaging these differences to obtain the Mean Absolute Differences. This index evaluates the model's accuracy, with smaller values indicating a better fit to the actual data. This approach ensures that the data entered into the probability models were independent and accurately represented the observed precipitation patterns. The results of this comparison are presented in Tab. 4, showing the differences and ranking the distributions based on their fit to the observed data. Accordingly, the values of the variable of interest for different return periods are calculated using the frequency distribution (Mostafazadeh et al., 2023). In the next step, the maximum 24-hour precipitation values for various return periods (2, 5, 10, 25, 50, and 100 years) were computed using the CumFreq program. Then, the range of variations in the computed precipitation values for different return periods was plotted as box plots, and the range of variation among the computed values at the studied synoptic stations was interpreted.

Trend detection

In this regard, the trends in maximum 24-hour precipitation values were evaluated using the Mann-Kendall statistical test over the study period for each station. The Mann-Kendall test is a widely used non-parametric method for detecting trends in time series data, such as maximum daily precipitation, over a given period (Malik & Kumar, 2020). One of its primary advantages is its robustness to non-normally distributed data and its ability to handle missing values without requiring data interpolation (Garba & Udokpoh, 2023). The test is particularly suited for analyzing environmental and hydrological datasets, as it is not affected by outliers or abrupt changes in the dataset (Parchami et al., 2024). Additionally, it evaluates monotonic trends, allowing for the identification of increasing or decreasing patterns over time. The Mann-Kendall test is straightforward to implement and can provide both the direction and significance of trends, making it a reliable choice for analyzing long-term precipitation records in diverse climatic settings (Roshani et al., 2021). The details and steps of the Mann-Kendall method are presented below.

The S statistic is commonly used for time series analysis (here, maximum 24-hour precipitation values) and is calculated statistically as described by Kisi and Ay (2014):

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

$$\text{sign}(\theta) = \begin{cases} +1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} \tag{2}$$

To compute this value, it is essential to determine the variance of S, denoted as "Var(S)" (Chattopadhyay et al., 2012):

$$\text{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_p(t_p - 1)(2t_p + 5)\right] \tag{3}$$

The equation accounts for tied values, which are data points equal to one another. Here, "n" denotes the total number of data values (years of data series), "m" represents the number of groups with tied values, and "tp" refers to the number of data values (years based on available maximum rainfall data) in the PP-th group. The Kendall test statistic (Z-value) is derived using the calculated values of Var(S) and S (Chattopadhyay et al., 2012):

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

To determine the trend in the data series, if the relationship is proven, the null hypothesis will be accepted:

$$|MK| \leq Z_{S/2} \tag{5}$$

To evaluate the significance of trends in the data, the Mann-Kendall (MK) test result is compared to critical thresholds. If the absolute value of the MK test statistic exceeds 1.96, the trend is significant at the 5% level. If it exceeds 2.56, the trend is significant at the 1% level. A positive Z statistic indicates an upward trend in the data series, while a negative Z statistic signifies a downward trend.

3 RESULTS AND DISCUSSION

The results of the present study regarding the ranking of fitted statistical distributions, the optimal fit, and the mean absolute differences between the computed and observed cumulative frequencies of maximum daily (24-hour) precipitation at the synoptic stations studied in Ardabil Province are presented in Tab. 4. In CumFreq, the ranking of fitted distributions is based on statistical criteria (e.g., Mean Absolute Differences) that assess the model's fit to observed data. After fitting various distributions, evaluation metrics are calculated, and distributions are ranked by the lowest error values. In this study's software, average and higher-order moments are not used to determine fit quality.

The fitted statistical distributions and the mean absolute differences between the calculated and observed cumulative frequency values for various synoptic stations have been presented in Tab. 4. Among the first-ranked distributions, "Dagum gen." stands out at Ardabil and Bilesavar, with mean absolute differences of 1.82% and 2.90%, respectively. These values are considerably lower than other stations, with the next ranked distributions having differences of 2.76% (Ardabil Airport) and 3.62% (Firouzabad), indicating the relatively better fit of "Dagum gen." for these stations. The differences in the first-ranked distribution clearly show the significance of region-specific precipitation patterns, with Ardabil and Bilesavar fitting better to the "Dagum gen." distribution.

The second-ranked distributions also exhibit notable variations. The "Frechet (Fisher-Tippet T2)" distribution is consistently ranked second for stations such as Ardabil, Nir, and Parsabad with mean differences of 1.87%, 2.75%, and 2.75%, respectively. This suggests a common tendency for maximum precipitation patterns across these stations to fit the "Frechet" model. However, for other stations like Firouzabad and Sareyn, the "Gen. Laplace" and "Laplace (std.)" distributions are ranked second, with mean differences of 3.64% and 2.69%, showing the diversity in distribution choices for different areas.

Looking at the third-ranked distributions, “mirr. Weibull” appears at Ardabil (1.89%), Namin (2.84%), and Firouzabad (3.65%), further indicating the variability in fit across the stations. The third rank also indicates that the choice of distribution tends to shift based on station location and its unique climatic conditions. The “Frechet (Fisher-Tippet T2)” appears again at Bilesavar and Firouzabad (3.01% and 3.65%), suggesting a preference for this distribution in more variable precipitation regimes.

As a conclusion, the rank order of statistical distributions demonstrates that while some distributions such as “Dagum gen.” and “Frechet (Fisher-Tippet T2)” are well-suited for several stations, the differences in the first, second, and third ranks indicate the varying climatic and precipitation patterns across Ardabil province. The significant variations in mean absolute differences (e.g., 4.02% for Nir and 1.82% for Ardabil in the first rank) prove the importance of choosing the appropriate distribution based on regional precipitation characteristics. Thus, tailored statistical models are crucial for accurate precipitation predictions in diverse climatic conditions.

The cumulative frequency of best-fitted distribution applied to maximum precipitation values at the synoptic stations studied in Ardabil province is presented in Fig. 2 and Fig. 3.

The maximum daily precipitation values (24-hour) with different return periods, based on the optimally selected probability distributions, are shown for the synoptic stations in the study area of Ardabil province in the Tab. 5.

The Tab. 5 presents maximum precipitation values with different return periods based on the optimally selected probability distributions at various synoptic stations in Ardabil province. Significant differences are observed between stations when comparing the precipitation values across the same return periods (Tr). For instance, at the Tr = 2 return period, the highest value is recorded at Bilesavar (41.31 mm), while the lowest is at Namin (15.92 mm). This substantial difference of (25.39 mm) indicates the variability in precipitation patterns across the region. Looking at higher return periods, the station differences become even more pronounced. For the Tr = 50 return period, values range from 44.55 mm at Ardabil Airport to 106.68 mm at Nir, a difference of (62.13 mm). Similarly, at Tr = 100, the precipitation value in Nir (156.48 mm) is considerably higher than at Ardabil Airport (49.44 mm), marking a difference of (107.04 mm). This comparison indicates the disparity in precipitation intensities, with stations like Nir and Parsabad exhibiting much higher maximum precipitation values than others.

The variability across the stations suggests that geographical and climatic factors influence the maximum precipitation levels at different locations. Stations like Bilesavar, Firouzabad, and Nir consistently report higher values across all return periods, especially at Tr = 50 and Tr = 100. On the other hand, stations such as Namin and Ardabil Airport have lower precipitation values, particularly at shorter return periods, indicating less precipitation.

Since the statistical distributions were fitted based

Tab. 4. Rank of fitted statistical distributions and mean absolute differences between calculated and observed cumulative frequency values at the studied synoptic stations

Rank	Ardabil	Abs diff (%)	Ardabil Airport	Abs diff (%)	Bilesavar	Abs diff (%)	Firouzabad	Abs diff (%)	Germi	Abs diff (%)	Khalkhal	Abs diff (%)
1	Dagum gen.	1.82	Laplace (std.)	2.76	Dagum gen.	2.90	Gamma (Erlang)	3.62	Dagum gen.	2.24	Laplace (std.)	2.35
2	Frechet (Fisher-Tippet T2)	1.87	Gen. Cauchy	3.36	mirr. Weibull	2.98	Gen. Laplace	3.64	Gen. exp. (Poisson-type)	2.24	Logistic	2.61
3	mirr. Weibull	1.89	Gen. logistic	3.36	Frechet (Fisher-Tippet T2)	3.01	Log-logistic	3,65	Frechet (Fisher-Tippet T2) mirr.	2.28	GEV	2.78
4	GEV	2.15	Gumbel gen.	3.38	Frechet (Fisher-Tippet T2) mirr.	3.14	Log-normal std.	3.88	Burr gen.	2.35	Normal opt.	2.80
5	Burr gen.	2.24	Burr gen.	3.40	GEV	3.15	Dagum gen.	3.89	Log-normal opt.	2.53	Normal std.	2.82
6	Log-normal opt.	2.37	Cauchy	3.42	Log-normal opt.	3.18	Laplace (std.)	4.03	Gumbel gen.	2.61	Gamma (Erlang)	2.89
7	Frechet (Fisher-Tippet T2) mirr.	2.60	Fisher--Tippett type 3	3.46	Gamma (Erlang)	3.25	Log-normal opt.	4.05	GEV	2.63	Frechet (Fisher-Tippet T2) mirr.	2.91
8	Gamma (Erlang)	2.84	Logistic	3.60	Burr gen.	3.52	Frechet (Fisher-Tippet T2)	4.11	Frechet (Fisher--Tippet T2)	2.65	Gumbel gen.	2.93
9	Laplace (std.)	2.93	Gen. exp. (Poisson--type)	3.61	Log-logistic	3.93	Root-normal opt.	4.12	Gumbel	2.70	Gompertz gen	2.96
10	Log-normal std	3.34	Frechet (Fisher-Tippet T2) mirr.	3.62	Gen. exp. (Poisson--type)	4.00	Frechet (Fisher-Tippet T2) mirr.	4.15	Fisher-Tippett type 3	2.70	Weibull	3.01
11	Gen. exp. (Poisson-type)	3.37	Root-normal opt.	3.66	Laplace (std.)	4.12	Gumbel gen.	4.16	Gamma (Erlang)	2.74	Root-normal opt.	3.02
12	Log-logistic	3.42	Gompertz gen.	3.68	Log-normal std.	4.22	Gumbel	4.32	Log-logistic	2.86	Log-normal opt.	3.08
13	Root-normal opt	4.92	Dagum gen.	3.68	Gumbel	4.74	Fisher-Tippett type 3	4.32	Root-normal opt.	3.01	Fisher-Tippett type 3	3.41
14	Gumbel	5.11	Gen. normal	3.71	Fisher-Tippett type 3	4.74	GEV	4.33	Kumaraswamy	3.44	Mirr. Gumbel	3.55
15	Fisher-Tippett type 3	5,11	Weibull	3.72	Root-normal	5.52	Burr gen.	4.34	Gompertz gen.	3.45	Fisher-Tippett type 3 mirr	3.55

on observational data, the accuracy of the estimated values for different return periods was evaluated using the "Absolute Difference (%)" index, as presented in the Tab. 3. This index was the basis for selecting the best-fit statistical distribution. It is worth noting that the computed extreme precipitation values are consistent with the climatic conditions and geographical locations of the studied stations. In conclusion, the analysis of maximum precipitation values reveals significant regional differences in precipitation patterns within Ardabil province. The largest disparities are observed in stations like Nir, which consistently report higher precipitation values than others such as Namin.

The boxplot of the estimated maximum daily precipitation values (24-hour) with the best-fit probability distribution at different return periods for the synoptic stations in the study area of Ardabil province is shown in Fig. 4.

Based on the information provided in Fig. 4 (which is an extension of the results from Tab. 5), the Nir station experiences the highest precipitation compared to other stations, with the maximum precipitation value significantly higher than at the other stations. In contrast, Ardabil and Ardabil Airport have the lowest precipitation values. Overall, the range of precipitation variations between the stations is quite large, indicating considerable differences in climatic and topographic conditions across the regions. At stations like Nir and Parsabad, the disparity between the maximum and minimum precipitation values is substantial. This suggests that precipitation in these areas is highly variable, and they may experience alternating wet and dry periods. Such fluctuations in precipitation could have implications for water resource management and flood risk planning in these areas. In contrast, stations like Ardabil and Ardabil Airport show a smaller difference between maximum and minimum precipitation values. This suggests that the precipitation in these locations is more consistent, with less variation in intensity over time. These stations might not experience extreme variations in weather patterns, which could lead to different water management strategies compared to regions with more unpredictable precipitation. In conclusion, the significant differences in precipitation patterns across the stations emphasize the diverse climatic conditions in Ardabil province. Stations like Nir and Parsabad with high precipitation variability may require more adaptive strategies for managing heavy precipitations.

The trend of temporal variations in maximum daily precipitation values (24-hour) and the results of the Mann-Kendall test at the synoptic stations in the study area of Ardabil province are shown in Fig. 5.

Based on the information presented in Fig. 5, it can be observed that the precipitation trends across the stations vary significantly. Some stations show a decreasing trend, others indicate an increasing trend, and some display a nearly constant trend.

The station at Sareyn is the only location with a statistically significant increasing trend in maximum daily precipitation (Tau = 0.477, p-value = 0.0116). This indicates a notable rise in extreme precipitation events, with implications for flood risk and water management in the area. The station at Nir shows a slight increasing trend (Tau = 0.156), but the p-value of 0.592 makes it statistically insignificant, suggesting no definitive trend. Most other stations exhibit slight to moderate decreasing trends, though none are statistically significant:

- Germi, Khalkhal, and MeshginShahr show moderate decreases (Tau = -0.133, -0.131, -0.149), but p-values (0.546, 0.306, 0.321) indicate no significance.
- Bilesavar, Firouzabad, Namin, and Parsabad also show slight decreases (Tau = -0.0766 to -0.0340), with p-values (0.729 to 0.854) confirming no significance.
- Ardabil and Ardabil Airport show almost no trend (Tau = -0.00334 and 0, p-values = 0.983 and 1), indicating stable precipitation patterns.

Tab. 4. Cont. Rank of fitted statistical distributions and mean absolute differences between calculated and observed cumulative frequency values at the studied synoptic stations

Rank	MeshginShahr	Abs diff (%)	Namin	Abs diff (%)	Nir	Abs diff (%)	Parsabad	Abs diff (%)	Sareyn	Abs diff (%)
1	Normal opt.	2.82	Gen. Laplace	2.69	GEV	2.49	Gen. Laplace	2.05	GEV	4.02
2	Gen. normal	2.83	Laplace (std.)	3.64	Frechet (Fisher--Tippet T2)	2.75	Laplace (std.)	2.36	Gen. Laplace	4.22
3	Logistic	2.84	Log-normal opt.	3.96	Frechet (Fisher--Tippet T2) mirr.	2.82	GEV	2.03	Frechet (Fisher--Tippet T2)	4.35
4	Weibull	2.84	Burr gen.	4.16	Gen. expontial (Poisson-type)	2.88	Frechet (Fisher--Tippet T2)	3.03	Log-normal opt.	4.45
5	Frechet (Fisher--Tippet T2) mirr.	2.86	Gen. normal	4.45	Burr gen.	2.89	mirr. Weibull	3.11	Laplace (std.)	4.90
6	Gompertz gen.	2.92	Gamma (Erlang)	4.50	Laplace (std.)	3.35	Dagum gen.	3.33	Gamma (Erlang)	5.13
7	Gumbel gen.	2.93	Log-normal std.	4.84	mirr. Weibull	4.32	Burr gen.	3.87	mirr. Weibull	5.20
8	Fisher-Tippett type 3	2.93	Gen. Ray-leigh	4.85	Gumbel	5.22	Log-normal opt.	4.31	Frechet (Fisher--Tippet T2) mirr	5.37
9	Gen. exp. (Poisson-type)	3.02	Gen. logistic	4.82	Fisher-Tippett type 3	5.22	Gamma (Er-lang)	4.74	Dagum gen.	5.55
10	Degum gen.	3.09	Root-normal opt.	4.91	Log-normal opt	5.57	Gen. exp. (Poisson-type)	4.81	Burr gen.	5.79
11	Root-normal opt.	3.10	Gumbel gen.	4.93	Gamma (Erlang)	5.90	Log-normal std.	4.85	Gen. exp. (Poisson-type)	5.95
12	Burr gen.	3.12	GEV	4.94	Log-logistic	6.01	Log-logistic	4.86	Log-normal std.	6.09
13	Normal std.	3.12	Frechet (Fis-her-Tippet T2)	4.95	Root-normal opt.	6.02	Frechet (Fis-her-Tippet T2) mirr.	4.95	Log-logistic	6.42
14	GEV	3.22	Gumbel	4.95	Normal opt.	6.44	Gumbel	6.14	Root-normal opt.	7.52
15	Gamma (Erlang)	3.29	Fisher-Ti-ppett type 3	4.95	Logistic	6.83	Fisher-Tippett type 3	6.14	Kumaraswamy	8.36

In summary, Sareyn is the only station with a significant increasing trend, while other stations show either insignificant decreases or no trend.

This study indicates the urgent need for region-specific water management and flood risk strategies in Ardabil Province, especially under climate change and human impacts. The stark variability in precipitation (high in Nir and Parsabad but stable in Ardabil and Ardabil Airport) calls for tailored policies. High-variability areas need adaptive infrastructure like drainage systems and flood barriers, while stable regions should focus on sustainable water storage. Climate change may worsen these disparities, increasing extreme weather and droughts. Policymakers must prioritize climate-resilient infrastructure, early warning systems, and urban planning that integrates green infrastructure and rainwater harvesting to counter human-induced hydrological changes. The study's temporal trends, like increasing precipitation in Sareyn, stress the need for continuous monitoring and adaptive management. Investing in data collection, predictive modelling, and collaboration among communities, governments, and researchers is vital to address both immediate and long-term challenges from climate change and human activities.

As indicated in this study, the variability in maximum precipitation patterns across Ardabil Province is significantly influenced by a combination of physical and geographical factors. The region's diverse topography, ranging from mountainous areas to plains and foothills, is crucial in shaping precipitation distribution. For instance, stations like Ardabil, Firouzabad, and Khalkhal, located in mountainous regions, exhibit distinct precipitation patterns due to orographic effects, where moist air masses are forced to rise, cool, and condense, leading to higher precipitation. In contrast, stations such as Ardabil Airport and Parsabad, situated in flat plains, experience relatively lower and more uniform precipitation due to the absence of significant elevation changes. Another key factor is the proximity to moisture sources, such as the Caspian Sea, which influences the amount and intensity of precipitation. Stations closer to the Caspian Sea, like Namin and Ardabil Airport, may receive more moisture-laden air,

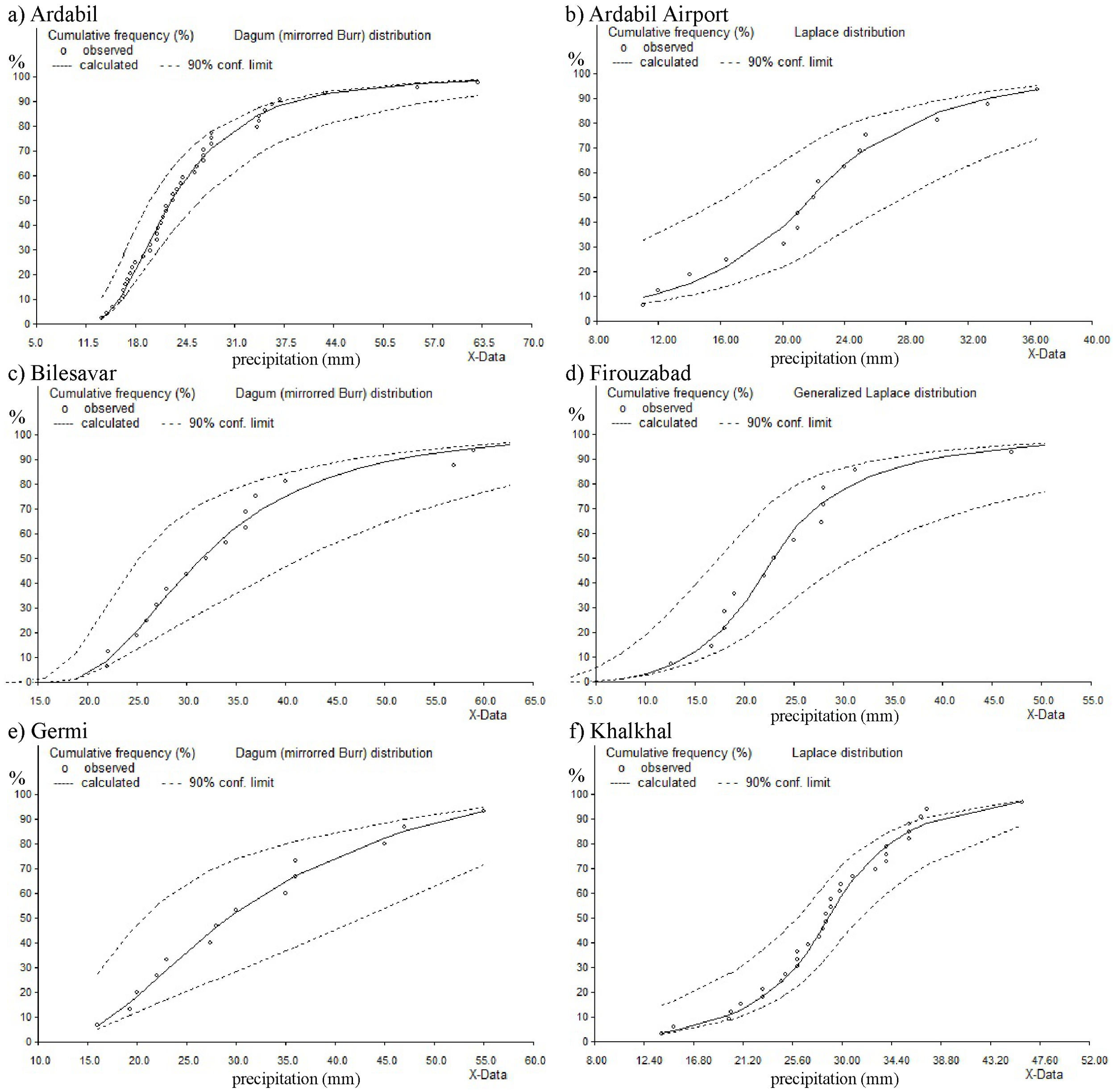

Fig. 2. The cumulative frequency of fitted maximum precipitation values at the studied synoptic stations, a) Ardabil, b) Ardabil Airport, c) Bilesavar, d) Firouzabad, e) Germi, f) Khalkha

resulting in higher precipitation levels. Additionally, the interaction of atmospheric systems, including the influence of westerlies and local wind patterns, further contributes to precipitation variability. For example, the Frechet (Fisher-Tippet T2) distribution's better fit in some stations suggests the influence of extreme weather events driven by these atmospheric dynamics. The climatic classification based on the Emberger method also proves the role of temperature and aridity in precipitation variability. Stations with cold semi-arid climates, such as Ardabil, experience more pronounced seasonal variations, while those with moderate semi-arid or cold semi-humid climates, like Parsabad and Khalkhal, exhibit different precipitation regimes. In conclusion, the interplay of topography, proximity to moisture sources, atmospheric systems, and climatic conditions collectively drives the observed precipitation variability across Ardabil Province. These results prove the need for further research into the specific mechanisms linking physical and geographical factors to maximum precipitation variability in the study area.

This study aligns with previous research, such as Schaefer (1990) and Casas et al. (2008), in emphasizing regional analysis and statistical distributions for extreme precipitation. However, while Najafi and Moazami (2016) reported declining trends in northern Iran, we found a significant increase in Sareyn, indicating localized variability. Unlike Desa and Rakhecha (2007) and Santos et al. (2016), who focused on spatial variations, we compared precipitation amounts across stations, revealing stark differences, such as the 107.04 mm disparity between Nir and Ardabil Airport at Tr = 100. While DeGaetano (2009) noted increasing return period trends in the U.S., our results show mixed trends, with only Sareyn exhibiting a significant increase, indicating the role of regional climatic factors. Additionally, unlike Mailhot et al. (2010) and Saidi et al. (2015), who indicated intensifying extremes, our Mann-Kendall test revealed no significant trends at most stations, contrasting with global studies. This adds a novel dimension to understanding localized precipitation variability.

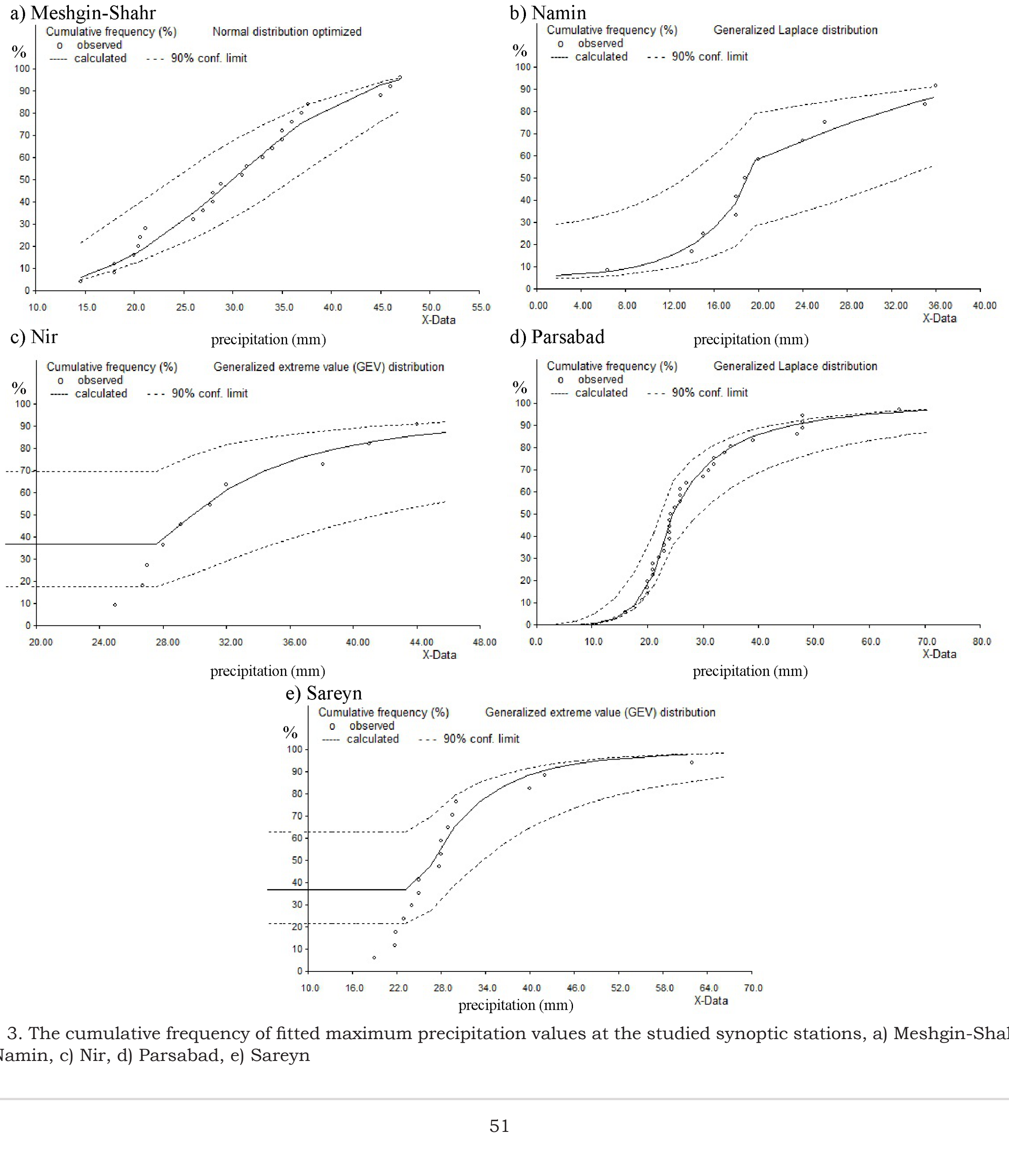

Fig. 3. The cumulative frequency of fitted maximum precipitation values at the studied synoptic stations, a) Meshgin-Shahr, b) Namin, c) Nir, d) Parsabad, e) Sareyn

Tab. 5. Maximum precipitation values (mm) with different return periods (years) based on the optimally selected probability distributions at the synoptic stations of Ardabil province

Station	Tr=2	Tr=5	Tr=10	Tr=25	Tr=50	Tr=100
Ardabil	22.78	31.53	38.80	49.67	58.53	67.15
Ardabil Airport	21.86	28.32	33.21	39.66	44.55	49.44
Bilesavar	41.31	42.61	51.31	62.61	69.96	75.49
Firouzabad	22.90	31.02	38.97	52.59	65.87	82.41
Germi	29.24	43.19	51.51	58.77	61.63	63.52
Khalkhal	28.73	34.24	38.42	43.93	48.11	52.28
MeshginShahr	29.94	38.56	43.07	47.88	50.99	53.78
Namin	15.92	31.32	39.27	47.88	53.51	58.63
Nir	29.84	39.03	50.20	75.08	106.68	156.48
Parsabad	24.50	35.03	45.82	65.17	84.89	110.39
Sareyn	26.92	34.54	41.34	52.63	63.52	77.04

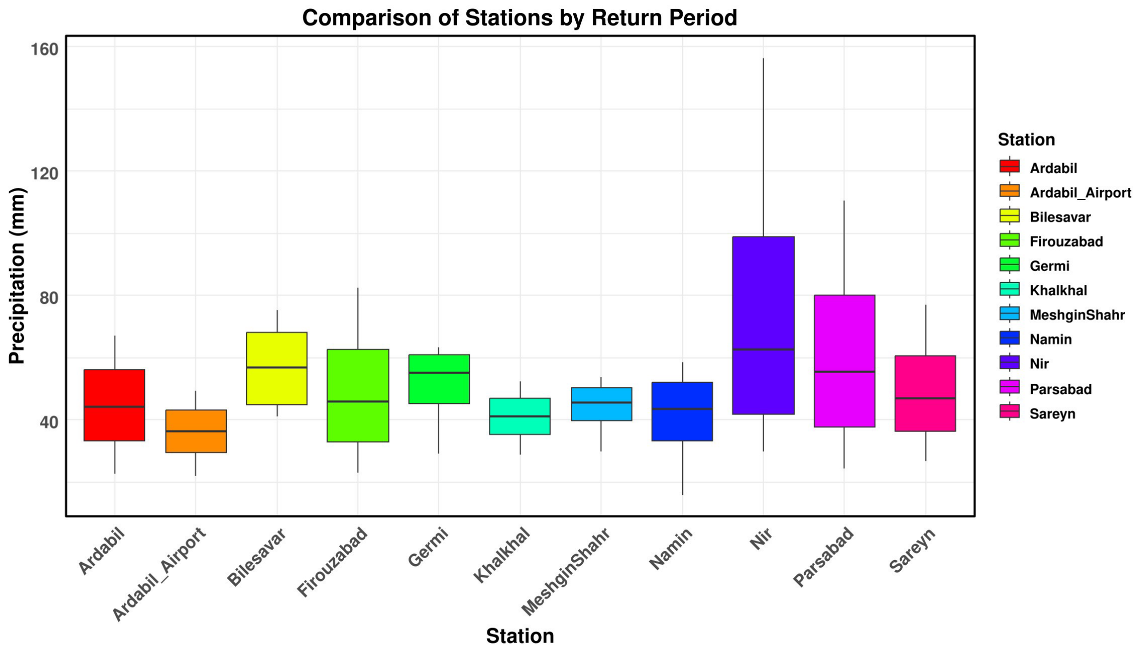

Fig. 4. Boxplot of the variations in the estimated maximum daily precipitation values (24-hour) at different return periods for the synoptic stations in Ardabil province

Implications and suggestions

The results of this study indicate the existence of regional variability when estimating maximum daily precipitation events for designing water infrastructure and flood management measures. The varying precipitation trends across stations can guide future planning for flood risk mitigation and water resource management in the region. Additionally, further studies on the impact of climate change on precipitation patterns in this area are recommended to better understand potential future risks.

Limitations and future research directions

Future research could expand the analysis to include more stations and incorporate climate model projections to assess how future climatic changes might influence precipitation trends. Additionally, further investigation into the spatial correlation of heavy precipitation patterns and their impact on runoff generation, erosion and sediment yield, and flood damages could provide valuable indications for flood management strategies produced by extreme rainfall events.

4 CONCLUSION

The objective of this study was to analyze the trends and probability distributions of maximum daily precipitation values across various return periods in northwest Iran, with a focus on synoptic stations in Ardabil Province. The results revealed significant spatial variability in precipitation patterns, influenced by regional climatic and geographical factors. The study identified the most appropriate probability distributions for the maximum 24-hour precipitation data, with “Dagum gen.” and “Frechet (Fisher-Tippet T2)” emerging as the best fits for several stations. The differences in distribution fits emphasize the necessity of considering local climatic conditions when estimating maximum precipitation patterns at different return periods.

The variability in maximum precipitation patterns across Ardabil Province is strongly influenced by climatic-geographical factors, which can be grouped into distinct clusters based on similar precipitation regimes:

a) Mountainous Stations (Cold Semi-Arid and Cold Semi-Humid Climates): Stations like Ardabil, Firouzabad, Khalkhal, and MeshginShahr are located in mountainous regions, where orographic lifting plays a significant role. As moist air masses

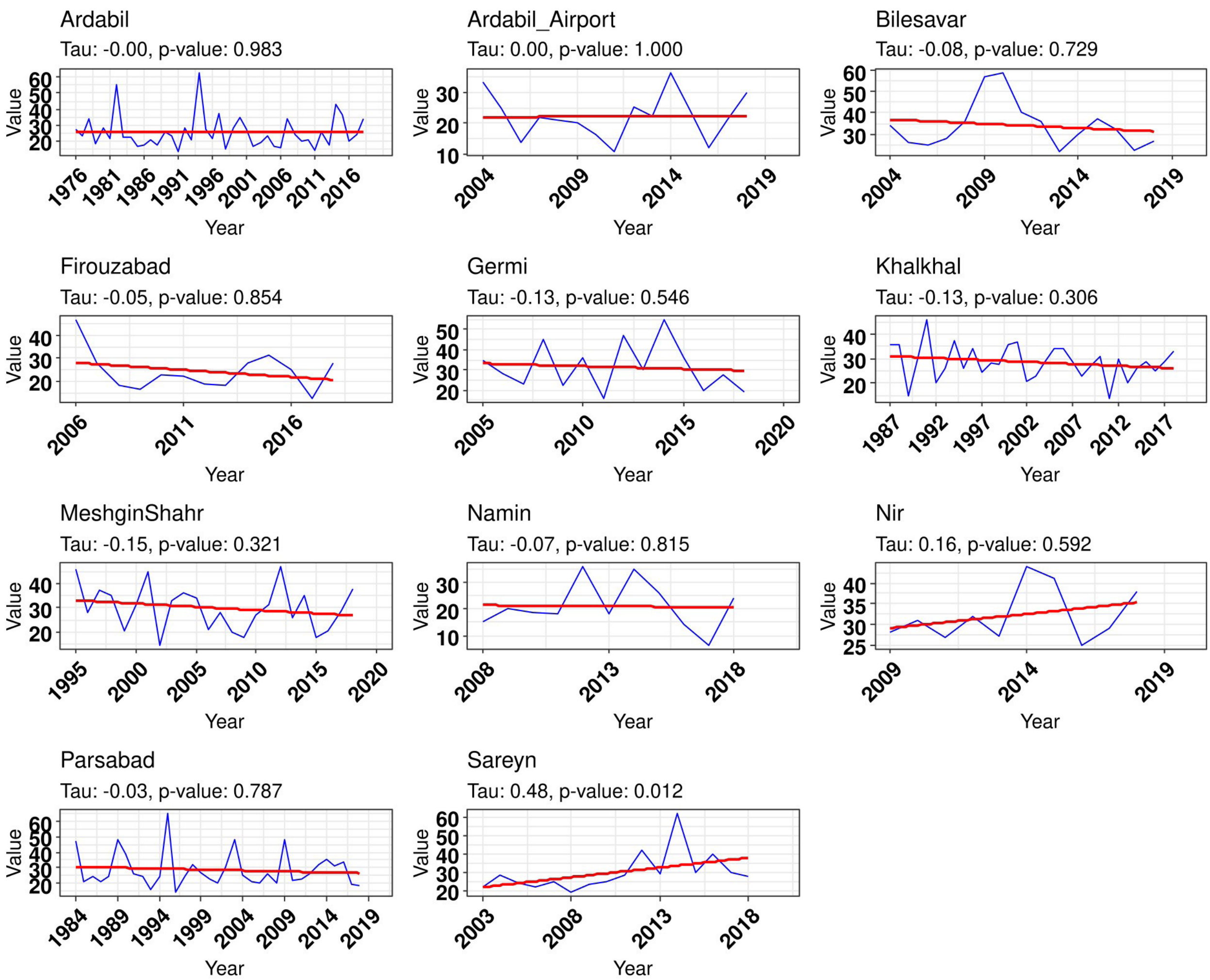

Fig. 5. Temporal trend of maximum daily precipitation values with the Mann-Kendall test at the synoptic stations in Ardabil province

rise over these elevations, they cool and condense, leading to higher precipitation. The cold semi-arid and cold semi-humid climates in these areas further contribute to seasonal variability, with wetter conditions during colder months.

b) Plain Stations (Moderate Semi-Arid Climates): Stations such as Ardabil Airport, Parsabad, and Bilesavar are situated in flat plains. These areas experience lower and more uniform precipitation due to the absence of significant elevation changes. The moderate semi-arid climate produces less pronounced seasonal variations, with relatively stable precipitation patterns.

c) Semi-Mountainous and Foothill Stations: Germi and Namin stations fall into this category. Their intermediate topography results in a mix of orographic and convective precipitation mechanisms. These areas often experience moderate precipitation levels, influenced by both elevation and proximity to moisture sources.

d) Proximity to Moisture Sources: Stations closer to the Caspian Sea, such as Namin and Ardabil Airport, receive more moisture-laden air, leading to higher precipitation. In contrast, inland stations like Nir and Sareyn exhibit more variability due to their distance from major moisture sources.

e) Atmospheric Systems and Extreme Events: The influence of westerlies and local wind patterns, combined with extreme weather events, explains the better fit of distributions like Frechet (Fisher-Tippet T2) in some stations. These factors contribute to the high variability observed in stations like Nir and Parsabad.

The analysis of precipitation values across different return periods (2, 5, 10, 25, 50, and 100 years) indicated substantial differences between stations. For example, Bilesavar recorded the highest precipitation values at lower return periods, while Nir exhibited the largest discrepancies at higher return periods, such as Tr = 50 and Tr = 100. These results suggest significant regional variation in precipitation intensities, with certain areas like Nir and Parsabad experiencing higher levels of extreme precipitation compared to stations like Namin and Ardabil Airport. This variation can have important implications for flood risk management, sediment yield resulting from heavy rainfalls, management of reservoir dams in heavy floods, and water resource planning in the region. Additionally, the Mann-Kendall test revealed a mix of trends in maximum daily precipitation over time. While some stations showed significant increasing trends, such as Sareyn, others demonstrated either decreasing or no significant changes. This indicates that precipitation patterns in Ardabil Province may be subject to local climatic shifts, possibly influenced by broader climate change trends. Overall, the study emphasizes the importance of region-specific analysis in understanding extreme precipitation events and indicates the need for targeted water infrastructure planning and flood risk management strategies in different parts of Ardabil Province.

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