



Regional Climate Change and Drought Dynamics in Tunceli, Turkey: Insights from Drought Indices

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Abstract

Global warming and climate change are causing temperatures to rise, which is having a negative impact on water resources. Climate change is a worldwide problem that affects and will continue to affect the frequency and intensity of natural disasters in many regions of the world. Tunceli region in Turkey, which until 10 years ago was known as an environmentally friendly city with abundant water resources and frequent rainfall, is experiencing a decrease in precipitation during the snowy winter season. This situation has made the investigation of climate change impacts an important issue in the region. Therefore, effective climate change adaptation strategies need to be developed. To determine these strategies, in this study, we assessed long-term drought conditions using multiple drought indices such as Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI), Normal Precipitation Index (PNI), and Aridity Index (AI). The SPI and RDI analyses were performed in annual reference periods on a time scale of 3, 6, 9, and 12 months using temperature, precipitation, and evaporation data. Consequently, the SPI and RDI results were compared, and both indices show similar behavior in dry, wet, and normal seasons. Nevertheless, RDI shows less variation between different time scales, which is an advantage over SPI and is probably due to the inclusion of potential evapotranspiration in RDI. The variations in PNI between humid and dry sub-humid categorizations throughout the years, combined with the AI results, indicate that the Tunceli region predominantly experiences a climate ranging from dry sub-humid to semi-arid. This study could help decision-makers take effective measures to become more resilient to climate change in temperate climate regions and take important steps toward sustainable water resources management.

Keywords Climate change · Drought · RDI · SPI · Water scarcity

Introduction

Climate change poses a significant threat worldwide, leading to severe and erratic weather events such as extreme rainfall, droughts, and forest fires [2]. One of the most notable impacts of climate change is drought, which poses a major threat and has a particular impact on agriculture, water resources, ecosystems, and human life. In drought-prone

countries like Turkey, developing effective drought mitigation and adaptation strategies is crucial [20].

Drought is a temporary and often severe shortage of water resources and is caused by short-term climatic fluctuations. Unlike aridity, drought can occur in both arid and non-arid regions and is considered an anomaly, not a permanent climate feature. Aridity, on the other hand, is a long-term climate feature and is the result of low rainfall and high evaporation rates. Aridity is usually determined by geographical factors and is measured using climatic indices such as De Martonne's aridity index (Iar-DM) [3, 59].

Thus, drought is a natural phenomenon that has adverse effects on water resources and human activities, especially agriculture [17, 34, 38, 57]. It can be defined as a temporary but natural imbalance of water, characterized by less frequent, variable duration and intensity of rainfall below average [44]. It is an event that is difficult to predict or model, leading to reduced availability and carrying capacity of

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water resources in ecosystems [37]. Various indices have been proposed and used to define and analyze droughts. The most commonly used drought index is the Standardized Precipitation Index (SPI), a normalized index for calculating deviations from normal precipitation conditions. The SPI requires only monthly precipitation data, is easy to calculate, and is standardized to allow easy comparison between different periods or regions [28].

Merabti et al. [29] compared two drought indices, the SPI and the RDI, at the local level in northeastern Algeria on a time scale of 3, 6, and 12 months. Both indices showed similar and consistent results when applied to different sites and climatic zones. Only minor differences were found between the indices for the 3-month scale [30]. In arid and semi-arid regions, the SPI detected more drought events, while in wetter climates, both the SPI and RDI detected more wet events. This behavior suggests that drought and humidity events in semi-humid climates are primarily related to precipitation and thus play a less significant role in differentiating between SPI and RDI based on potential evapotranspiration (PET). Drought indices such as SPI and RDI allow an in-depth analysis of drought risk [19].

Kim and Jehanzaib [21] discuss the rapid expansion of drought risk analysis, prediction, and assessment due to climate change and emphasize the importance of accurate monitoring and comprehensive assessment for reliable decision-making on drought risks and water resources. They present new approaches for drought monitoring and risk prediction. Meza et al. [33] provide an integrated assessment of drought risk for both irrigated and rain-fed agricultural systems on a global scale and identify regions with high drought risk, such as Southeast Europe and Northern and Southern Africa. Ahmadi et al. [1] assess drought risk at the national level across Africa, examine the impact of climate change, population growth, and socio-economic vulnerabilities on drought risk, and emphasize the importance of adaptation measures to mitigate drought risk.

Liu and Chen [25] analyzed future global socio-economic risks for droughts under different climate change scenarios, identified regions with high socio-economic risks, and highlighted the inequality of future socio-economic risks for droughts between countries. Sahana and Mondal [41] assess future trends in drought hazard, vulnerability, and risk in India, highlight the influence of societal developments on drought vulnerability, and point to the need for strong mitigation and adaptation planning. Lehner et al. [24] examine changes in drought and risk of successive drought years under 1.5 °C and 2 °C global warming scenarios and find significant regional differences in future drought risk. Dai et al. [9] propose a drought assessment framework to investigate the changes in drought characteristics and risks in China under climate change, providing useful information for effective long-term adaptation strategies. The volume

of the world's water resources remains constant due to the water cycle. Still, climate change is altering water availability at different temporal and spatial scales, jeopardizing several ecosystem services [11].

In drought-prone countries such as Turkey, a handful of studies have recently focused intensively on drought assessment at regional [15, 31, 35, 50] and country scale [7, 20, 47]. Nevertheless, to the best of our knowledge, there is no comprehensive study that analyzes droughts in higher resolution and using multiple drought indices in the Tunceli region [22]. Furthermore, since the region is characterized by a temperate climate, effective management of the water resources is crucial to secure sufficient water for water supply, agriculture, and electricity generation through several dams built in the region.

Factors such as decreasing river flow as a result of global warming, increasing evaporation losses from reservoirs due to rising temperatures, increasing water demand due to increasing population and industrial production, and decreasing irrigation water amount reveal the need to make water use more efficient. As a result, dams are built to meet the water demand. Indeed, dams play an important role in storing water and then using it for purposes such as irrigation, electricity generation, and drinking water supply. However, the disadvantage of these structures is that evaporation losses increase with the increase in the surface area of water reservoirs. Building more dams as a precaution against drought is certainly not a solution. The dams that have already been built need to be reviewed, and evaporation losses can be reduced by not retaining water in some of them or covering them with floating PV, which at the same time provides some extra clean energy [39]. In addition, the increasing demand for irrigation and drinking water causes the water reserves in dams to decrease [51]. Therefore, for sustainable management of water resources, dams should be planned, built, and managed strategically by taking into account the effects of climate change.

Additionally, the regional effects of forest fires on global warming are significant, and the increasing fire activity is linked also to climate change by exacerbating the environmental conditions. Changes in the ratios of tree species and a decrease in tree regeneration under drought conditions make forests more susceptible to more frequent and severe fires [48, 53]. In the Mediterranean and other regions, the frequency and severity of fires induced by weather conditions have increased, making these areas more vulnerable to fires.

In the 2013–2018 period, the number of forest fires generally remained at low levels, while the amount of burned area was minimal. However, in 2019, there was a dramatic increase in both the number of fires and the amount of burned area. In particular, eight fires broke out in 2019, burning a total area of 53.68 ha. This represents a significant increase compared to previous years, suggesting that

fires in 2019 were more severe or more difficult to contain. It shows that they increased as a result of the effects of climate change or other environmental factors, among others. In recent years, especially in the summer of 2021, the wildfires in Turkey have caused significant losses. Pre-fire temperatures have been observed to be affected by heat waves at many stations [10].

Thus, this study focuses on the assessment of drought risk in Tunceli, a region in the eastern part of Turkey known for its natural beauty and pristine environment. Tunceli experiences heavy snowfall in winter, but in recent years, precipitation has decreased due to climate change [5]. This situation has made climate change a major issue in the region and beyond. Tunceli is one of the regions considerably affected by the impact of climate change and is, therefore, at potential risk of drought [47]. Consequently, it is important to develop effective strategies to adapt to climate change. For that purpose, in this study, we employed multiple drought indices to assess the long-term dynamic of droughts in the Tunceli region. In this context, the study aims to determine the drought risk in Tunceli in order to help stakeholders consider

appropriate climate change adaptation strategies, especially focusing on better management of water resources.

Materials and Method

Study Area

The Tunceli region lies in the Upper Euphrates Basin in the Eastern Anatolia region of Turkey and is located between longitudes 38°19'—40°26' east and latitudes 39°36'—38°46' north. As shown in Fig. 1, this region is surrounded by the regions of Bingöl, Erzincan, Elazığ, and Keban Reservoir. It covers an area of 7,774 km² with an altitude that ranges from 800 to over 3000 m above sea level. The region consists of 70% mountains, 25% plateaus, and 5% plains, which indicates the high and rugged terrain of Tunceli. Among the most important geographical features of Tunceli are the high mountains such as the Munzur, Mercan, Gobarti, Zel, and Sevdin Mountains.

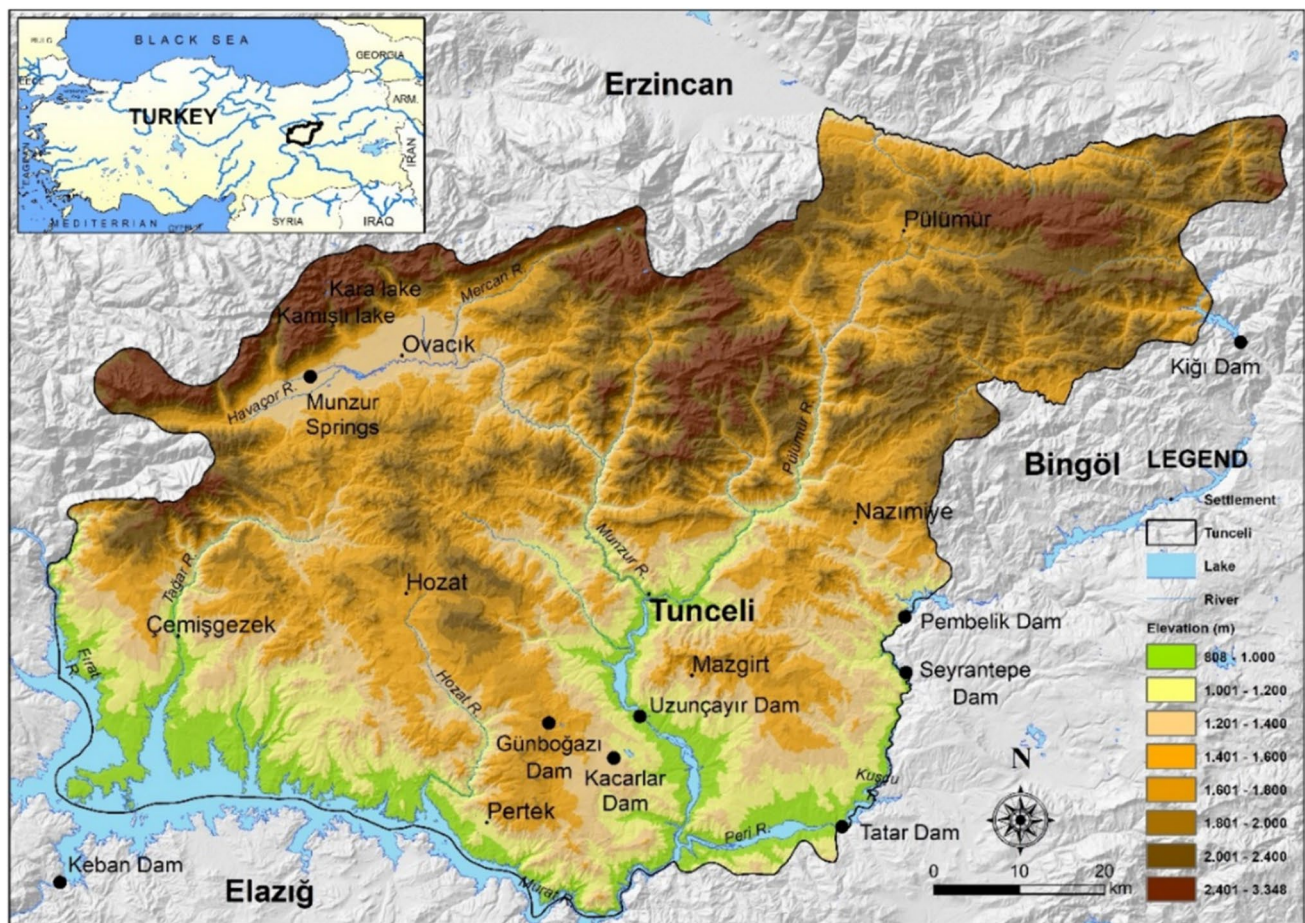


Fig. 1 The location of Tunceli region in Turkey

These mountains allow for significant rainfall under harsh continental climate conditions and the formation of deep valleys by strong flowing rivers. Important rivers such as Munzur, Mercan, Pülümür, Tağar, and Peri flow into the Keban reservoir. There are no significant plains or flatlands in the region, but there are craters and glacial lakes. The natural beauties of Tunceli are mainly concentrated in areas such as the Munzur Valley, Zage, Ali Boğazı, Kutudere, and the Pülümür Valley [32]. Considering the climate and topography of Tunceli, the rainfall distribution data presented in Fig. 2 could be crucial for planning regarding various aspects such as agriculture, settlements, infrastructure, and natural resource management.

Higher elevations tend to receive more precipitation, while valleys and low-lying areas may receive less. Rainfall maps are an important tool in decision-making related to water resource management, droughts, and flood risks.

Dataset

Climate change assessments generally use meteorological data from the last 30 years. This study provides a solid foundation for understanding the effects of climate change in the region using 43 years of average rainfall data and making predictions about future climate scenarios [49]. Stations used in the Tunceli region generally exhibit characteristics of a terrestrial climate. The region experiences heavy snowfall during the winter months, while summers are hot and dry. Due to the high altitudes at which the stations are located, annual average temperatures are usually low, and precipitation varies. When examining the climate data of the Tunceli, Pülümür, Çemişgezek, Hozat, Nazımiye, Ovacık, Pertek, and Mazgirt stations, it is observed that these areas generally fall into dry, humid and semi-arid climate classifications. Particularly in recent years, increases in temperatures and decreases in precipitation levels indicate that the region is affected by climate change. Meteorological data were obtained from the Meteorological Data Bank System (MEVBİS, 2022) (Table 1). Missing entries were identified

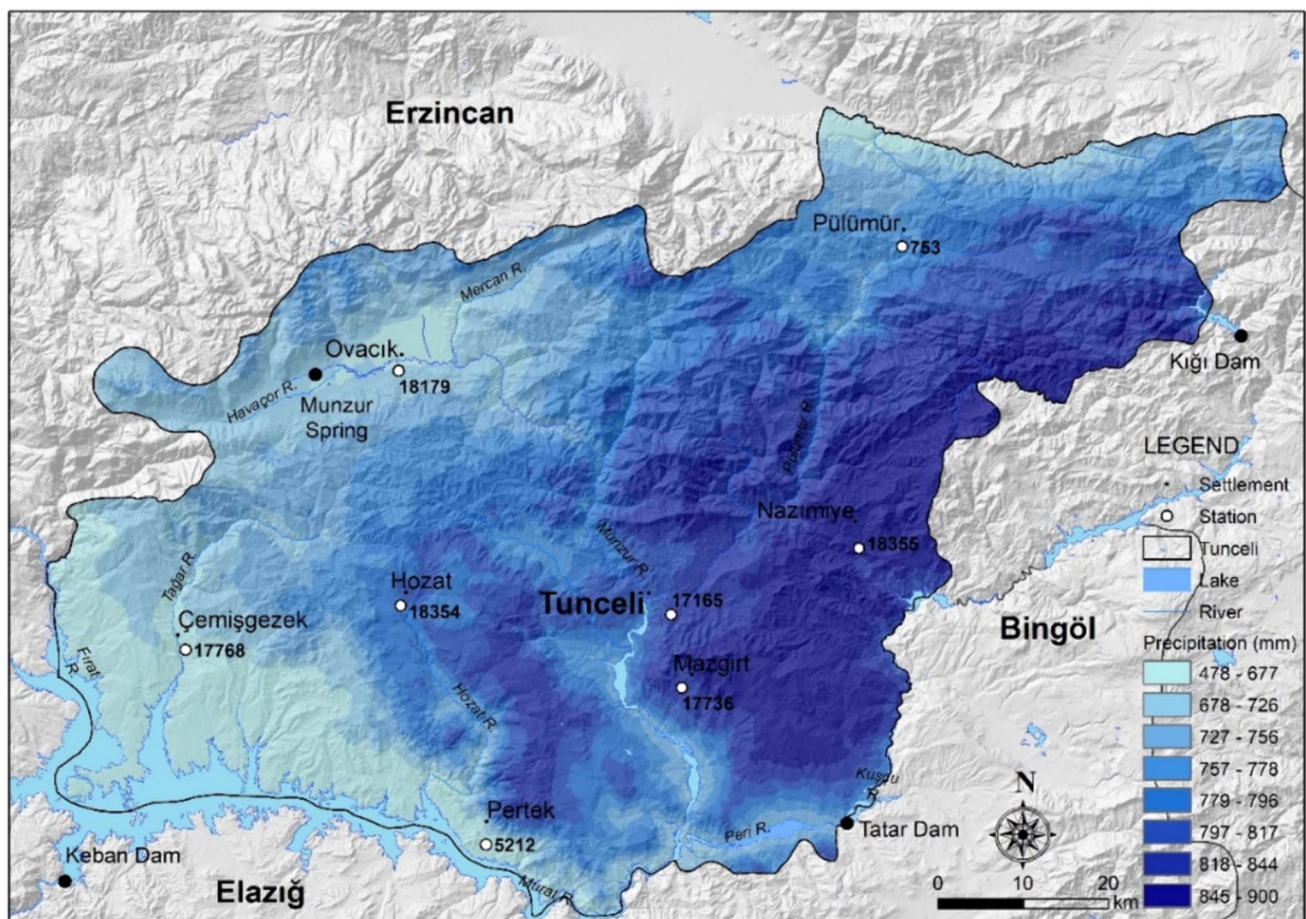


Fig. 2 Precipitation map for Tunceli region in eastern Anatolia, Turkey

Table 1 Selected stations in Tunceli region—temperature and precipitation trends

Station No	Station Name	Climate Classes	Elevation (m)	Latitude (E)	Longitude (N)	Mean Temperature (°C)		Mean Precipitation (mm)	
						1979	2023	1979	2023
17165	Tunceli	Dry Humid	981	39.10	39.54	10.9	13.4	711	620
753	Pulumur	Dry Humid	1550	39.48	39.89	6.8	9.6	980	884
17768	Çemişgezek	Semi-Arid	898	39.06	38.91	12.1	14.9	548	476
18354	Hozat	Semi-Arid	1485	39.10	39.22	11	13.4	639	565
18355	Nazımiye	Dry Humid	1602	39.18	39.82	8.2	11.3	954	872
18179	Ovacık	Dry Humid	1280	39.35	39.21	11	13.4	639	565
5212	Pertek	Semi-Arid	1000	38.86	39.32	12	14.7	652	589
17736	Mazgirt	Dry Humid	1400	39.0	39.60	10.9	13.4	711	620

in the evaporation dataset sourced from MEVBIS. Missing data are a common issue in research studies and are typically addressed using various statistical methods [6].

In this study, a linear regression model was employed to estimate the missing evaporation data. Linear regression is an effective tool for predicting missing data in areas such as hydrology and water resources management [6, 26]. The linear regression model defines the relationship between a dependent variable.

The components of this equation are Eq. 1:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_p X_p + \varepsilon \quad (1)$$

Y The predicted value, such as monthly evaporation.

β_0 The intercept term of the model.

β_i The coefficients of the independent variables, each representing the impact of variables in the dataset on evaporation.

X_i The independent variables of the model may include meteorological factors like temperature and wind speed.

ε A random error term representing the variation not explained by the model.

p Represents the p_{th} observations of the variable X_1, X_2, X_3, X_p respectively.

Drought Analysis

In this section, we delve into the analysis of drought dynamics and trends in the Tunceli region using a comprehensive array of indices: the Standardized Precipitation Index (SPI),

the Reconnaissance Drought Index (RDI), the Precipitation Normalization Index (PNI), and the Aridity Index (AI). This approach allows us to quantify the severity and duration of droughts, assess variations in precipitation against long-term averages, and evaluate the degree of aridity based on evaporation and precipitation balances. Through this multifaceted assessment, the study aims to provide a thorough understanding of the impact of drought conditions on the region's hydrological cycle.

The RDI quantifies the intensity of drought by incorporating elements of the hydrological cycle, such as precipitation and evaporation. The SPI is calculated by standardizing precipitation data against long-term averages to identify anomalies in precipitation over different periods and assess the onset and duration of droughts. The following “reference periods” and “calculation time intervals” were used in this study, namely, 12, 6, 3, or 1 month, starting in October [45].

12 months: From October to September.

6-month: Options from October to March or April to September.

3-month: Quarterly intervals, starting from October.

1-month: Monthly analysis, beginning in October.

The Standardized Precipitation Index (SPI)

The SPI is calculated exclusively on the basis of precipitation data and, therefore, requires less data and computing time. It can be calculated on different time scales, e.g., 1 month, 3 months, 6 months, 9 months, or 12 months, and can detect approaching droughts earlier than the Palmer Index. According to Eq. 2, the SPI is derived by dividing the deviation of the precipitation series from its mean value by the standard deviation [52].

$$SPI = \frac{P_i - P_0}{\sigma} \quad (2)$$

where $P_i, P_1, P_2, \dots, P_n$; standardized precipitation series, P_0 ; the mean value of the series, σ ; the standard deviation. Due to the complexity of calculating precipitation events, the precipitation series are first adjusted to a normal distribution. The SPI method is applied to at least 30 years of continuous monthly precipitation data, and drought classifications are made according to the categories listed in Table 2.

The meteorological droughts consider the impact of precipitation deficits on water resources and calculate them over periods of 1, 3, 6, 9, and 12 months. These periods are selected on the basis of the duration over which the effects of precipitation deficits on available water resources may be evident. For instance, a decrease in precipitation in a given month may have an immediate impact on soil moisture [34]. At the same time, the effects on groundwater and rivers may be evident over a longer period [25].

Reconnaissance Drought Index (RDI)

The RDI is a drought analysis method that uses potential evapotranspiration (PET) and precipitation data. Data on minimum and maximum temperatures are used to calculate the PET values [46]. The initial α_0 values for estimating the RDI index values in the reference periods are determined from Eq. 3 ($i = 1$ to N and $j = 1$ to 12):

$$\alpha_0^i = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PET_{ij}} \quad (3)$$

Here, P_{ij} and PET_{ij} represent the precipitation and evaporation values for the i year and j month, typically starting in October, and N is the total number of years. Potential evapotranspiration is calculated based on Eq. 4 (H. Hargreaves and A. Samani, 1985; [46]).

$$PET = 0.0023 \left(\frac{T_{max} + T_{min}}{2} + 17.8 \right) \sqrt{T_{max} - T_{min}} \cdot R_a \quad (4)$$

where T_{max} maximum temperature, T_{min} minimum temperature; R_a is the extraterrestrial solar radiation, which depends on the month of the year and the latitude of the observation

area. The Normalized RDI (RDI_n) for each year is calculated using Eq. 5, where the α_0 parameter is the arithmetic mean of the α_0 values calculated over N years:

$$RDI_n^i = \frac{\alpha_0^i}{\bar{\alpha}_0} - 1 \quad (5)$$

The Standard RDI (RDI_{st}) is calculated using Eq. 6:

$$RDI_{st}^i = \frac{y^i - \bar{y}}{\sigma_y} \quad (6)$$

where y^i is the value of $\ln \alpha_0^i$, $\bar{y}$ is the arithmetic mean, and σ_y is its standard deviation. The classification of RDI is similar to that of SPI, which is provided in Table 2.

The Normal Precipitation Index (PNI)

The PNI index calculates the deviation of precipitation from its long-term average value. The normal value is 100% and can be calculated for a month, a season, or a year [13]. The PNI is one of the basic indicators for drought assessment and is effective for dry and wet time series over a given season. The PNI is calculated using Eq. 7:

$$PNI = \frac{P_i}{P_0} * 100 \quad (7)$$

where P_i , Annual precipitation, P_0 ; the long-term average. The classification of PNI is similar to that of SPI, and RDI provided in Table 2.

Aridite Index (AI)

The AI can be calculated using the RDI in the DrinC model [45]. In contrast to the PNI, the AI indicates the degree of dryness, taking into account factors beyond precipitation. Since high or low temperatures can lead to increased or decreased evaporation, the degree of dryness is often expressed by dividing the annual precipitation amount by the potential evaporation amount, resulting in the AI. The AI is usually expressed as the ratio of annual precipitation (P) to annual potential evaporation (E_p) [4]. The Aridity Index (AI) is typically calculated using the formula, Eq. 8:

$$AI = \frac{P}{E_p} \quad (8)$$

AI is considered an uncertain term, as potential evaporation cannot be measured directly and can only be estimated. AI defines the ratio between annual potential evaporation and average annual precipitation. Depending on the value of AI, typical climate characterizations are as follows:

Hyper-arid: $AI < 0.05$.

Arid: $0.05 < AI < 0.20$.

Table 2 Drought classification of SPI, PNI, and RDI [28, 36, 46]

Drought class	SPI and RDI	PNI
Extremely wet	≥ 2	≥ 110
Very wet	1.5—1.99	
Moderately wet	1.0—1.49	
Normal	0.99—0.99	80—110
Moderately dry	−1 to −1.49	55—80
Severely dry	−1.5 to −1.99	40—55
Extremely dry	≤ -2	≤ 40

Semi-arid: $0.20 < AI < 0.50$.

Dry sub-humid: $0.50 < AI < 0.65$.

Humid: $AI > 0.65$.

Results and Discussion

Precipitation and Evaporation Trends

This study examines how a region far from urbanization and industrialization is affected by climate change. It demonstrates that the changes in rainfall and droughts in recent years are closely linked to climate change and global warming [47]. The results of this study provide crucial insights into the climate dynamics of the Tunceli region, particularly in relation to precipitation, temperature anomalies, and drought conditions. Analysis of 43 years of precipitation and evaporation data shows a clear upward trend in annual precipitation. If precipitation remains constant over a longer period and temperatures rise, it is supposed that drought conditions occur in the region [12]. Theoretically, the intensity of drought is best explained by calculating drought indices based on potential evaporation and precipitation data. As mentioned above, at least 30 years of data are required to calculate the drought indices [30]. In this study, 43 years (1980 to 2023) of precipitation and evaporation data were used for the analysis. The first 20 years (1980–2000) constitute the first half, while the subsequent 23 years (2001–2023) form the second half. This trend analysis, based on the Innovative Trend Analysis method, underscores significant variations

in precipitation patterns, critical for regional climate assessments [42]. Figure 3 (left side) shows the total annual rainfall per unit area of approximately 794.27 mm. The upward trend line in the scatter plot on the right shows an increasing trend in rainfall over time, indicating that the climate in the region is becoming increasingly wetter.

Figure 3 (right) illustrates an overall increasing trend in precipitation across multiple locations in the Tunceli region, as indicated by the majority of data points lying above the $y = x$ line, suggesting enhanced precipitation (rainfall) in the second half of the time series compared to the first. The graph illustrates the relationship between precipitation amounts in the first half of the analyzed time series (on the x-axis) and precipitation amounts in the second half (on the y-axis). The low R^2 value (0.016) shown in Fig. 3 (left) indicates that the trend line explains only a small portion of the variance in precipitation amounts. This suggests that there may be other factors influencing precipitation that can only be uncovered by a more detailed analysis [46]. To summarize, the upward trend line in the distribution diagram in Fig. 3 (right) indicates a tendency towards increasing precipitation over time, suggesting that the climate in the region may be becoming wetter.

Precipitation and Temperature Anomalies

The long-term goal of the Paris Agreement is to keep the global temperature rise well below 2°C compared to pre-industrial levels, ideally at 1.5°C [40]. Achieving this goal will require a gradual reduction in the use of fossil fuels (i.e.,

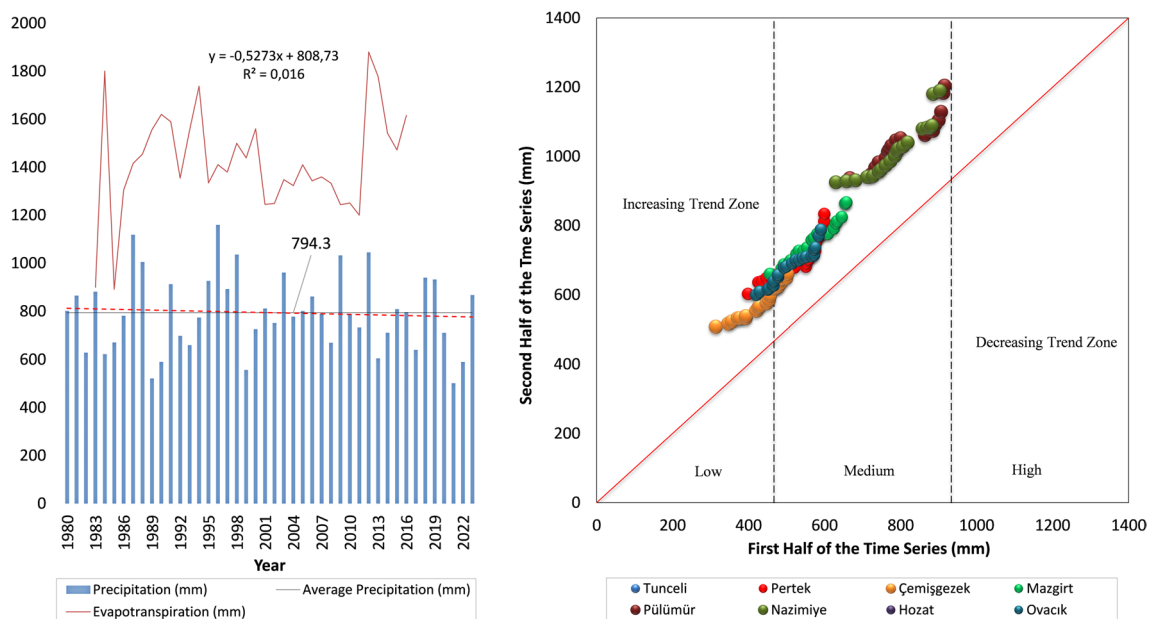


Fig. 3 Representation of annual precipitation and evaporation (left) for the region of Tunceli and precipitation trend (right) at eight stations in Tunceli

oil and coal) and a switch to renewable energy sources. The effects of climate change are already present; these include rising air temperatures, melting glaciers, shrinking polar ice caps, rising sea levels, increasing desertification, and more frequent extreme weather events such as heatwaves, droughts, floods, and storms [1, 18]. Climate change does not affect all regions equally and has a greater impact on some areas than others.

Figure 4 shows the average annual temperature for the Tunceli region taken from Meteoblue [32]. The data source is taken from ERA5, the fifth generation of atmospheric reanalysis of global climate by ECMWF, which covers the period from 1979 to 2023 with a spatial resolution of 30 km. The data may not accurately reflect conditions at a given location. Therefore, temperatures will often be higher than shown, especially in urban areas, and precipitation may vary locally depending on topography [27].

The dashed line represents the linear trend of climate change. If the trend line rises from left to right, this indicates a positive temperature trend, suggesting that Tunceli is experiencing warming due to climate change. A horizontal trend line would not indicate a clear trend, and if the trend line is decreasing, this indicates that temperatures in Tunceli are cooling over time [14]. The lower part of the graph shows warming stripes. Each colored stripe represents the average temperature for a year, with blue representing cooler years and red representing warmer years. Figure 4 displays a clear trend of rising temperatures at Tunceli station over the long years. This trend has become increasingly prominent since 2014, with temperatures consistently exceeding previous records. Furthermore, examining the color bands in Fig. 4 reveals that global climate change, which is evident through

the gradual increase in temperature, has been on the rise since 1998. Figure 5 presents the average total precipitation forecast for Tunceli; data are taken from Meteoblue [32].

The dashed line in the figure represents the linear trend of climate change. If the trend line slopes upward from left to right, it indicates a positive precipitation trend. If it is horizontal and runs flat, no clear trend can be observed. However, a downward slope suggests that conditions are gradually leading to less precipitation, indicating that Tunceli is becoming drier over time, which is surprising in contrast with the precipitation trend based on ground observation data presented in Fig. 3. This discrepancy may be mainly due to the issues regarding the assimilation of precipitation from the ERA5 data set [43]. Still, it may also be due to the quality of the ground observation data [23]. The graph at the bottom of Fig. 5 displays precipitation bars; each colored bar represents the total precipitation for a year, with greener bars indicating wetter years and brown bars indicating drier years. Overall, based on Fig. 5, it can be observed that as temperatures increase, precipitation decreases in Tunceli. Nevertheless, as suggested by many studies, we have carried out the drought risk analysis using the ground observation data set [47].

Drought Dynamic According to SPI

Understanding how precipitation amounts change over time is vital for water resource management and agricultural planning. Figure 6 shows the SPI calculated over a 3-month period on an annual basis. The analysis reveals that the 3-month SPI values in Tunceli typically range between -1 and 1, indicating drought conditions within normal limits.

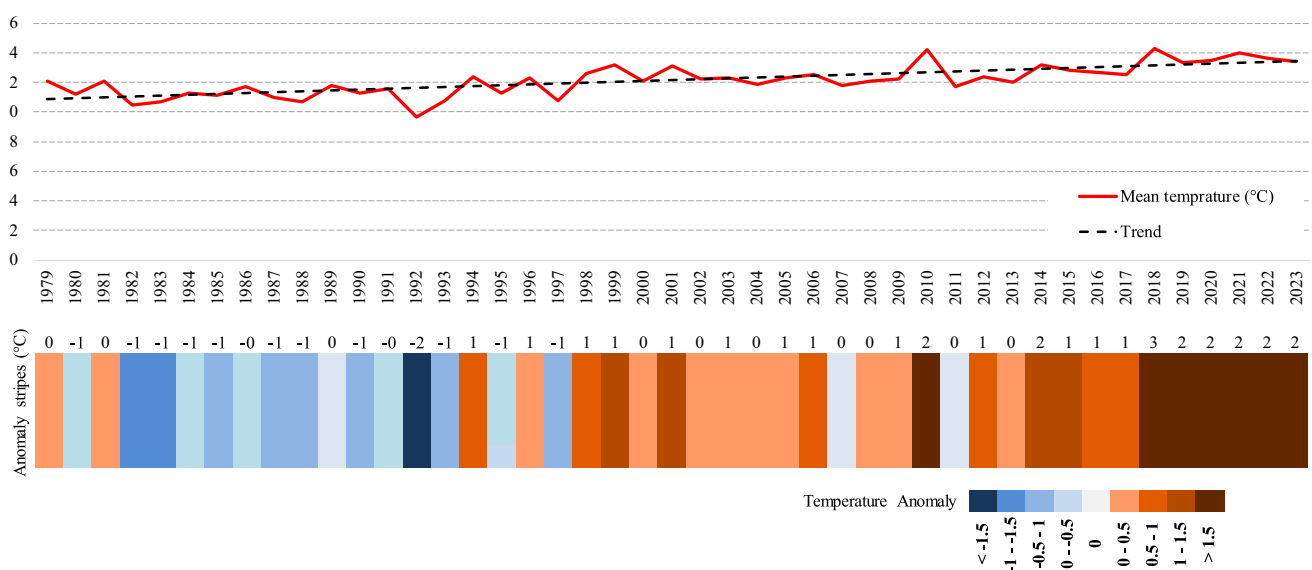


Fig. 4 Mean annual temperature trend and anomalies for Tunceli region

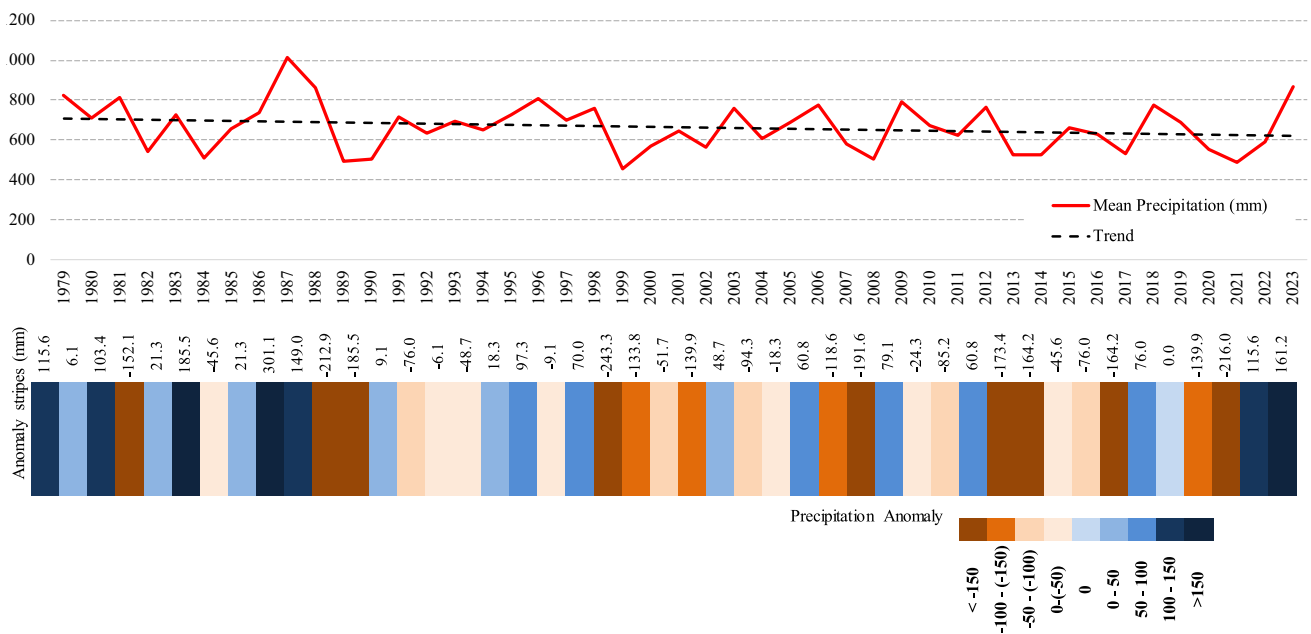


Fig. 5 Mean annual precipitation trend and anomalies for Tunceli region

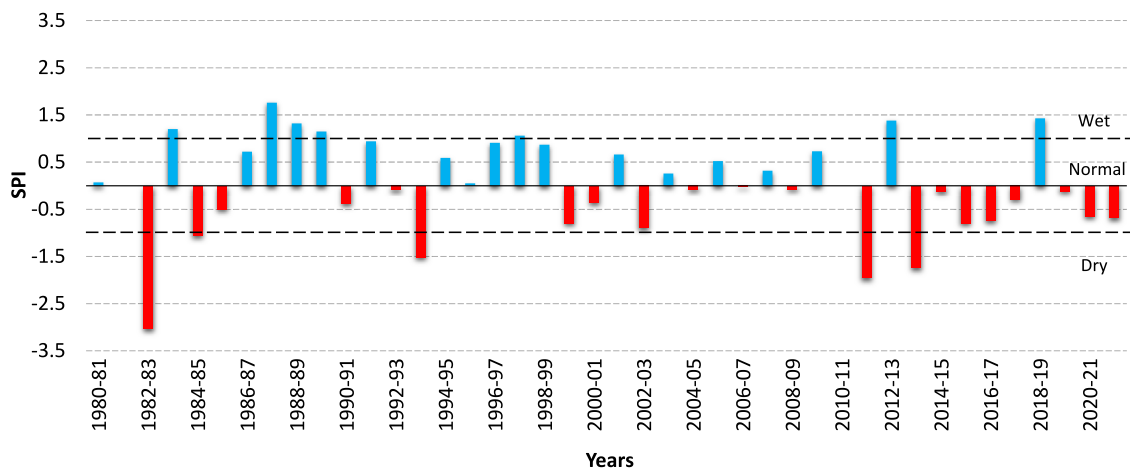


Fig. 6 Results of SPI (3-month period)

Generally, values > -1 signify wet, while values < -1 signify drought conditions.

The SPI is a measure that indicates whether precipitation in a particular region is above or below the long-term average. A positive SPI value ($+1.0$ or greater) suggests above-normal precipitation, indicating wet conditions, while a negative value (-1.0 or less) indicates below-normal rainfall, which can lead to dry conditions. The SPI value is calculated for each year and period and is represented by a bar graph. The height of the bars illustrates the magnitude of the SPI value, and the direction indicates whether it is positive (upward) or negative (downward).

Figure 7 shows the SPI values for each month from 1980 to 2023, indicating the dry years, drought duration, and also the interval between drought events. From the graph, it appears that there is no long-term extreme drought in the Tunceli region. It is crucial to understand the frequency and recurrence of droughts, as this helps predict future climate patterns and take preventive measures to manage water resources better.

Figure 8 shows the SPI values for different periods (3–6–9–12 months) over several years. The 3-month SPI values can predict short-term droughts, which can fluctuate more frequently and suddenly due to seasonal changes.

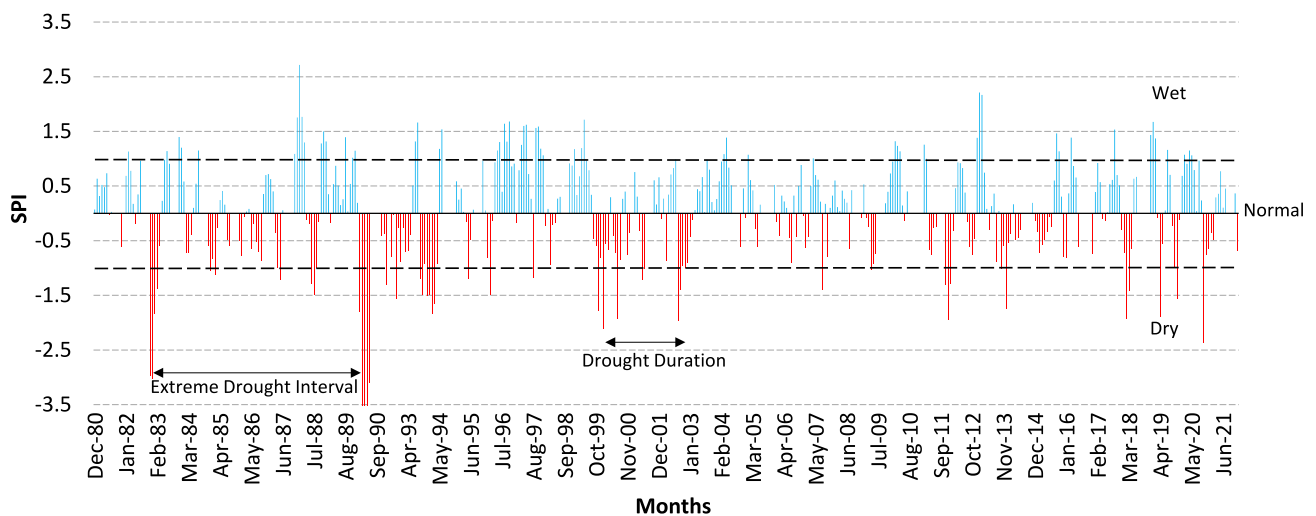
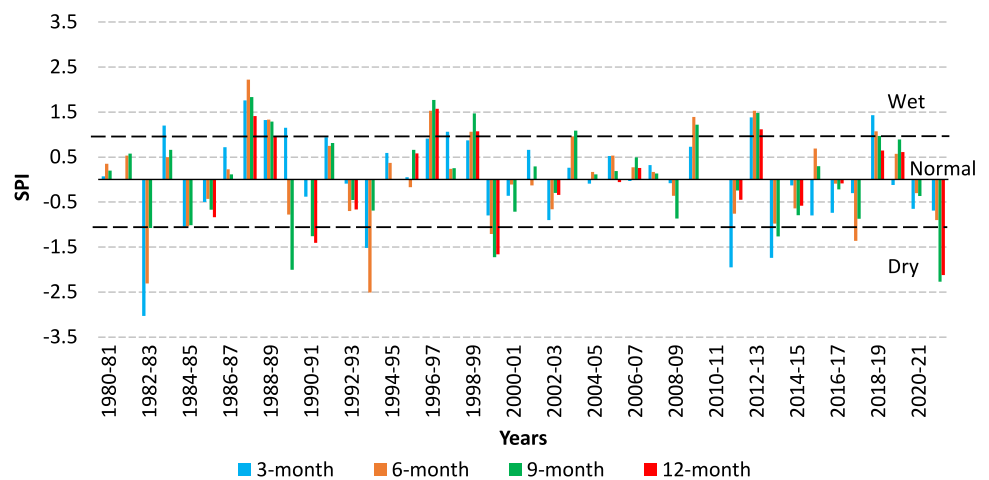


Fig. 7 Results of SPI (3-month period)

Fig. 8 Results of SPI (3–6–9–12 month period)



As shown in Fig. 8, the 3-month SPI values are higher. On the other side, the 6-month SPI analysis smoothens some of the variability observed in the 3-month SPI and provides a better explanation of medium-term moisture trends. The 9-month SPI analysis results align more closely with annual cycles. At the same time, the 12-month SPI reflects long-term trends by smoothing out most short-term fluctuations and highlighting broader drought patterns or periods of high precipitation. As per the results shown in Fig. 9, the SPI values calculated for 3, 6, 9, and 12 months over the years generally fall in the normal drought class. In Fig. 9, the SPI was calculated over 9 months. The pie chart shown alongside indicates the percentage distribution of different SPI categories such as Dry, Normal, and Wet.

Negative SPI values indicate drier conditions (i.e., below-average precipitation), whereas positive values indicate wetter conditions (i.e., above-average rainfall). So, there are significant fluctuations between wet and dry periods in

the time series. The cyclical nature of SPI values highlights the variability in precipitation over time, suggesting that the region experienced normal drought conditions throughout the period.

Drought Dynamic According to RDI

The RDI Index is a measure that analyzes drought conditions by using precipitation and potential evapotranspiration data over a reference period. This allows for comparisons to be made between different periods and climates. A positive RDI value indicates normal or humid conditions, while negative values indicate dry conditions. Looking at Fig. 10, we can see that the 3-month RDI values in Tunceli are generally between -0.5 and 0.5, indicating that the current drought is within normal limits. From 1980 to 2023, the data has mainly fluctuated between -0.5 and 0.5, indicating

predominantly normal dryness with occasional deviations to mild stress conditions.

Figure 11 shows a composite analysis of the RDI over several time scales: 3, 6, 9, and 12 months. This

multiscale approach allows the observation of drought conditions with different durations and intensities. During these periods, the RDI values hover around the zero mark, indicating a state of equilibrium in terms of moisture

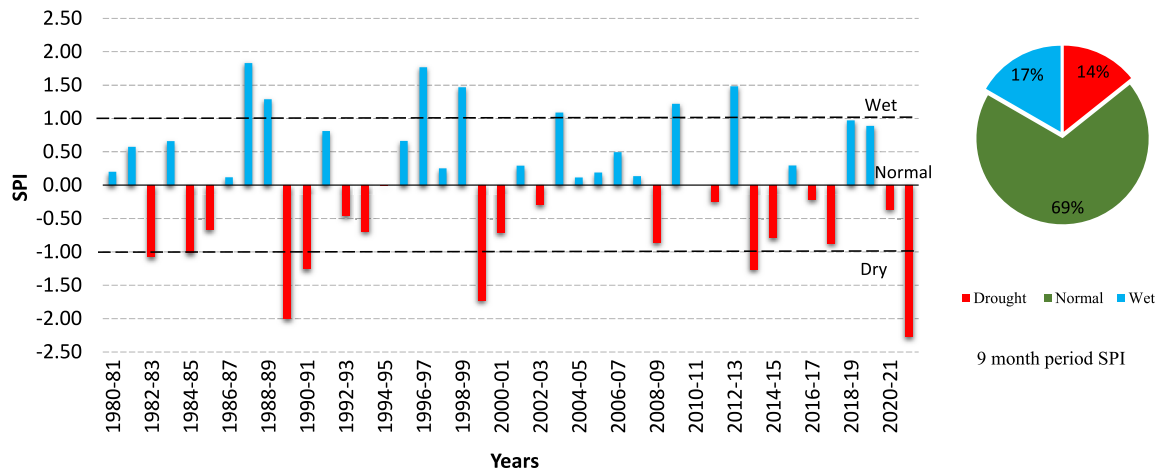


Fig. 9 Results of SPI (9-month period)

Fig. 10 Results of RDI (3-month period)

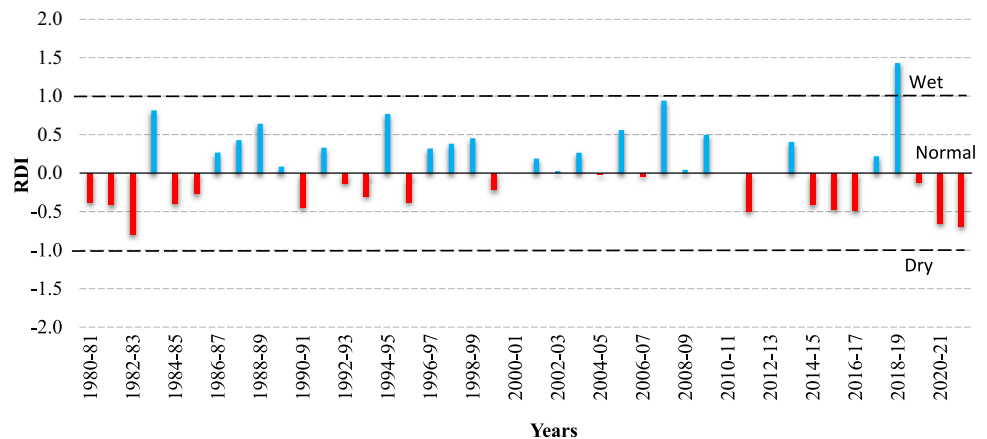
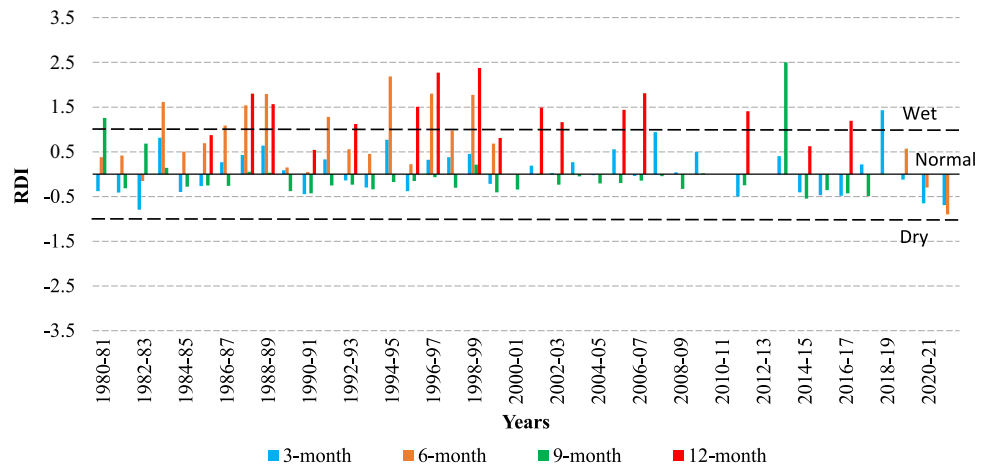


Fig. 11 Results of RDI (3–6–9–12mmmonth period)



availability. The analysis is in a stable range of normal drought with no significant long-term deviations toward extreme drought or wetness.

Figure 12 shows SPI values for 9 months in Tunceli from 1980 to 2021. The SPI values are mostly just below zero, indicating a general tendency towards normal moisture conditions in most years. A spike on the right side of the graph represents a significant drought event within this annual interval.

However, the accompanying analysis of the pie chart shows that drought events account for only 5% of the observed period, which yet falls within the Normal conditions during 95% of the analyzed period. This indicates that droughts are less frequent in the Tunceli region, and hydrological conditions are generally stable.

Drought Dynamic According to PNI and AI

Figure 13 presents the PNI results for Tunceli, which a single station represents over several years. The PNI index uses only precipitation data to analyze its results. The PNI values fluctuate from year to year, surpassing several drought category thresholds. It is important to note that none of the years fall into the “hyper-arid” category. In contrast, many years fall into the “humid” and “dry sub-humid” categories, indicating a fluctuating but mostly non-arid climate. This variability underscores the impact of global warming and necessitates the development of new drought management strategies.

Figure 14 shows the AI, categorized into different Aridity Thresholds, calculated over different RDI time scales: 3, 6, 9, and 12 months. The index values indicate a generally dry, sub-humid to semi-arid climate in the region. The 9-month

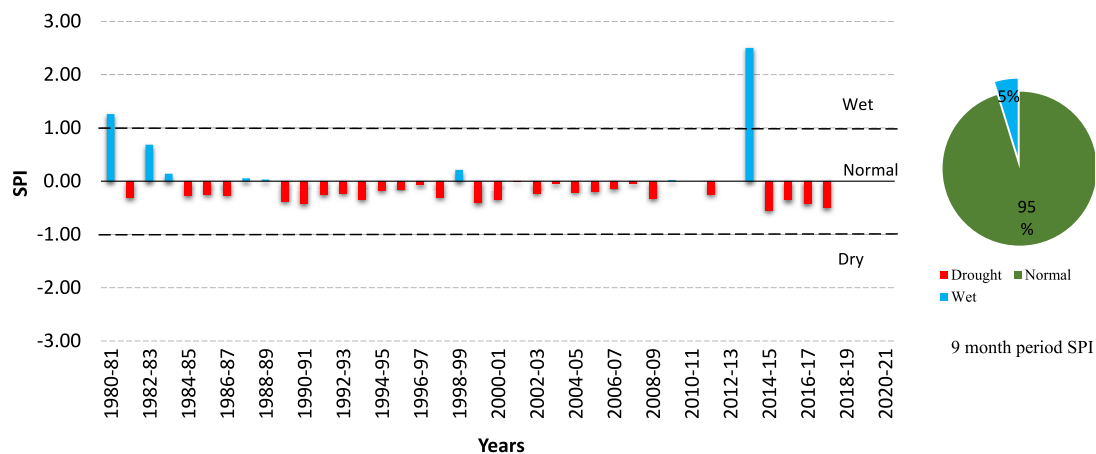


Fig. 12 Results of SPI (9-month period)

Fig. 13 Precipitation Normality Index (PNI) results from 1980 to 2021

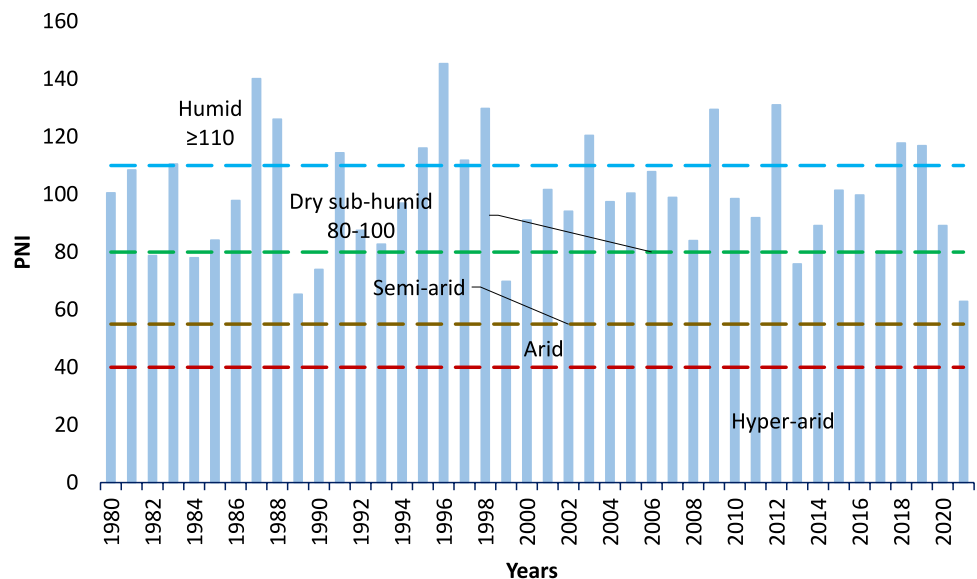
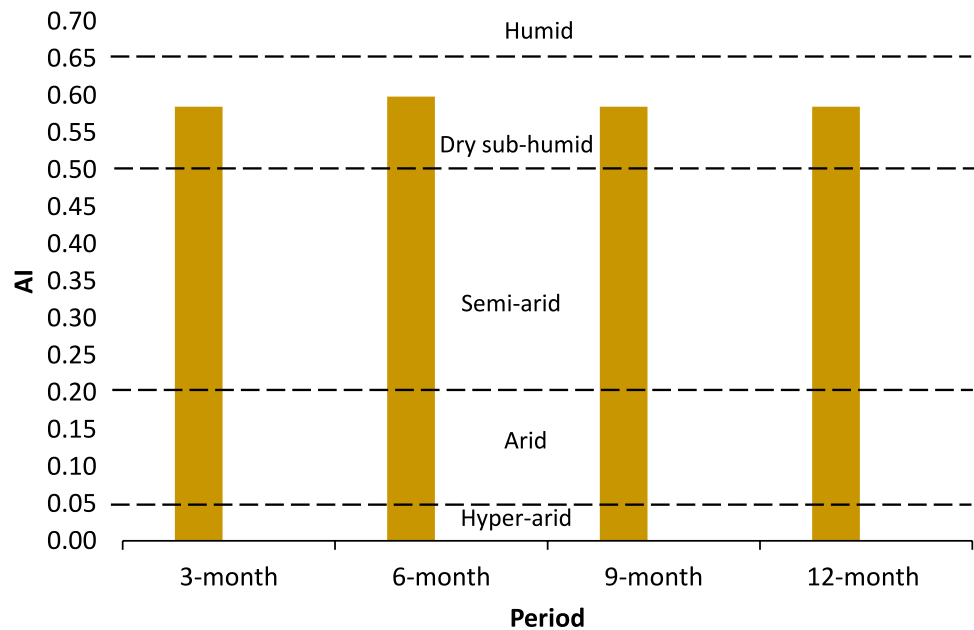


Fig. 14 Results of Aridity Index (AI) for different periods

RDI period shows a trend towards drier conditions compared to the other periods, which could indicate seasonal patterns or longer-term shifts in regional aridity. This analysis is crucial to understanding the degree of drought and its distribution over time, which is essential for regional planning and sustainable water resource management.

If the AI value is 0.59, the Tunceli region falls into the climate characterization “dry sub-humid,” which indicates the prevailing moderate aridity conditions. The 3-month, 6-month, 9-month, and 12-month RDI values in the graph are used to measure how arid a region is during specific periods. The values shown range between 0.5 and 0.65, representing the “dry sub-humid” category. Higher AI values indicate that the region is more humid and less stressed by water scarcity. The 12-month RDI is typically used to assess climate conditions over a year, reflecting general trends during that time. The other periods (3, 6, and 9-months) are used to observe seasonal changes and short-term climate fluctuations more closely. Figure 15 shows the average temperature anomalies for eight stations between 1980 and 2023.

The Paris Agreement aims to limit global warming to 1.5°C above pre-industrial levels [40]. Suppose the temperature data from 1980 to 2023 is examined in accordance with this target. The vertical and horizontal dashed red lines in Fig. 15 represent the 1.5 °C temperature increase limit for selected meteorological stations in the Tunceli region. The vertical dashed red line indicates the year when this limit was exceeded. In that case, it can be seen that the temperature has risen over time and was above 1.5°C at all stations, especially after 2017. A sudden rise in temperature was observed in 2010 when the temperature changes of the

stations were examined over the long term. After 2010, the temperature increase decreased but did not fall below 1.5°C in the last 7 years after 2017. Therefore, it can be said that the region is under the influence of global warming, and necessary strategies should be developed to comply with the Paris Agreement.

The R^2 values and equations calculated for the temperature and precipitation for eight stations are presented in Table 3. The R^2 values indicate how well the model explains the data, while trend equations are used to predict the amount of temperature or precipitation for a given year. In particular, when examining temperature trends, this study shows that R^2 values explain temperature changes relatively well. An examination of the precipitation data shows that irregularities in the precipitation regime lead to low R^2 values. Therefore, in studies on drought, climate change, and water resources, more cautious predictions should be made when examining precipitation data.

x: Represents the number of years elapsed since the starting year of 1979. For example, $x=0$ for the year 1979, $x=1$ for the year 1980, and $x=44$ for the year 2023.

y: Mean Trend Temperature (°C) / Mean Trend Precipitation (mm).

A linear equation was derived from the precipitation data for the years 1979 to 2023, and the future scenario of the precipitation data is shown in Fig. 16. The linear regression model predicts a considerable decrease in the average annual precipitation in the period from 1979 to 2050. This decrease in rainfall in the near future makes it even more important to investigate and monitor the drought situation in the region.

The spatial distribution of the analyzed drought frequencies during the seasonal and annual periods varies in

Fig. 15 Mean temperature change for eight stations (1979–2023). The vertical dashed red line indicates the year when the 1.5 °C temperature increase limit was exceeded, the horizontal dashed red line indicates the 1.5 °C threshold

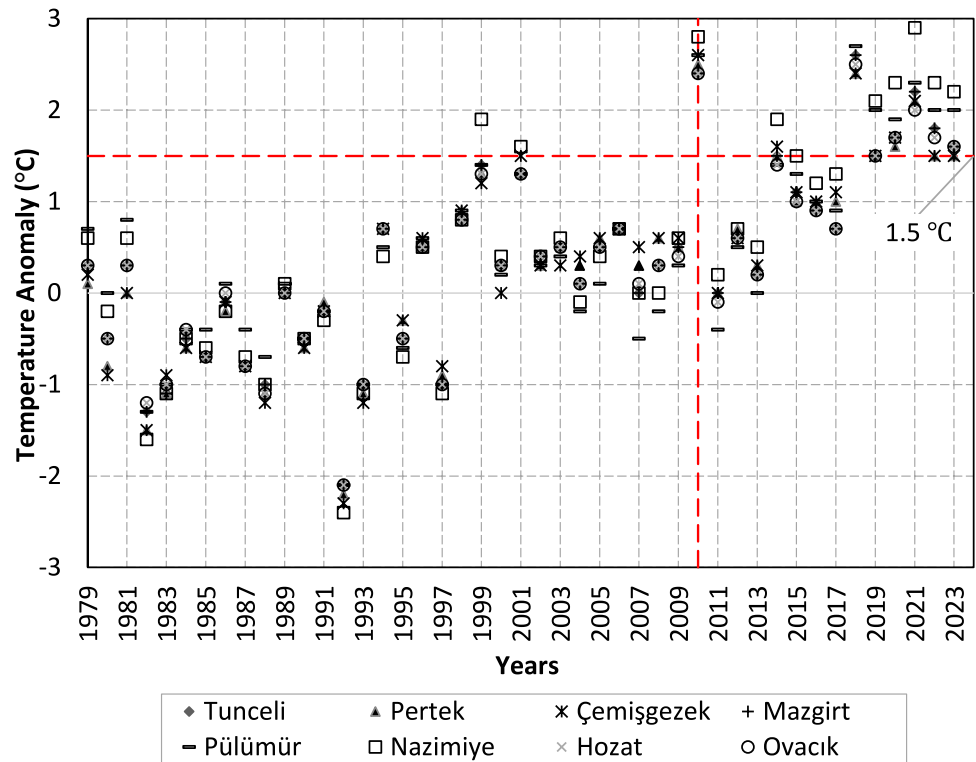


Table 3 Temperature and precipitation equations and R^2 values for eight stations

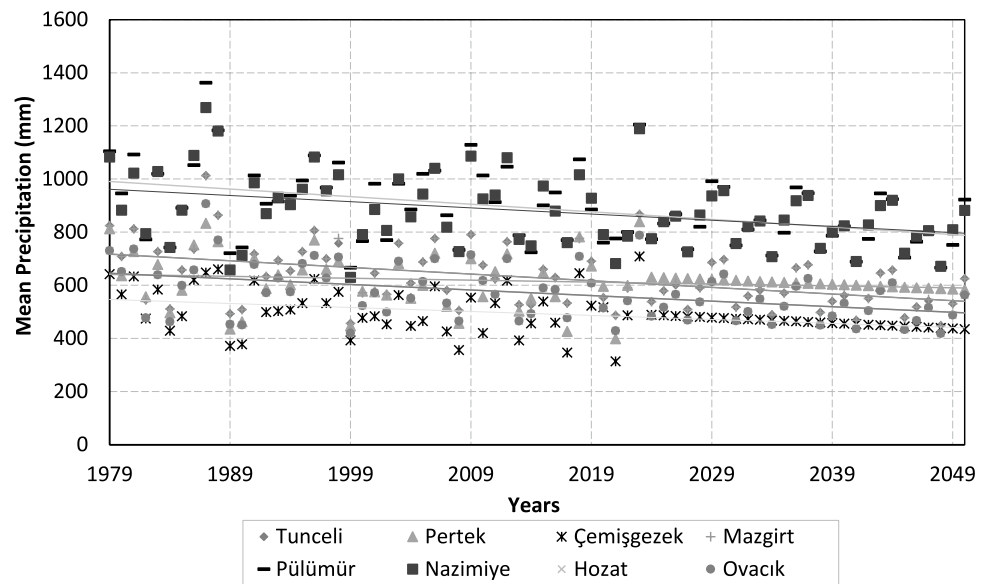
Station No	Station Name	Mean Trend Temperature (°C)		Mean Trend Precipitation (mm)	
		R^2	Equation	R^2	Equation
17,165	Tunceli	0,5423	$y=0,0577x+10,812$	0,0482	$y=-2,0438x+712,12$
753	Pulumur	0,4284	$y=0,054x+6,7763$	0,0347	$y=-2,176x+982,08$
17,768	Çemişgezek	0,5902	$y=0,063x+12,024$	0,0505	$y=-1,6348x+549,76$
18,354	Hozat	0,5465	$y=0,0565x+10,908$	0,0402	$y=-1,6791x+640,19$
18,355	Nazımiye	0,5601	$y=0,0732x+8,0691$	0,0263	$y=-1,8343x+955,42$
18,179	Ovacık	0,543	$y=0,563x+10,91$	0,0402	$y=-1,6791x+640,19$
5212	Pertek	0,5956	$y=0,0612x+11,932$	0,0286	$y=-1,4476x+653,86$
17,736	Mazgirt	0,5423	$y=0,5777x+10,812$	0,0483	$y=-2,0513x+712,68$

each period, but only the results from 1980 to 2023 were evaluated in this study. Various indices, such as the SPI, the RDI, the PNI, and the AI, were used to analyze the drought dynamics and climate sensitivity of Tunceli's water resources. Drought calculations were performed over 3-, 6-, 9- and 12-month periods by organizing the precipitation data from October to September for drought analysis using the SPI index. The drought classification of this region seems to be within normal limits due to its climatic characteristics. Nevertheless, a dry period was observed between August 1989 and May 1999. The SPI values for the periods of 3, 6, 9, and 12 months are generally within the normal range. However, the most recent data points (2020) show negative SPI values for all periods, indicating a significant dry period.

Regarding the RDI, most of the values are the limits of the normal drought class. The analysis indicates a stable climate regime with no significant long-term deviations towards extreme drought or wetness. Our results show that during the observed period from 1980 to 2021, only 5% of the time was characterized by drought, while normal or wet conditions in Tunceli characterized the remaining 95%.

Although the PNI values fluctuate from year to year, none of the years were “extremely dry,” while some years were “wet.” This indicates a “dry sub-humid” climate that is not prone to long-term drought [35]. The AI values for the 3-month, 6-month, 9-month, and 12-month time scales indicate how dry a region is in certain periods. The values displayed range from 0.5 to 0.65 and represent the category

Fig. 16 Future forecast of mean precipitation change for eight stations from 1979 to 2050



“dry-semi-humid.” The results of the study show quite similar patterns when comparing different indices, with precipitation being the common parameter, which explains the similarity of the results. This study consisted of a detailed analysis of critical drought indices and long-term drought risks in order to develop effective water resource management and climate adaptation strategies in the region.

In summary, this study provides a detailed assessment of climate trends and drought dynamics in the Tunceli region. It reveals a complex interplay between rising temperatures and increasing precipitation in some specific stations within the region. Overall, the current drought conditions in the Tunceli region are classified as normal [8]. Nevertheless, future temperatures and precipitation trends show that drought conditions in the Tunceli region, like in many regions around the globe, will most likely exacerbate if necessary measures are not taken globally [40]. The results highlight the importance of continuous monitoring and adaptive management strategies to ensure sustainable water supply and agricultural productivity in the face of ongoing climatic changes. Future research should focus on identifying the underlying factors influencing precipitation variability and exploring the potential impacts of extreme weather events on the region's climate and hydrology. Additional studies may also be necessary to assess the potential environmental, social, and economic impacts of the increasing trend in precipitation data.

Conclusions

This study presents a comprehensive analysis of drought and climate trends in the Tunceli region, utilizing indices such as SPI, RDI, PNI, and AI. The results indicate that there is currently no extreme drought in the region. However, when

examining temperature and precipitation anomalies, it is evident that the region is significantly impacted by global warming. The detailed evaluation of temperature and precipitation trends clearly highlights the significant effects of global climate change in the region. The continuous increase in temperatures and the decrease in precipitation make the risks to water accessibility and quality in Tunceli more pronounced. Both the SPI and the RDI were used to analyze precipitation irregularities and drought trends from 1980 to 2021. Our analysis of the SPI has shown that the values for the 3-months typically oscillate between -1 and 1, indicating a normal level of drought variability. This suggests that extreme deviations from average rainfall patterns are not frequent in the region in the short term.

Conversely, the RDI analysis for the 9-months highlighted years of pronounced drought at times, but the overarching pattern suggests that the region generally experienced normal or wet conditions. These results are particularly instructive as they highlight the lack of a long-term, persistent drought trend in the region while recognizing the presence of short-term droughts and seasonal fluctuations that need to be addressed carefully by respective stakeholders.

The results of the PNI and the AI have enabled a more comprehensive assessment of the regional climate. The fluctuations in PNI values between humid and dry sub-humid classifications over the years, together with the AI values, show that the region falls largely within a dry sub-humid to semi-arid climate band.

Taking into account all the analyses carried out, no significant long-term trend towards drought could be identified in the region of Tunceli. However, this does not exclude the importance of looking at short-term drought events and seasonal variations. The knowledge gained from this study can guide regional authorities in the management of water

resources and the development of effective drought adaptation strategies. It also highlights the need for further research into how regional drought conditions may evolve in the context of climate change.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Ethics Approval (Not applicable).

Consent to Participate (Yes).

Consent for Publication (Yes).

Conflict of Interest The authors declare no competing interests.

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