

Research Article

Drought hazard in Bulgaria under conditions of climate change

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Abstract

The Shared Socio-economic Pathways (SSPs) presented in the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) indicate that increased variability and more frequent extremes in precipitation are expected to raise the risk of droughts and floods in South-Eastern Europe. According to climate projections, the potential increase in precipitation in the region is insignificant, while the rising temperatures and the associated increase in potential evapotranspiration may lead to a substantial intensification of drought severity in the future. This study reviews previous research on droughts in Bulgaria and the analytical methods applied, thereby justifying the selection of the proposed methodological approach based on the Standardized Precipitation Evapotranspiration Index (SPEI-12 and SPEI-48). The SPEI data were obtained from the Global SPEI Database and cover the period from 1950 to 2024. The spatial characteristics of the index for the territory of Bulgaria are represented by grid cells with a spatial resolution of 0.5 degrees. The study examines changes in drought conditions across Bulgaria over the period 1950–2024, using SPEI-48 data. Long-term fluctuations in average SPEI values reveal a pronounced negative trend since 1984. The index reached its lowest value during the period 2000–2003 (–1.6), which is classified as a severe drought. Average SPEI-48 values range between 0.8 and –0.8 across the decades from 1950 to 2024, and have remained predominantly negative over the last five decades. In this context, the study highlights the need to implement measures for climate change adaptation and to address the increasing risk of drought.



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1. Introduction

According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), drought is defined as “an exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature and/or wind)” (IPCC 2023). The specific parameters of this phenomenon are determined in relation to the prevailing climatic conditions and agricultural practices within a given geographic region. In Bulgaria, a dry spell lasting at least ten consecutive days is considered a drought event (Draganov and Gyurova 1982). It can occur during any season. The main types of drought are distinguished as meteorological drought, when plants transpire

more water than they receive through their roots; soil drought, when the moisture content in the soil becomes insufficient to meet the needs of plants and agrometeorological drought, when both meteorological and soil drought occur simultaneously. The most severe impacts arise from droughts lasting several consecutive years. Such prolonged periods may lead to hydrological drought, characterized by a general decline in water resources, the drying of rivers, the lowering of groundwater levels, the disruption of river transport, and shortages in water supply for affected populations. The intensification of hydrological drought depends not only on natural preconditions but also on the effectiveness of water resources management.

Historically, droughts in Bulgaria have accompanied human settlement from antiquity to the present. In the 20th century, three prolonged drought periods were recorded: 1902–1913, 1942–1953, and 1982–1994. During the first period, dry years accounted for approximately 20% of the time, in the second, this increased to 40%, and in the third, to nearly 50% (Raev et al. 2003).

The drought that began in 1982 cumulated in a severe crisis with catastrophic consequences in 1993–1994. Crop losses in 1993 were estimated at USD 260 million (2% of GDP), and in 1996, maize and wheat production reached only 44% and 50%, respectively, of the average yields for 1961–1990. The impacts were widespread and multifaceted: Coniferous forests began to die off, forest fires increased, water rationing was imposed almost nationwide, morbidity rates rose, and water levels in the Iskar Reservoir (a total volume of 673 million m³) approached the sanitary minimum. For the first time, water consumption restrictions were introduced in the capital, and water prices doubled. In the regions of Rila and Sapareva Banya, civil disobedience erupted in response to the government's decision to implement a project to divert waters from the Rila Mountain to Sofia (Raev et al. 2003).

The crisis had a significant public impact, affecting all levels of governance and stimulating research interest across multiple scientific disciplines to analyze it in the context of potential climate change in the region (Knight et al. 2004).

Research indicates that the trend toward decreasing precipitation and increasing drought persisted throughout the last two decades of the 20th century (Koleva and Alexandrov 2008). The year 2000 was exceptionally dry across the entire non-mountainous territory of Bulgaria, with total annual precipitation ranging between 250 and 400 mm, or between 40% and 70% of the climatic norm in different parts of the country (Latinov 2001). Dry periods and agrometeorological droughts of varying intensity were recorded in 14 of the first 15 years of the 21st century, affecting every month of the vegetation season in Bulgaria (Georgieva et al. 2017). According to an analysis by the European Copernicus Climate Change Service, the summer of 2024 was the hottest ever recorded in Europe's meteorological history, marked by prolonged heatwaves throughout the season. Southeastern Europe experienced a record number of days with "severe heat stress." In Bulgaria, record-high temperatures were also recorded during the summer of 2024 (NIMH 2025).

This brief chronicle illustrates that drought is an adverse phenomenon inherent to Bulgaria's climate. It has been the subject of long-standing research due to its significant impact on key economic sectors such as agriculture, water resources, forestry, ecosystems, transportation, and energy. One of the earliest studies on drought in Bulgaria was conducted by Hershkovich (1984), in which

the country's territory was zoned based on the average balance of atmospheric and soil moisture during the June–August period. Three main zones were identified: humid, semi-arid (with four subzones—slightly semi-arid, moderately semi-arid, semi-arid, and very semi-arid), and arid. The humid zone, with a positive moisture balance, includes areas at altitudes of 300–400 m in Northern Bulgaria and above 600–800 m in Southern Bulgaria. The slightly semi-arid subzone has a moisture balance ranging from slightly negative to positive and covers areas at 200–300 m in Northern Bulgaria and 350–700 m in Southern Bulgaria, as well as parts of the Black Sea coast and the high plains of Western Bulgaria. In the very semi-arid subzone, the moisture deficit reaches 200–250 mm and includes the valleys of the Maritsa, Tundzha, Arda, Struma, and Mesta rivers, along with the eastern regions of the country. The arid zone, with a moisture deficit of 400 mm, encompasses the southernmost part of the Struma valley (the Petrich and Sandanski plains), where droughts occur annually (Yordanova and Donchev 1997).

According to the map of the humidity coefficient (the difference between precipitation and evapotranspiration) during periods when air temperatures exceed 10°C, the following zones are distinguished: strongly semi-arid, moderately semi-arid, optimally humid, and over-humid (Hershkovich 1982). The map characterizes atmospheric drought conditions, with strongly semi-arid areas including the Danubian lowlands, depressions around Varna and Burgas, the Thracian lowland, and the Struma valley.

Alexandrov (2011) assessed the risk of atmospheric, soil, and combined soil-atmospheric drought in Bulgarian municipalities based on precipitation data and soil type and structure. The study identified the Thracian lowland and the Black Sea coastal region as zones with high risk of soil-atmospheric drought.

Drought severity is also assessed using various indices that characterize moisture conditions. For the territory of Bulgaria, several indices have been analyzed over different time periods, including the Standardized Precipitation Index (SPI), Soil Moisture Index (SMI), and Streamflow Drought Index (SRI) (Georgieva et al. 2017; Ilcheva et al. 2022). The Precipitation Anomaly Index (PAI), SPI, Reconnaissance Drought Index (RDI), and Palmer Drought Severity Index (PDSI) were calculated and analyzed in the context of climate change using data from over 30 meteorological stations representing diverse climatic conditions across Bulgaria for the period 1960–2009 (Gocheva et al. 2010).

The results indicate that droughts in Bulgaria after 1984 have been moderate in intensity, with summer peaks observed in certain regions during 1993, 2000, and 2007. Radeva and Nikolova (2020) analyzed hydrometeorological drought in Northern Bulgaria using SPI, the Standardized Precipitation Evapotranspiration Index (SPEI), and the Streamflow Drought Index (SDI) with a 12-month time step for the period 1961–2012. Their findings show that Northern Bulgaria is highly vulnerable to drought conditions.

This brief overview demonstrates that drought has been a subject of scientific research over the years; however, studies specifically addressing the influence of climate change on the intensity and spatial characteristics of droughts in Bulgaria remain relatively limited. With the context of climate change scenarios, droughts are increasingly recognized as the result of both natural and anthropogenic factors. They result from natural events, such as reduced precipitation and rising temperatures, and human-induced factors, including chang-

es in water and land use, agricultural practices, climate risk management, and adaptation measures (AghaKouchak et al. 2021).

The frequency and duration of droughts in Europe, along with trends for the period 1950–2012, have been studied using three indicators on a monthly scale and a 12-month accumulation period (SPI-12, SPEI-12, and RDI-12). Findings indicate that in Central Europe and the Balkans, where precipitation increases are not significant, rising temperatures and the associated increase in potential evapotranspiration may lead to greater drought severity in the future (Spinoni et al. 2015). Eastern Europe may experience more complex effects and impacts, as some projections indicate increasing drought risks, while others suggest similar or even decreasing risk due to the interplay of drying/wetting dynamics and higher variability in precipitation (Rossi et al. 2023).

The most commonly used agroclimatic indices for drought assessment include those developed by De Martonne, Selyaninov, and Thornthwaite (Thornthwaite 1957; Popov and Topliyski 1999; Mitkov and Topliyski 2017), as well as the atmospheric moisture balance and the Aridity Index (AI), among others. These indices are applied to evaluate both thermal conditions and moisture availability across a given territory. Among them, the Aridity Index is most frequently used in agrometeorology, as it provides a reliable measure of actual moisture deficit over a specific period (Kazandjiev et al. 2022).

The SPI is applied by national meteorological and hydrological services worldwide for drought analysis. SPI is a probabilistic precipitation indicator valid across various time scales, based on long-term data, and it characterizes both the duration and intensity of drought events. A drought period begins when the index becomes consistently negative and ends when it returns to positive values (NIMH 2009). In addition to SPI, other widely used indices for assessing meteorological drought include the Palmer Drought Severity Index (PDSI) and Palfai's Aridity Index (PAI). These indices are primarily based on precipitation data. Beyond its meteorological dimension, drought also has an agro-ecological aspect, combining various elements of meteorological, soil, and hydrological drought and their impacts on crop development and ecosystems. Accordingly, another group of drought assessment indices, such as the Soil Moisture Index (SMI) focuses on soil moisture deficit and the difference between actual and potential evapotranspiration (Webb 2010).

Hydrological drought parameters are characterized by indices such as the Streamflow Drought Index (SDI), the Standardized Runoff Index (SRI), and the Surface Water Supply Index (SWSI). The Reconnaissance Drought Index (RDI) is also a key indicator for assessing drought severity, based on the ratio between precipitation and potential evapotranspiration (Tsakiris 2004).

The Standardized Precipitation Evapotranspiration Index (SPEI) is widely used as a measure of moisture deficit at a given location, as it more accurately accounts for the influence of precipitation, temperature, evaporation, and transpiration. This index has the advantage of describing moisture conditions in the context of global warming, serving as a proxy for soil water availability expressed in terms of standard deviations from normal water availability (Vicente-Serrano 2010, 2012; Rossi et al. 2023).

The present study aims to track changes in the average values of SPEI-48 across the territory of Bulgaria during the period 1950–2024 and to identify signals of a potential link between drought risk and climate change in the country.

2. Materials and methods

The three key characteristics that distinguish one drought from another are intensity, duration, and spatial extent. Intensity depends on the degree of precipitation deficit and the length of the dry period. Droughts typically develop over a span of two to three months, but their impacts can persist for months or even years afterwards.

The majority of indices used for drought assessment are based on precipitation data, despite the direct proportional relationship between rising temperatures and soil moisture deficit. The SPEI accounts for the contribution of temperature-dependent evapotranspiration and provides insight into whether pressure on water resources is increasing or decreasing. Similar to SPI, SPEI measures drought severity in terms of both intensity and duration and identifies the onset and end of drought episodes. SPEI enables comparisons of drought severity across time and space, as it can be calculated for a wide range of climates.

In the SPEIbase v1.0, the Thornthwaite equation (Thornthwaite 1948) is used. In the SPEIbase v2.0, which is used in this study, the FAO-56 Penman–Monteith equation is used (Allen et al. 1998).

Drought conditions in Bulgaria were quantified using the SPEI obtained from SPEIbase v2.0, which provides a globally consistent, multi-scalar drought dataset. SPEI is based on the climatic water balance and explicitly incorporates the effect of temperature through potential evapotranspiration (PET), making it particularly suitable for analyses of climate variability and climate change (Vicente-Serrano et al. 2010).

In SPEIbase v2.0, PET is estimated using the FAO-56 Penman–Monteith equation, which is a physically based method widely recommended for hydrological and climatological applications (Allen et al. 1998), incorporating various climatic variables such as temperature, precipitation, wind speed, solar radiation, and others (Vicente-Serrano et al. 2012).

The primary variable used for SPEI computation is the monthly climatic water balance, defined as the difference between precipitation and potential evapotranspiration (Eq. 1):

$$D_i = P_i - PET_i \quad (\text{Eq. 1})$$

Where P_i represents the total monthly precipitation (mm) and PET is the monthly potential evapotranspiration (mm). This formulation allows both precipitation deficits and increased atmospheric evaporative demand to influence drought severity. It provides a simple measure of the water surplus or deficit for the analyzed month.

To capture drought processes operating at different temporal scales, the climatic water balance is accumulated over a time scale by temporal aggregation. Short accumulation periods (1–3 months) reflect meteorological drought, medium scales (6–12 months) are related to agricultural and hydrological drought, and longer periods (24 months or more) describe long-term moisture conditions.

For each accumulation time scale, the aggregated climatic water balance series is fitted to a three-parameter log-logistic distribution, which is capable of representing both positive and negative values and has been shown to perform well for drought analysis (Vicente-Serrano et al. 2010). The distribution param-

eters are estimated using the L-moments method, which provides robustness against outliers and extreme values. The cumulative probability derived from the fitted distribution is then transformed into a standardized normal variable.

The probability distribution function of D according to the Log-logistic distribution is given by Eq. 2:

$$F(x) = \left(1 + \left(\frac{\alpha}{x - \gamma} \right)^\beta \right)^{-1} \quad (\text{Eq. 2})$$

With $F(x)$, the SPEI can easily be obtained as the standardized values of $F(x)$ following the approximation of Abramowitz and Stegun (1965) (Eq. 3–4):

$$SPEI = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3} \quad (\text{Eq. 3})$$

Where:

$$W = -2\ln(P) \quad (\text{Eq. 4})$$

If $P \leq 0.5$, P being the probability of exceeding a determined D value, $P = 1 - F(x)$. If $P > 0.5$, P is replaced by $1 - P$, and the sign of the resultant SPEI is reversed. The constants are: $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

The resulting SPEI series has a mean of zero and a standard deviation of one, allowing direct comparison of drought conditions across different regions and climatic regimes. An SPEI of 0 indicates a value corresponding to 50% of the cumulative probability of D , according to a Log-logistic distribution.

The severity levels for SPEI are the same as those for SPI. Negative SPEI values indicate dry conditions, where values ≥ 2.0 represent extremely wet conditions, and values ≤ -2.0 indicate extreme drought.

The advantage of SPEI over other widely used drought indices that incorporate PET is its multiscalar nature, which allows for the identification of different types of droughts and their impacts in the context of global warming (Beguería et al. 2023). For this reason, we analyze SPEI values for the territory of Bulgaria using smoothed (moving average) values with 12, 24 and 48-month steps. SPEI-48 is the most stable version of the index. It is used to identify long-term drying trends associated with climate change rather than natural year-to-year variability. Its values change slowly, providing a “big picture” view of the region’s aridity. While SPEI-1/3 months detects short-term or seasonal meteorological and agricultural drought, the SPEI-12 reflects agricultural and hydrological droughts, and is applied for medium-term (annual) hydrological drought monitoring. SPEI-1/3 can be used for short- and medium-term planning in the agriculture and forestry industry, while SPEI-12 is particularly useful for water supply and hydropower management. The 1-month SPEI timescale is effective for short-term drought monitoring but may not fully reflect long-term hydrological drought trends (Sabzevari et al. 2025).

Because the main focus of this study is to analyze the long-term general trend toward arid conditions and to smooth the effects of the short-term fluctuations, we choose to analyze the dynamics of SPEI-48 between 1950 and 2024, and also compare the SPEI-48 with the SPEI-24 and SPEI-12.

The SPEI-48, SPEI-24, and SPEI-12 data were extracted from the Global SPEI Database v2.10 and analyzed in Google Earth Engine Editor. The data covers the period from 1950 to 2024. SPEIbase is based on the FAO-56 Penman-Monteith estimation of potential evapotranspiration. This represents a major difference compared to the SPEI Global Drought Monitor, which uses the Thornthwaite PET estimation. The Penman-Monteith method is considered superior, and therefore SPEIbase is recommended for most applications, including long-term climatological analysis. To reduce uncertainty across different regions, SPEI uses the Standardized Parameterization FAO-56.

The FAO-56 (Allen et al. 1998) standards remain the global benchmark for quality control (QC) and gap-filling of meteorological data for evapotranspiration (ET_0) calculations. Because the Penman-Monteith equation requires multiple inputs (radiation, temperature, humidity, and wind), FAO-56 provides specific protocols to estimate missing data and validate existing data, which have been applied in the SPEIbase.

The Global SPEI Database is an open-access dataset developed by the Spanish National Research Council (CSIC), providing standardized drought indices based on the Standardized Precipitation-Evapotranspiration Index. It is widely used in climate and environmental research, particularly for assessing drought severity and long-term trends.



Figure 1. Grid cells used to calculate the average SPEI-48 values for Bulgaria (1950–2024) (Global SPEI Database 2023; Beguería et al 2023).

The spatial resolution of the index for the territory of Bulgaria is based on grid cells of 0.5 degrees. Each grid cell represents an area of approximately 50 × 50 km, and only those cells falling within the national borders are used for analysis. The monthly average values of SPEI-48 are calculated by averaging the values of all grid cells over Bulgaria for each month in the period 1950 – 2024 (Fig. 1).

Data on selected climate change indicators, characterizing moisture and temperature conditions (mean and maximum air temperature, number of hot days with T > 35°C, and precipitation) according to various Shared Socio-economic Pathways (SSP) scenarios from the Sixth Assessment Report (AR6) of the IPCC (2023) were also used in this study. These data include scientific publications, reports from national and international institutions, as well as annual (2020–2024) and monthly Bulletins from the National Institute of Meteorology and Hydrology (NIMH 2025), IPCC (2023), the World Bank (WBG 2021), and the Climate Change Knowledge Portal (WBG 2023).

3. Results

The main factors contributing to increased drought risk include reduced or absent precipitation and rising air temperatures. According to all climate change scenarios, Bulgaria is expected to experience higher temperatures and decreased rainfall by the end of this century (WBG 2021). Projected trends in selected climate change indicators, based on various SSP scenarios from the Sixth Assessment Report (AR6) and data from CMIP6, are illustrated in fig. 2.

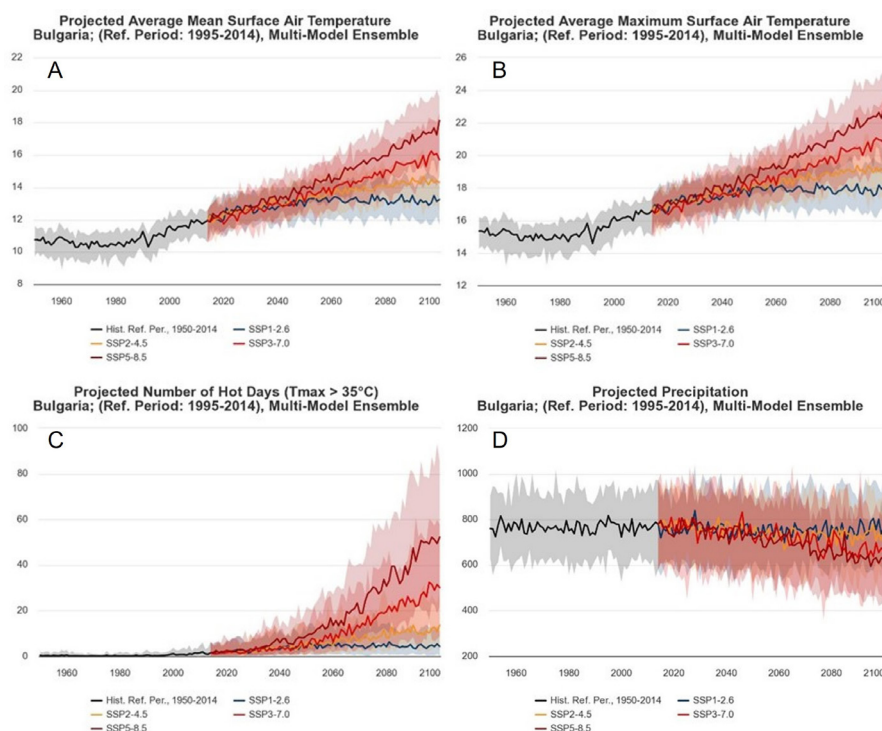


Figure 2. Projections of changes in Bulgaria (WBG 2023). **A** mean air temperature in Bulgaria by 2100 according to SSP scenarios from AR6 **B** mean maximum air temperature in Bulgaria by 2100 according to SSP scenarios from AR6 **C** number of hot days (Tmax > 35°C) in Bulgaria by 2100 according to SSP scenarios from AR6 **D** annual precipitation totals in Bulgaria by 2100 according to SSP scenarios from AR6.

The trends projected in climate change indicators shown in fig. 2 (A–D) are largely confirmed by observed changes in these indicators in Bulgaria during the period 1950–2020. A comparison between two reference periods, 1961–1990 and 1991–2020, reveals that the mean temperature increased by 0.96°C in the latter period, while the annual precipitation total decreased by 25.13 mm (NIMH 2021, 2023). Observed annual precipitation totals exhibit pronounced variability, with fluctuations becoming more evident since the 1990s. Notable extremes include the exceptionally dry year 2000, with an annual precipitation total of 475.9 mm, and the extremely wet years 2005 and 2014, with 1026.88 mm and 1109.56 mm, respectively. During the period 1961–2019, over 90% of meteorological stations across the country recorded a statistically significant trend of increasing hot days with maximum temperatures above 32°C, averaging approximately 3.5–3.6 additional days per decade (NIMH 2020).

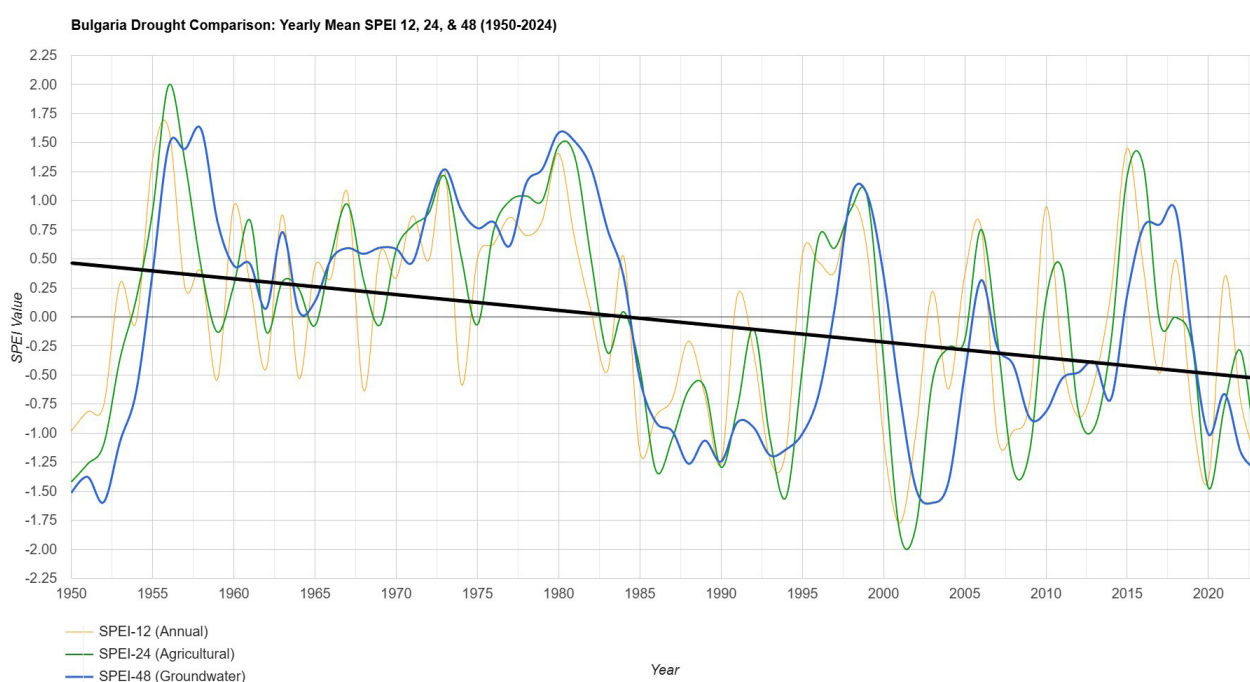


Figure 3. Smoothed SPEI values at 48-, 24- and 12-month scales for the territory of Bulgaria (1950–2024) with a negative trend line.

Long-term fluctuations in the average SPEI values, as shown in Fig. 3, reveal a clearly pronounced negative trend in the index after 1984. This trend is most evident in SPEI-48 and SPEI-24. The SPEI-12 exhibits similar dynamics, although the annual fluctuations obscure the pattern slightly, the overall negative trend remains intact. From 1950 to 1953, the SPEI values of all three time scales steadily increased, surpassing zero by 1953, and remaining mainly positive until 1984. SPEI-12, due to yearly fluctuations, occasionally shows slightly negative values. SPEI-48 values most frequently ranged between 0.5 and 1 during 1953–1984, with only brief periods around 1957–1958 and 1980 reaching the “severely wet” category. After 1984, SPEI-48 values abruptly shifted to negative levels and remained low for nearly 10 years until 1995. From that point until 2024, SPEI values generally fluctuated between +1 and –1.5, reaching their lowest point during the 2000–2003 (–1.6) period, classified as a

“severe drought”. Throughout the study period, years with normal to moderate drought conditions predominated. SPEI-24 and SPEI-12 display similar trends, albeit with more pronounced short-term fluctuations.

The abrupt change in the SPEI-48 values in 1984 is also confirmed by the Pettitt test for abrupt change point detection (Fig. 4). The conclusion is valid for SPEI-24 and SPEI-12 as well, although there is a slight temporal gap between the peaks of U12, U24 and U48. For example, U12 peaks first, followed by U48 approximately two years later, illustrating a “lag effect” in which surface drying gradually propagated to deplete deeper groundwater reserves. The highest peak is observed in U48, indicating that SPEI-48 underwent the most statistically significant change. Long-term indices such as SPEI-48 typically exhibit higher Ucap values because the “memory” of the 4-year window amplifies the transition from wet to dry conditions, making the shift more distinct and abrupt.

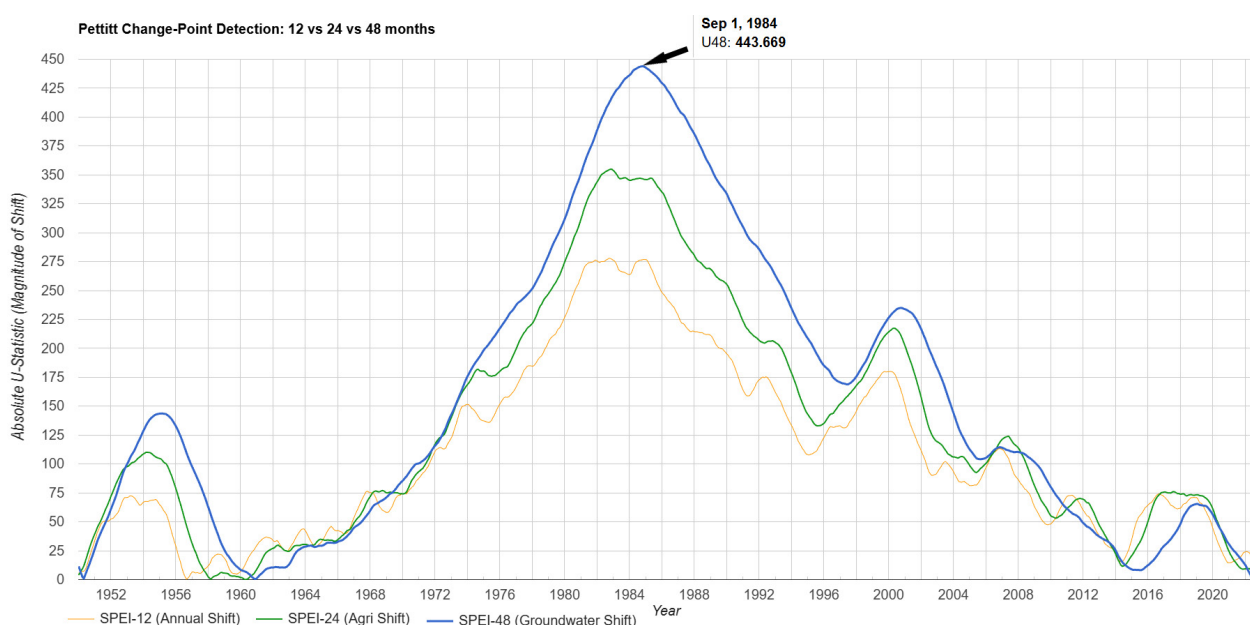


Figure 4. Pettitt abrupt change point detection.

Before this peak, Bulgaria generally experienced a “stationary” climate, characterized by balanced moisture. After this peak, the country entered a “non-stationary” phase dominated by more frequent and intense droughts.

The decadal average values of SPEI-48 fluctuate between 0.8 and 1.0 for the decades spanning 1950–2023, but remain consistently negative for each of the last five decades, except for the 2010s. A clear trend is observed, with the index shifting from -0.8 during the 1970s to -0.2 in the 1980s, and falling below -1.0 in the 2020s (Fig. 4). The same dynamic is observed for the short-scale SPEI-01-22 (Fig. 5).

The statistical significance of drought trends in Bulgaria (1950–2024) based on SPEI-48 is confirmed by the Mann-Kendall (MK) test for monotonic trends. The Tau value (the red/blue map) (Fig. 6A) indicates the strength and direction of the trend, where a negative Tau (red) corresponds to a monotonic drying trend. In our analysis, Tau values range from -0.001 to -0.4 , indicating that each decade is consistently drier than the preceding one. Tau values close to

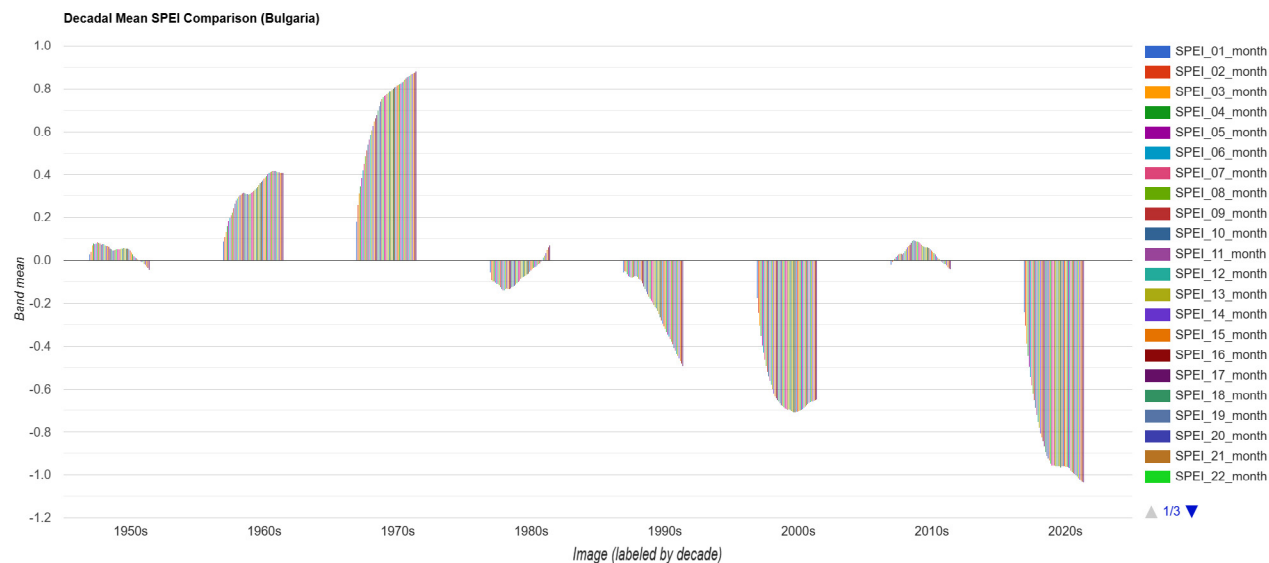


Figure 5. The average SPEI-1/48 values for Bulgaria per decades (1950–2024).

zero (white) indicate stable conditions (no monotonic trend). There are no positive Tau values (blue cells), confirming a long-term drying trend across Bulgaria during 1950–2024 (Fig. 6A).

At the spatial scale, the long-term drying trend is particularly pronounced in some regions, including the NE, NW, and SW parts of the country, where the Tau value approaches -0.4 (Fig. 6A). The statistical importance of this drying trend is further confirmed by the Z-score, with $|Z| > 1.96$, indicating a 95% probability that the drying trend is a permanent climatic shift.

The results of the Mann-Kendall test for SPEI-12 are generally consistent, with $|Z| > 1.96$ and Tau values ranging between -0.04 and -0.3 , again confirming a long-term drying trend (Fig. 6B).

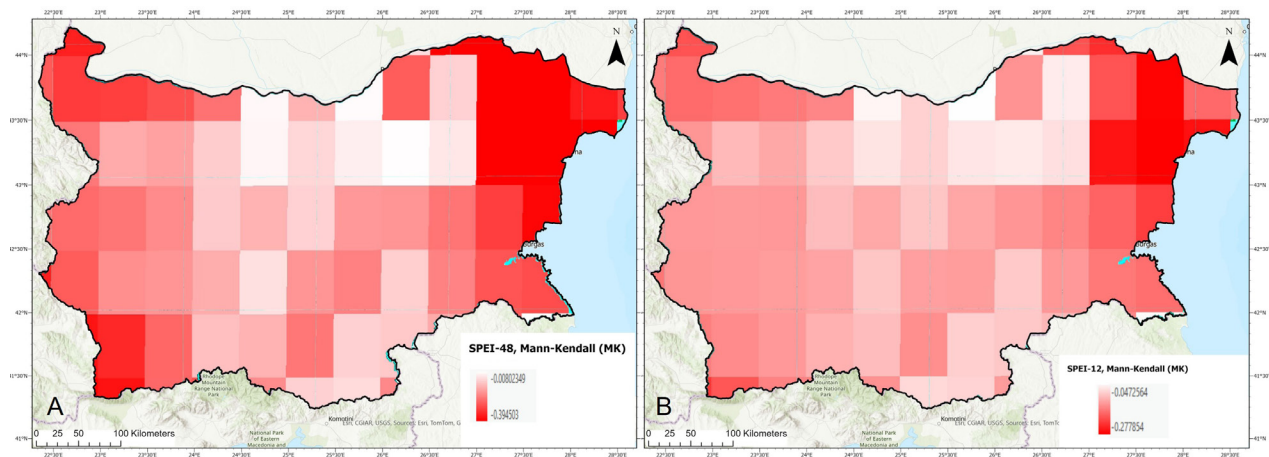


Figure 6. Results of the Mann-Kendall (MK) test. A SPEI-48 B SPEI-12 (WGS 1984).

To analyze the frequency of drought occurrence, a Drought Frequency Analysis based on SPEI-12 and SPEI-24 for Bulgaria was conducted. This analysis shows how often SPEI values fall below specific drought thresholds. SPEI values below -1.0 indicate a moderate drought, values below -1.5 indicate severe

drought, and values ≤ -2.0 indicate extreme drought. For the purposes of this analysis, a threshold of -1.0 was adopted (Fig. 7). The results show that the return period for annual drought (SPEI-12) in Bulgaria is approximately two years on average for the country, compared to about 4.5 years for SPEI-48 (Fig. 8). Analysis of SPEI-12 (annual/hydrological drought) versus SPEI-48 (systemic/groundwater drought) indicates that Bulgaria experienced more “flash” drought events between 1950 and 2024. The spatial distribution of the return period for both SPEI-12 and SPEI-48 demonstrates that some regions of the country experienced droughts more frequently than others.

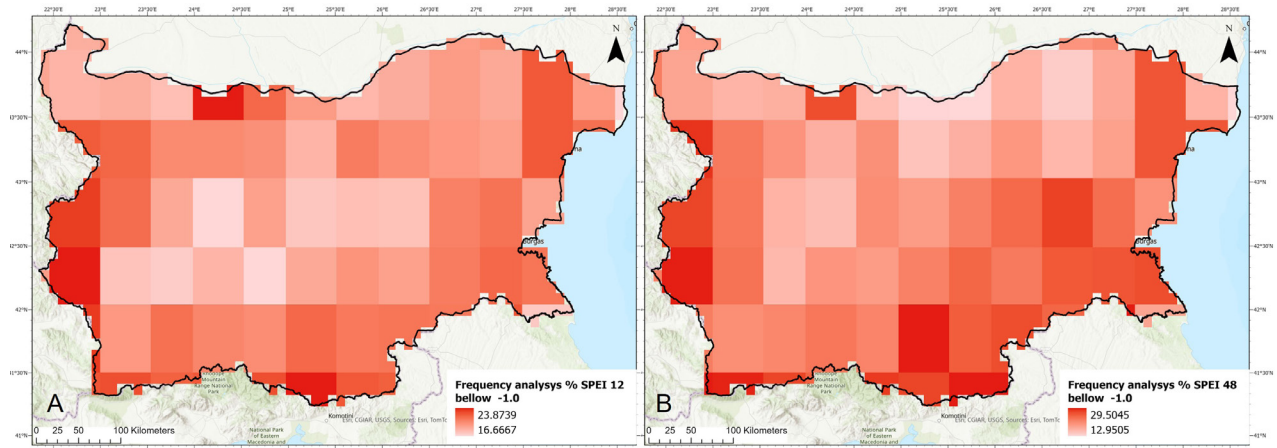


Figure 7. Spatial distribution of the frequency. A SPEI-12 B SPEI-48 falling below -1.0 , expressed in percent, (WGS 1984).

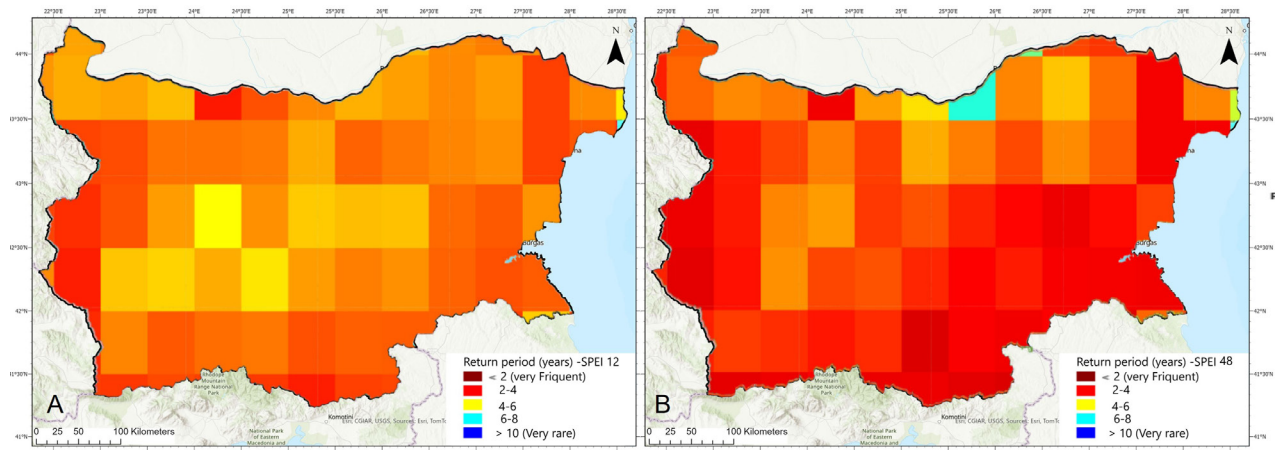


Figure 8. Spatial distribution of the return period. A SPEI-12 B SPEI-48 (WGS 1984).

According to the climate regional scheme of Velev (2002), Bulgaria is divided into the Continental Zone, Transitional Zone, and Continental-Mediterranean Zone, including the Black Sea Climate Region. Despite the relatively coarse resolution of the SPEI (50 km), the average annual SPEI values were analyzed according to Velev’s regional scheme. The results indicate that, from a spatial perspective, deviations of the index from the national average are observed across all climatic zones (Figs 9–10). Both SPEI-12 and SPEI-48 show that the Black Sea region experienced the largest deviations from the national average after

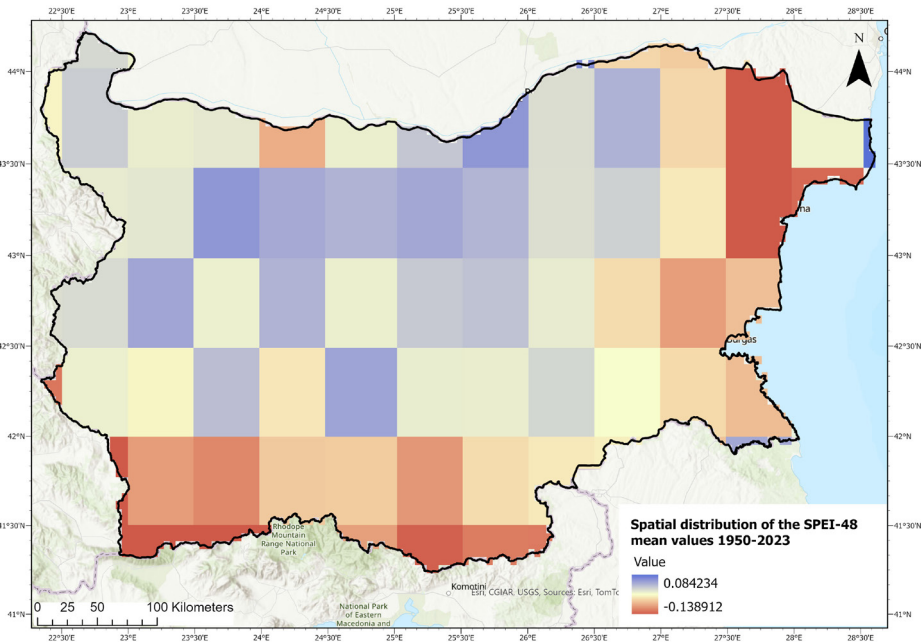


Figure 9. Spatial distribution of the SPEI-48 mean values 1950–2024 (WGS 1984).

the year 2000. The other zones exhibited smaller deviations, largely mirroring the dynamics of the national annual SPEI-12 and SPEI-48 averages. While SPEI-48 smooths the annual fluctuations of the SPEI-12, both indices generally display the same long-term tendency.

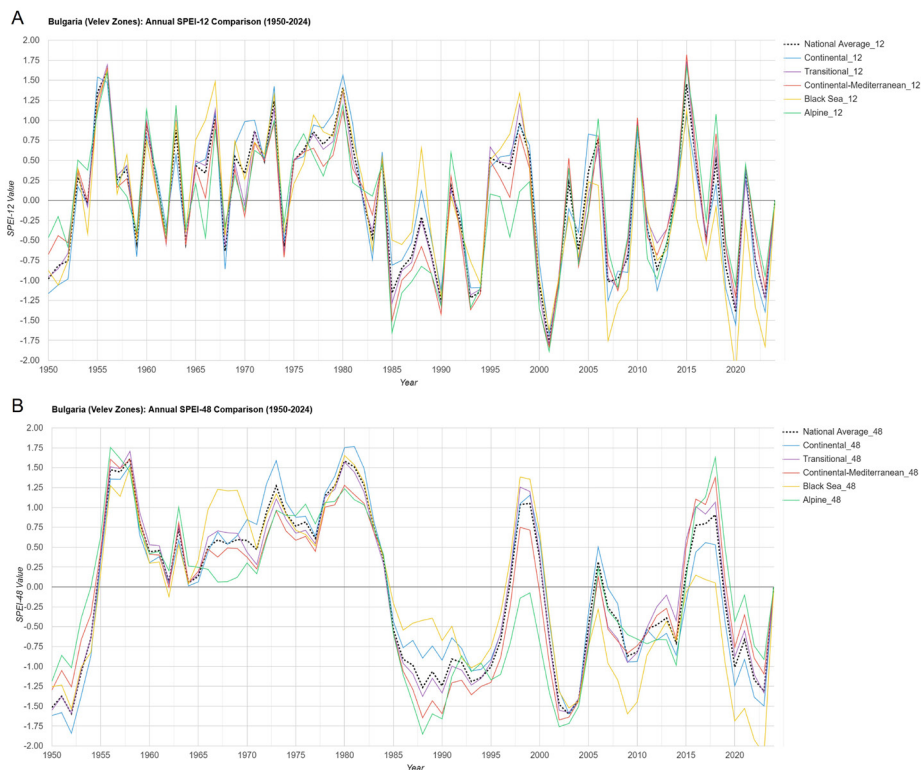


Figure 10. Dynamics of the annual, regional and national average values (1950–2024). A SPEI-12 B SPEI-48.

Analysis of the average SPEI-48 values reveals two distinct periods with contrasting index behavior. During the first period (1953–1983), cells-level averages are predominantly positive, whereas during the second period (1984–2024), values are mostly negative (Fig. 10B). The latter period includes four prolonged dry spells (1984–1997, 2000–2004, 2009–2016, and 2019–2024) and three shorter wet intervals (1998–1999, 2005–2007, and 2017–2018).

The spatial distribution of mean SPEI-48 values for 1950–2024 (Fig. 9) shows that southwestern and northwestern Bulgaria exhibit the lowest average index values (up to -0.13), corresponding to moderate drought conditions. In all other pixels, SPEI-48 remains slightly negative or slightly positive, indicating either moderate drought or near-neutral conditions.

This conclusion is supported by the magnitude of the drying trend, calculated as the negative change in cell-level average annual values for 1950–2024 (Fig. 11A). The results indicate that the drying trend is most pronounced in the northeastern and southwestern regions. Nevertheless, across the entire territory of the country, average SPEI-48 values remain predominantly negative.

A similar pattern is observed for SPEI-12 (Fig. 11B), although the magnitude of negative values is slightly lower due to higher interannual variability in SPEI-12. Despite these fluctuations, both indices consistently reflect the long-term drying trend across Bulgaria.

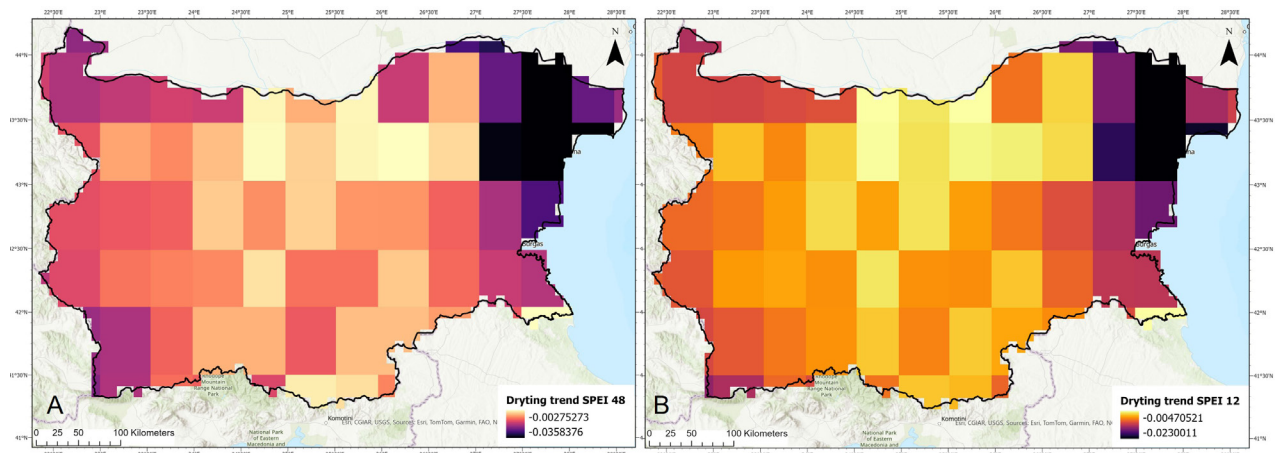


Figure 11. Spatial analysis of the drying trend magnitude (1950–2024, WGS 1984). **A** negative change by cells in the SPEI-48 **B** SPEI-12 mean annual values.

To evaluate the reliability of SPEI as a tool for drought analysis in the context of climate change, we compare the spatial distribution of the drying trend across Bulgaria with the spatial distribution of the magnitude of mean annual temperatures (Fig. 12) and mean annual precipitation (Fig. 13) derived from ERA5-Land reanalysis dataset, one of the most reliable climate datasets, which provides higher spatial resolution than the SPEI Database.

The results show that areas with a clearly defined warming trend generally coincide with regions exhibiting a pronounced drying trend. Analysis of precipitation also indicates that some areas experience a decline in annual precipitation, corresponding to regions where drought intensity and frequency are high, such as southwestern Bulgaria. In contrast, northeastern Bulgaria along the

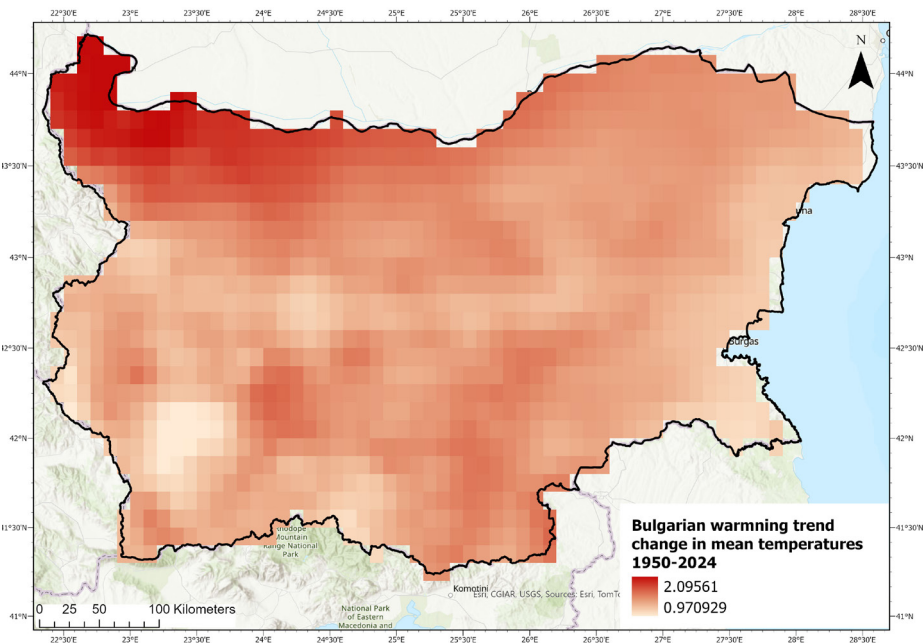


Figure 12. Change in mean temperature trends in Bulgaria, 1950–2024 (ERA-5) (C3S 2017).

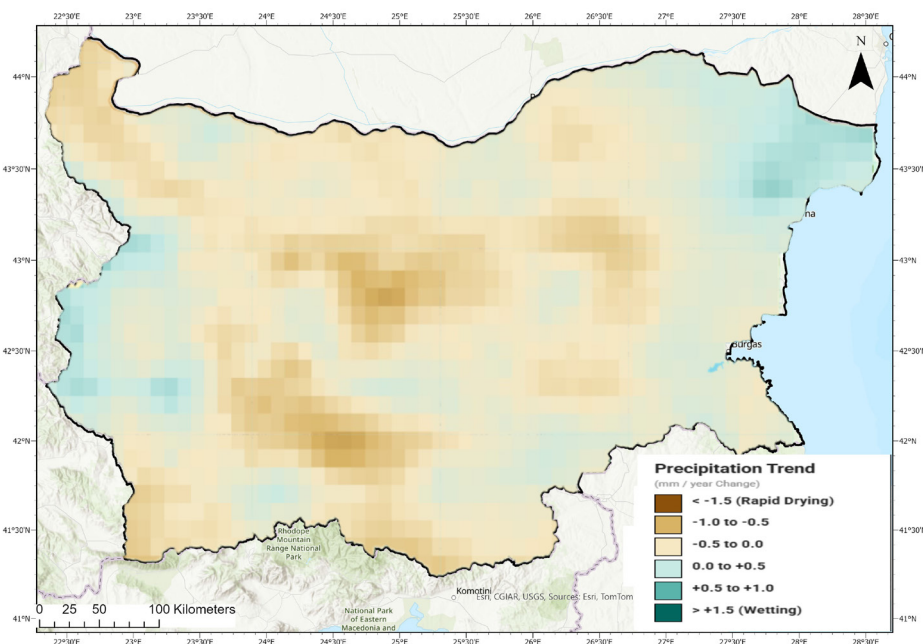


Figure 13. Change of mean annual precipitation trends (mm) in Bulgaria, 1950–2024 (ERA-5) (C3S 2017).

Black Sea coast shows a slight misalignment between SPEI and precipitation data. ERA5 indicates a slight increase in annual precipitation, whereas SPEI indicates a high drought hazard. This discrepancy is explained by the fact that SPEI accounts not only for precipitation and temperature but also for evaporation and transpiration. The highest average annual evaporation values are observed along the Black Sea coast during 1991–2020 (Nojarov 2024), likely offsetting the positive effect of slightly increased precipitation in that region.

Furthermore, anomalies in temperature and precipitation have increased, affecting yearly averages even if long-term precipitation trends remain modest. The climate can be divided into two periods, a wetter period before 1984, and a drier period afterwards. This pattern is further confirmed by Meteoblue data (fig. 14), which shows monthly temperature and precipitation anomalies from 1979 to the present, relative to the 30-year climate mean for 1980–2010. Observed trends include an increase in warmer months and more frequent extreme precipitation events, reflecting the effects of conditions of global warming and climate change.

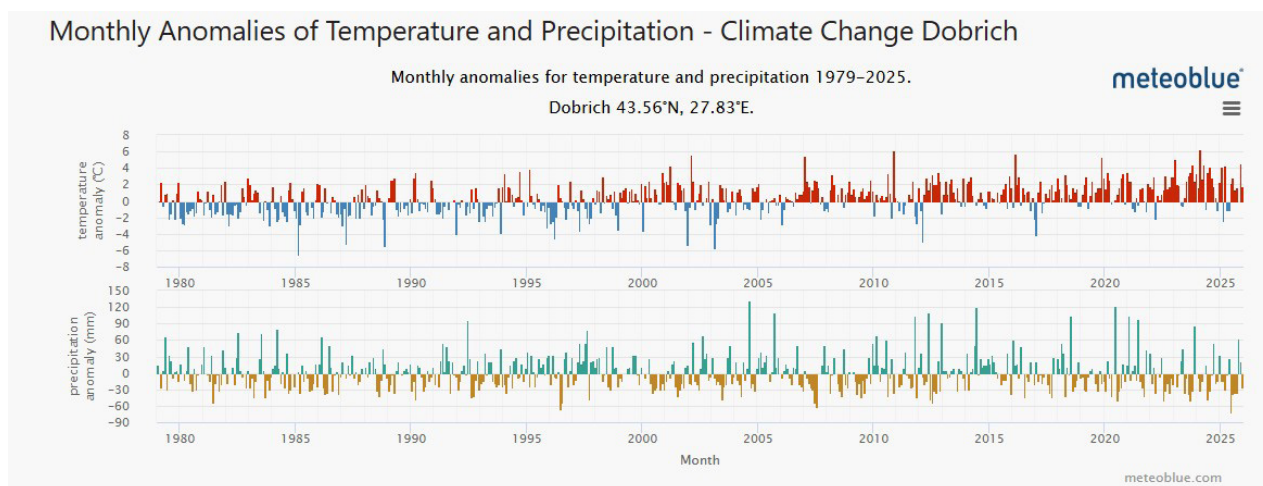


Figure 14. Monthly temperature and precipitation anomalies of Dobrich (1980–2025) (Meteoblue 2025).

Considering the uneven distribution of the precipitation throughout the year, the temperature rise, which increases evapotranspiration, likely reduces the beneficial effect of slightly higher precipitation. As a result, northeastern Bulgaria is classified as extremely vulnerable to droughts according to the SPEI analysis.

Two distinct periods are clearly identifiable in the long-term SPEI-48 values, prior to 1984 and afterwards (Fig. 10B). Comparing the mean changes in precipitation and temperature over northeastern Bulgaria (Dobrudzha) for both periods reveals that during the first period (1950–1984), the region experienced wet conditions with only a slight increase in temperature (Fig. 15A). During this period, the modest temperature rise was insufficient to offset the prevailing wet conditions, and SPEI values remain positive for the temperate continental climate region, including northeastern Bulgaria. In contrast, in the second period (1984–2024) (Fig. 15B), northeastern Bulgaria experienced pronounced drought conditions, characterized by declining precipitation, rising temperatures and negative SPEI values.

Considering the entire period (1950–1984), negative SPEI values dominate over positive values, and Fig. 11 shows that the magnitude of negative net changes in cell-level values define the long-term drying trend in northeastern Bulgaria. However, if only precipitation data (ERA-5) are considered, the positive effect of wet conditions during 1950–1984 (Fig. 15A) outweighs the drying trend of the second period (1984–2024) (Fig. 15B). Consequently, when averaged over the full 1950–2024 period, a substantial decrease in mean annual precipitation is not evident (Fig. 13).

SPEI, as an index, incorporates not only precipitation but also temperature, evaporation, and transpiration. This allows it to detect drought conditions even when mean annual precipitation does not change significantly over long periods, making SPEI a robust tool for long-term drought monitoring. These observations support the conclusion that drought conditions in Bulgaria are likely driven more by rising temperatures and the uneven intra-annual distribution of precipitation than by changes in total mean annual precipitation.

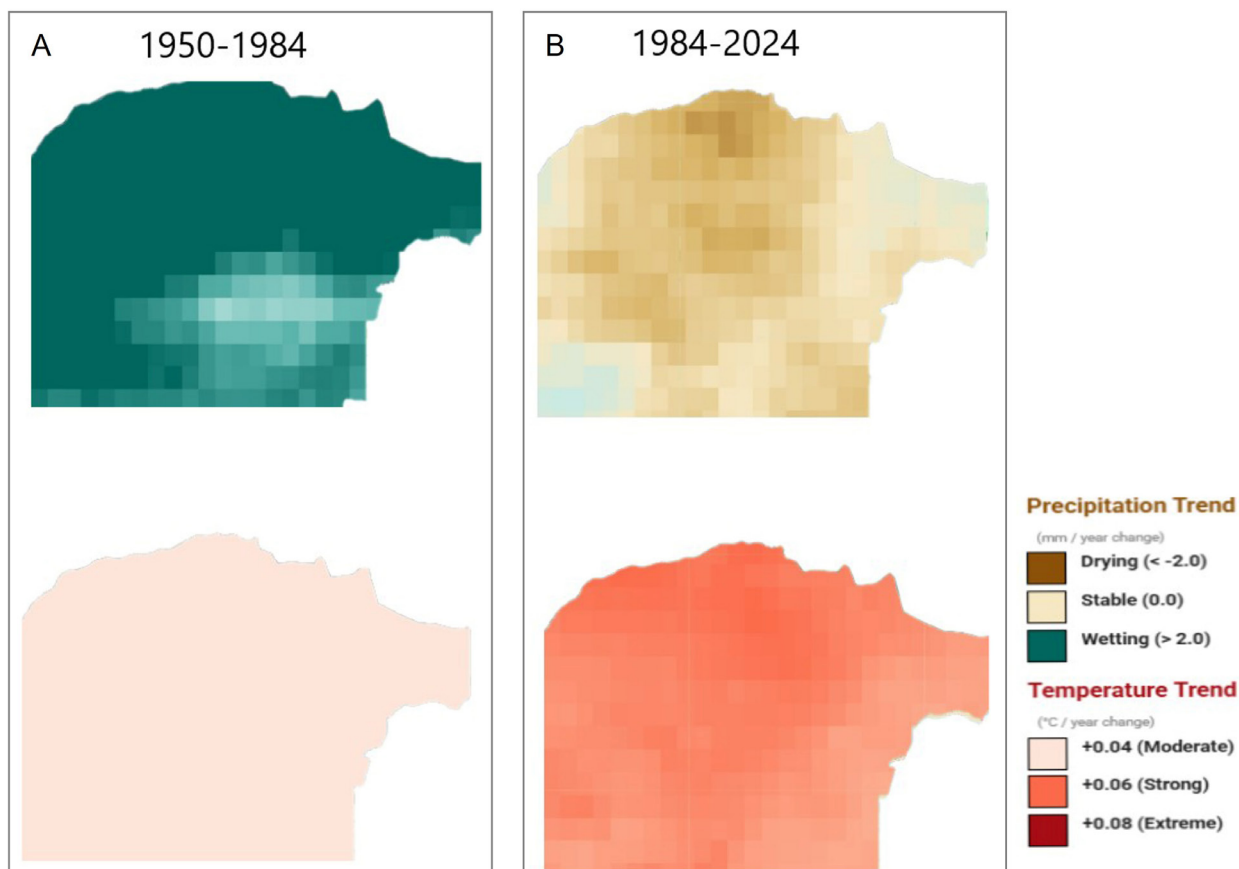


Figure 15. Mean annual change in precipitation and temperatures over northeastern Bulgaria. A 1950–1984 B 1984–2024.

These results complement previous studies and are consistent with observed climate changes in Bulgaria. The future magnitude and frequency of droughts in the country will largely depend on which climate change scenario unfolds. Under a high greenhouse gas emissions scenario (RCP 8.5), regional climate models project that temperatures in Bulgaria will increase by 2.2°C by mid-century and by 4.4°C by 2090. Despite substantial interannual variability in precipitation, the same high-emissions scenario projects declines in monthly precipitation totals relative to the 1986–2005 baseline by 4.4 mm by 2050 and 10.2 mm in the 2090s. The most pronounced decreases are expected during the summer months, which may exacerbate drought intensity and frequency (WBG 2021).

4. Discussion

In the context of climate change, droughts are increasingly recognized as “complex socio-natural events” (Rossi et al. 2023). The study by Knight et al. (2004) on the drought-induced crisis in Bulgaria during 1982–1994 provides a clear example of the complex nature of severe droughts, which can escalate to affect all economic sectors as well as social and political systems. In this context, the results of the present study demonstrate the potential of SPEI-48 for long-term assessment of drought conditions in Bulgaria, including the ongoing climate change.

Özçelik and Akkuzu (2023) also observed that SPEI has the potential to determine spatially drought periods on a long-time scale, as long-term SPEI values produce more reliable results to define uninterrupted long drought periods. Beiranvand et al. (2024) found that in the reconstruction of long-term drought events in the Zargos region, Iran, the most significant correlation between tree-ring-based data and different SPEI time scales was observed at a 48-month scale.

Regarding climate change, it is well understood that IPCC scenarios represent assumptions about possible future climate under different socio-economic pathways, rather than simple extrapolations of current climate conditions. In AR6, each Shared Socio-economic Pathway (SSP) drives a corresponding projection of greenhouse gas emissions and land-use changes according to its storyline. Which of these scenarios will ultimately unfold depends on the effectiveness of climate change mitigation and adaptation measures. Nevertheless, regardless of the scenario that materializes, the long-term negative trend observed in SPEI-48 highlights the need for Bulgaria to invest in both mitigation and adaptation strategies to address increasing drought hazards in the future.

The spatial distribution of the average values, return periods, frequency and trend analysis shows that both SPEI-12 and SPEI-48 in the east-northeast and south-southwest parts of the country experienced drought events more often and with higher drying trends than other regions of the country. The general SPEI-48 drying trend, with slight variations, is very well expressed all over the country. In both time series, SPEI-12 and SPEI-48, the return period is higher in the northeast, southwest and southeast parts of the country. These regions of Bulgaria appear the most vulnerable to drought hazard, also due to the intensive development of agricultural practices in these parts of the country. There are no specific publications on SPEI-48 in the scientific literature for Bulgaria, which makes it difficult to compare our results with previous studies in the region. However, there are studies for SPEI-12 that confirm some of the trends observed in this study in northeastern and southwestern Bulgaria. Previous assessments for Northern Bulgaria show the utility of SPEI-12 in identifying long-term drought occurrence and severity (Radeva and Nikolova 2020). Similarly, SPEI-12 has been applied to evaluate drought dynamics and hazard patterns across Southwest Bulgaria (Nikolova et al. 2024). Given the existing data on drought hazard in Bulgaria, the implementation of adaptation and prevention measures outlined in the National Climate Change Adaptation Action Plan (MOEW 2019) is of critical importance. The Strategy’s approach to drought includes development of early warning systems, improvements in water demand management, ecosystem-based solutions alongside irrigation infrastructure, as well as institutional and governance capacity building and awareness. Key

priority measures include modernisation of irrigation systems, promotion of drought-resistant crop varieties and climate-appropriate crop diversification, introduction of soil moisture conservation and water-efficient farming practices, prevention of land degradation and desertification through vegetation management and erosion control, and improvement of drought monitoring and public awareness regarding water saving during droughts, etc.

Irrigation infrastructure is a vital component of Bulgaria's water sector. The management and oversight of irrigation facilities and operations are carried out by the state-owned company "Irrigation Systems" EAD, which operates 254 irrigation systems and maintains 22 regional branches. State irrigation operators cover an irrigable area of 818,062 ha, of which 541,779 ha are suitable for irrigation. As of 2017, Bulgaria had 90 irrigation associations composed of physical or legal entities. These associations are municipally owned and serve approximately 350,000 ha. In 2020, the total volume of water used for irrigation was 273.55 million m³, of which 96.3% was allocated to agricultural land in Southern Bulgaria, primarily in South Central Bulgaria (223.23 million m³), while only 3.7% was used in Northern Bulgaria, with the highest consumption in the northeastern region (4.56 million m³) (NSI 2023).

The National Strategy for Management and Development of the Water Sector in the Republic of Bulgaria (MOEW 2012) aims to increase the irrigated area to 316,580 ha by 2030. The success of this strategy depends on the development of a Drought Risk Management Plan, which should include drought monitoring and early warning systems, vulnerability and impact assessment, and preparedness and response mechanisms for drought mitigation (UNDRR 2021). Although the EU Water Framework Directive (Directive 2000/60/EC) also requires the development of a Drought Risk Management Plan, such a plan has not yet been formulated in Bulgaria (Radeva and Nikolova 2021).

An essential component of current drought risk management is the use of early warning systems and drought risk analysis at global, regional, and national levels. These include the Global Drought Observatory (GDO 2023), the Global Drought Information System (GDIS 2023), the European Drought Observatory (EDO 2023), and the National Institute of Meteorology and Hydrology. The European Drought Risk Atlas represents a step toward impact-based drought assessment and can support the development and implementation of drought management and adaptation policies and actions. It characterizes how drought hazard, exposure, and vulnerability interact and affect various interconnected systems—agriculture, public water supply, energy, riverine transport, freshwater, and terrestrial ecosystems (Rossi et al. 2023).

5. Conclusions

Bulgaria has always been exposed to droughts of varying intensity and duration, but under climate change conditions, it is necessary to shift the paradigm and treat this hazardous phenomenon as a systemic issue rather than an isolated extreme event.

The analysis of the data on the values of the SPEI-48 shows a persistent, most often moderate, drought in the country over the last five decades. The results of the study demonstrate the need for continued applied, interdisciplinary, and decision-oriented research that directly supports policy design and the

implementation of adaptation strategies to ensure resilience to drought impacts. For the science-based implementation of drought mitigation and climate change adaptation strategies, further research priorities include the development of integrated surface–groundwater models to evaluate water availability under prolonged drought conditions, the assessment of compound and cascading risks associated with severe droughts, agro-ecological studies supporting climate-appropriate crop diversification, and scenario analyses to test the robustness of adaptation measures under different climate futures.

All economic sectors, across all levels of governance, including individual farmers, should have contingency plans in place to cope with drought-related threats, as the risk of droughts is expected to increase in the future, and the potential damages may be substantial.

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Additional information

Conflict of interest

No conflict of interest was declared.

Ethical statement

No ethical statement was reported.

Use of AI

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Author contributions

Conceptualization: MN. Data curation: XS. Formal analysis: MI. Funding acquisition: MN. Investigation: MN. Methodology: MN. Project administration: MN. Visualization: MI, XS. Writing - original draft: MN. Writing - review and editing: MN.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.