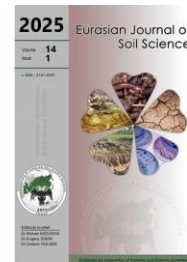




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Analysis of drought dynamics using SPI and SARIMA models: A case study of the Rostov Region, Russia

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Abstract

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Based on precipitation data from six weather stations covering the period 1960–2024, this study presents a retrospective analysis of drought dynamics in the Rostov Region, Russia, and evaluates the potential of the SARIMA model for forecasting moisture regime fluctuations. The Standardized Precipitation Index (SPI) was employed as the primary drought indicator. Two key phases of crop development were analyzed: the vegetation initiation period (March–May), assessed using the three-month SPI of May (SPI-3), and the full active growing season (April–September), assessed using the six-month SPI of September (SPI-6). The Mann-Kendall test revealed a non-significant positive trend in SPI-3 across all stations, while SPI-6 trends were non-significant and varied in direction. The highest frequency of drought events, based on both SPI-3 and SPI-6, occurred during 1960–1969, with a general decline in subsequent decades. The lowest drought frequency was observed during 2010–2019. Notably, the frequency of extreme droughts has shown an increasing trend, posing significant risks to agricultural productivity. Although SARIMA modeling proved useful for short-term forecasting, its application was limited by unrealistic long-term projections and deviations from climatic norms. Consequently, drought forecasts were restricted to a two-year horizon. Nonetheless, the SARIMA approach remains a valuable supplementary tool for anticipating precipitation dynamics and drought events.

Keywords: Drought forecasting, Standardized Precipitation Index (SPI), SARIMA model, Vegetation Dynamics, Precipitation variability.

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Introduction

One of the main manifestations of climate change is the noticeable shift in precipitation patterns. A key consequence of such changes is the increased frequency of drought events, generally defined as prolonged periods with significant precipitation deficit, accompanied by elevated temperatures and reduced air humidity (Wu et al., 2022). These events often have highly detrimental effects on ecosystems, agriculture, and other economic sectors. Therefore, the development of effective approaches for monitoring and mitigating drought has become a highly relevant and important task (Holgate et al., 2020).

Most drought assessment methods are based on analyzing the temporal dynamics of meteorological variables, with precipitation being the primary indicator. Drought characteristics are typically quantified using specialized indices (Van Ginkel and Biradar, 2021). Among the most widely used are the Palmer Drought Severity Index (PDSI), Reconnaissance Drought Index (RDI), Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI). Among these, SPI is particularly favored

due to its simplicity—it requires only precipitation data—and its universality, allowing for standardized drought assessment across different regions and time periods. For this reason, it is recommended by the World Meteorological Organization (Svoboda et al., 2012). SPI assesses the deviation of precipitation over a specific time period from the long-term average (Bouaziz et al., 2021), converting the data into a dimensionless index that facilitates comparative drought analysis (Docheshmeh Gorgij et al., 2022).

This study focuses on the Rostov Region of the Russian Federation, where drought monitoring is of particular importance due to the region's critical role in national agricultural production. Situated in the southern part of the East European Plain and in the Pre-Caucasus region (Figure 1), the Rostov Region is characterized by unstable moisture conditions, dry and hot summers, and relatively snow-deficient winters. Studies indicate that climatic conditions represent the primary risk factor for agriculture in this area (Lukyanets and Bragin, 2021). In particular, reduced precipitation and the resulting frequent droughts during the growing season are identified as major causes of crop failure (Gudko et al., 2022, 2024). Moreover, projections suggest an increasing trend in aridity across southern Russia, including the Rostov Region, under ongoing climate change scenarios (Kattsov et al., 2008).

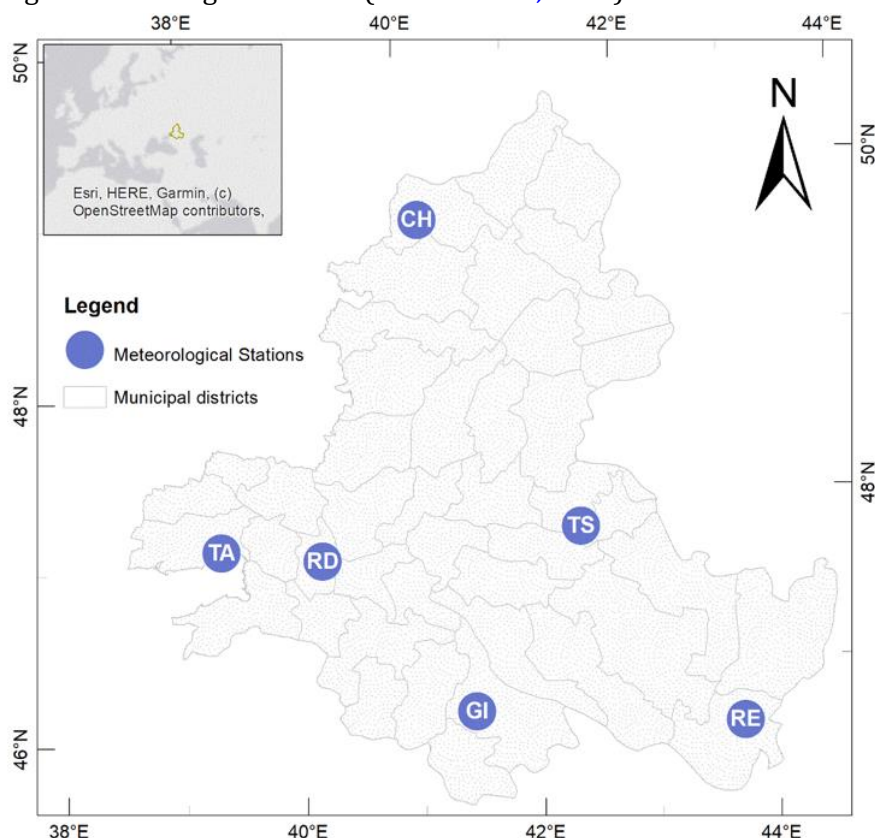


Figure 1. Study area and the meteorological stations considered

Given these factors, identifying trends and developing forecasting tools for drought events in the Rostov Region is an urgent research priority. Doing so would enable the development of timely response strategies to reduce the risk of agricultural losses. The present study aims to address this need by conducting a retrospective analysis of drought trends using multi-year precipitation data and by exploring the potential of the Seasonal Autoregressive Integrated Moving Average (SARIMA) approach to forecast fluctuations in the regional moisture regime.

Material and Methods

Precipitation dataset

This study utilized atmospheric precipitation (PR) data from six meteorological stations located in the Rostov Region, covering the period 1960–2024. These data were primarily obtained from the World Data Center of the Russian Research Institute of Hydrometeorological Information (RRIHI-WDS, 2025). Details of the selected meteorological stations are provided in Table 1 and illustrated in Figure 1.

To ensure data completeness, missing values in some stations were supplemented using records from the U.S. National Oceanic and Atmospheric Administration (<https://www.ncdc.noaa.gov/cdo-web/>). As a result, each time series achieved at least 95% completeness, in line with the recommendations of the World Meteorological Organization (WMO).

Table 1. List of meteorological stations, their WMO (World Meteorological Organization) number, latitude, longitude and altitude (m)

Station name*	WMO no.	Latitude (N)	Longitude (E)	Altitude (m)
Chertkovo (CH)	34432	49.23	40.10	136
Tsimlyansk (TS)	34646	47.38	42.07	66
Rostov-on-Don (RD)	34730	47.25	39.82	66
Taganrog (TA)	34720	47.20	38.95	30
Gigant (GI)	34740	46.52	41.35	79
Remontnoe (RE)	34759	46.34	43.40	106

* Meteorological stations are ordered from north to south

Methodological Framework

The methodological structure of the study comprises four main steps (Figure 2):

- Retrospective analysis of drought events based on the distribution of SPI values from 1960 to 2024;
- Time series analysis of precipitation using the SARIMA model;
- Model diagnostics and selection, followed by precipitation modeling;
- Drought forecasting through SPI values calculated from SARIMA-modeled precipitation data.

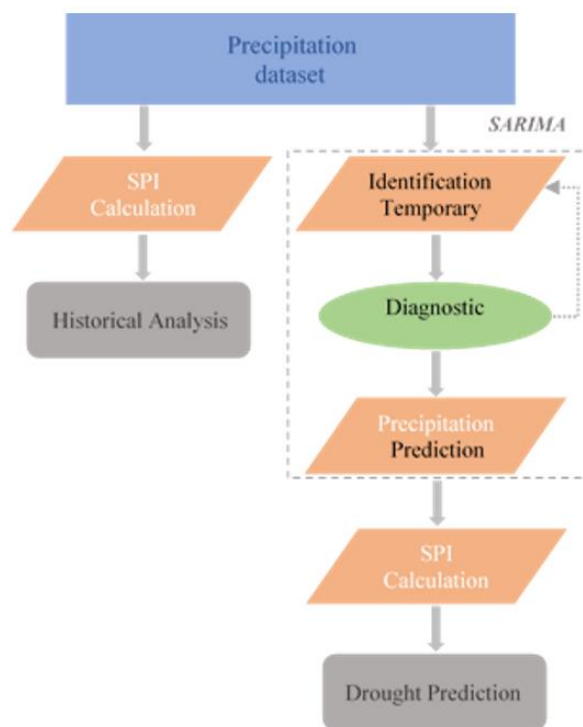


Figure 2. The framework for the proposed methodology

Standardized Precipitation Index (SPI)

The SPI is a standardized metric used to quantify precipitation anomalies over a specific time period (McKee et al., 1993). Since precipitation data rarely conform to a normal distribution, a gamma probability density function is fitted to the observed frequency distribution of monthly precipitation values. The resulting probabilities are then transformed into a standard normal distribution, yielding SPI values with a mean of zero and a standard deviation of one.

Positive SPI values reflect wetter-than-average conditions, whereas negative values indicate precipitation deficits. This standardization enables consistent assessment of drought and wet periods across different regions and time frames. Drought classification according to SPI thresholds is presented in Table 2.

Table 2. Drought classification according to SPI

SPI value	Drought classification
> 2.0	Extreme wet
from 1.50 to 1.99	Very wet
from 1.00 to 1.49	Moderately wet
from 0.99 to -0.99	Near normal
from -1.00 to -1.49	Moderately dry
from -1.50 to -1.99	Severely dry
< -2.0	Extremely dry

SPI calculation requires long-term precipitation data, with a minimum of 30 years recommended by the WMO. The index can be computed over various accumulation periods (e.g., 3, 6, 9, 12, and 24 months), each reflecting different hydrological and agricultural impacts (Panigrahi and Vidyarthi, 2024). Shorter periods (1–6 months) are relevant for assessing agricultural and soil moisture conditions, whereas longer periods (6–24 months) better capture impacts on river flows, groundwater levels, and reservoirs (Svoboda et al., 2012).

In this study, two SPI intervals were selected to assess drought during critical crop development stages in the Rostov Region ([Gudko et al., 2021](#)):

SPI-3 (May): representing moisture conditions from March to May, corresponding to the early vegetation phase;

SPI-6 (September): reflecting moisture availability during the entire active growing season from April to September.

Historical Analysis

Historical drought trends and moisture conditions in the Rostov Region were analyzed using SPI-3 and SPI-6 values over the 1960–2024 period. The Mann-Kendall test was employed to assess the presence of significant trends. Drought events were identified as years when SPI values were below -1.0 . For temporal comparison, the dataset was divided into seven periods:

Period I (1960–1969), Period II (1970–1979), Period III (1980–1989), Period IV (1990–1999), Period V (2000–2009), Period VI (2010–2019), and Period VII (2020–2024).

Seasonal Autoregressive Integrated Moving Average (SARIMA)

The SARIMA model, an extension of the ARIMA framework, was applied to forecast precipitation at each meteorological station. Unlike standard ARIMA, SARIMA incorporates seasonal components to account for cyclical patterns in time series data. The model includes autoregressive terms (AR), differencing (to address non-stationarity), and moving average (MA) components, along with their seasonal counterparts ([Ottom et al., 2023](#)). Technical details on SARIMA implementation can be found in [Huang and Petukhina \(2022\)](#).

- To evaluate model performance, several statistical metrics were applied, including:
- Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) for absolute deviation;
- Mean Absolute Percentage Error (MAPE) for relative accuracy;
- Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) for model comparison and complexity control ([Ding et al., 2017](#); [Ray et al., 2021](#)).

Forecasting was limited to a two-year horizon (2025–2026) due to the emergence of physically implausible precipitation values over longer intervals. In addition to statistical accuracy, the practical interpretability of forecasted values was also considered to ensure consistency with regional climatic norms. The resulting precipitation forecasts were used to compute SPI-3 and SPI-6 values for the same stations.

Spatial Distribution and Interpolation

To visualize spatial variability, SPI-3 and SPI-6 values derived from SARIMA-based forecasts were interpolated across the study area using kriging with a spherical variogram model in ArcGIS. Meteorological stations served as reference points. The resulting spatial distributions were classified according to the SPI categories shown in Table 2.

Results and Discussion

Historical Analysis

Dynamics of moisture conditions

The interannual dynamics of SPI-3 and SPI-6 values for the period 1960–2024 at the selected meteorological stations are presented in Figures 3 and 4. Overall, a weak positive trend in SPI-3 was observed across all stations, indicating a general improvement in moisture conditions during the early crop growth phase. Similar trends in SPI-6 were recorded at RE, TS, and CH stations, whereas at GI, RD, and TA stations, SPI-6 showed a slight, non-significant decrease.

The distribution of SPI-3 values suggests that normal moisture conditions prevailed during most of the study period. For example, normal conditions were recorded in 65% and 69% of years at GI and RE, and in 72%, 72%, and 75% of years at RD, TA, and TS, respectively. At CH station, normal moisture conditions were observed in 80% of the years, reflecting the most stable hydrological regime in the study area. Moisture surpluses during the early growing season ($\text{SPI-3} > 1$) were observed in 17%, 15%, 11%, 9%, 14%, and 6% of years for GI, RE, RD, TA, TS, and CH stations, respectively. Notably, the majority of very wet and extremely wet conditions were recorded between 2010 and 2024.

Regarding SPI-6, normal moisture conditions during the full vegetation period were recorded in 60%, 66%, and 62% of years for GI, RD, and TS stations, respectively, while at other stations the proportion ranged between 72% and 74%. The highest moisture levels were mostly observed in the decade 1970–1979, during which SPI-6 values reached 1.96 at RE, 2.14 at RD, 1.84 at TA, 2.48 at TS, and 1.86 at CH—values corresponding to very moist or extremely moist conditions (Figure 4).

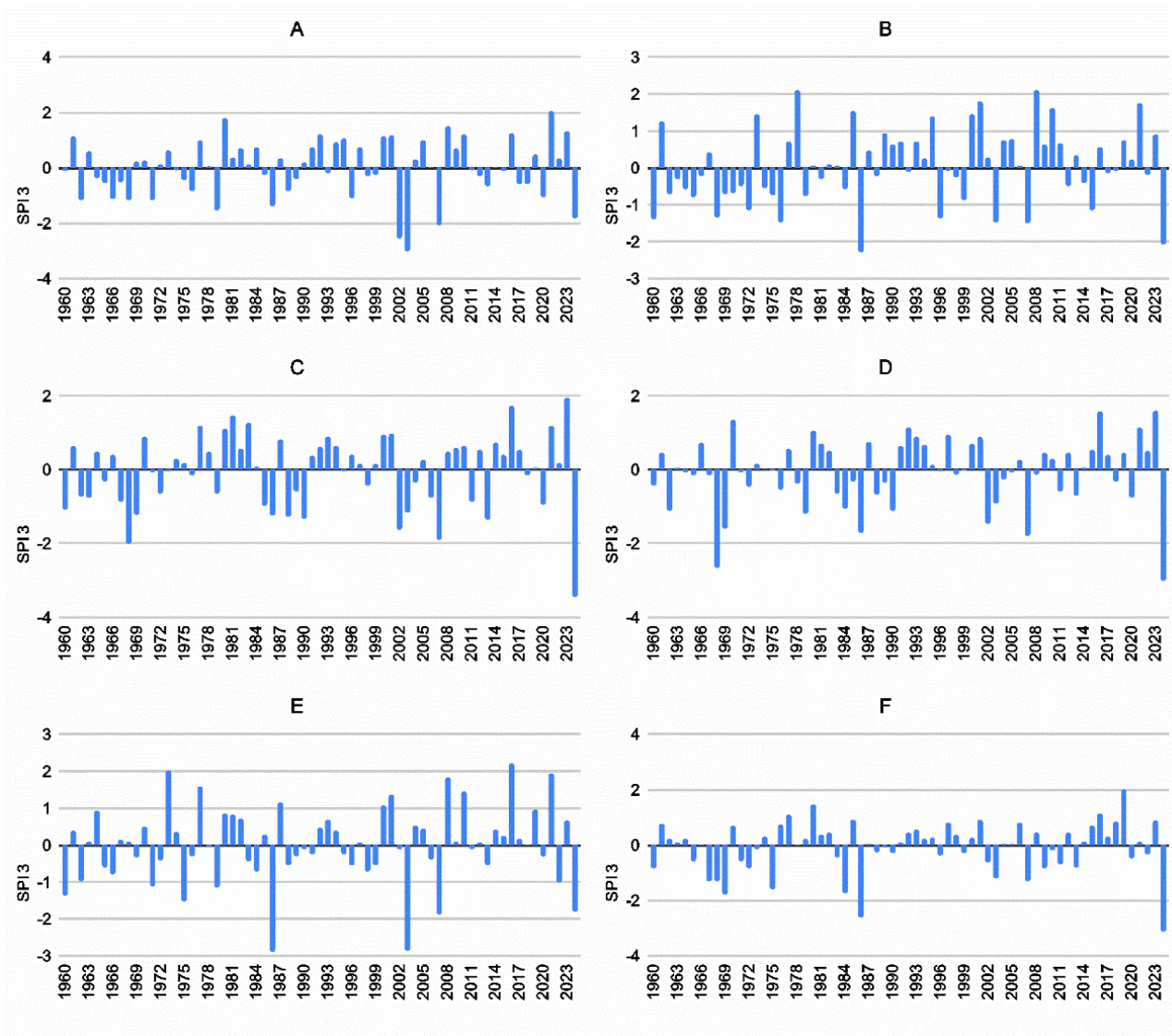


Figure 3. Dynamics of the SPI-3 indicator at the GI (A), RE (B), RD (C), TA (D), TS (E) and CH (F) meteorological stations in the period 1960–2024

The observed increase in SPI-3 values during the early growing season aligns with findings from other studies. In southern Russia, including Rostov Region, recent decades have seen a shift in precipitation from summer and autumn toward spring and winter months, contributing to more frequent years with normal or above-normal moisture availability ([Ashabokov et al., 2018](#); [Gudko et al., 2024](#)).

Analysis of the frequency of dry events

The frequency of drought events in the period 1960–2024 in relation to ten-year intervals is presented in Tables 3 and 4. According to the SPI-3 value, in general, the driest conditions in the initial growing season in Rostov Region occurred in the periods 1960–1969 and 2000–2009. In the period 1960–1969, the greatest number of drought events was observed. At the same time, while at meteorological station GI during this period during three years moderate drought was observed in the initial period of vegetation, for example, for RD and TA single cases of severe or extreme drought were observed. The frequency of drought events at the beginning of the growing season was lower between 1970 and 1979 (Table 3). No years with extreme drought were observed, but isolated cases of severe drought were observed for weather stations GI, TS, and CH. At the same time, for TS during this period moisture conditions were twice characterized as moderately dry. The period 1980–1989 was comparable to the previous period in terms of the total number of drought events. However, for weather stations RE, TS and CH, years with extreme drought in the initial growing season were recorded (Table 3).

Sufficiently favorable conditions in the initial growing season were observed in the period 1990–1999. In this time period, only at weather stations GI, RE, RD and TA single cases of moderate drought were observed, and years with severe or extreme drought were not observed. The 2000–2009 period was characterized by

an increase in the frequency of drought events of the initial growing season in the region. At the same time, a sharp increase in the frequency of extreme drought was observed. For meteorological station GI the number of such events in this period was repeated three times and a single case was recorded at TS. Cases of severe drought at the beginning of the growing season were observed in some years at some other weather stations, such as RD and TA (Table 3). During the period 2010–2019, the moisture conditions of the beginning of the growing season were the least drought conditions. According to the SPI-3 values obtained, the wetting conditions decreased only to the level of moderate drought and only for weather stations RE and RD.

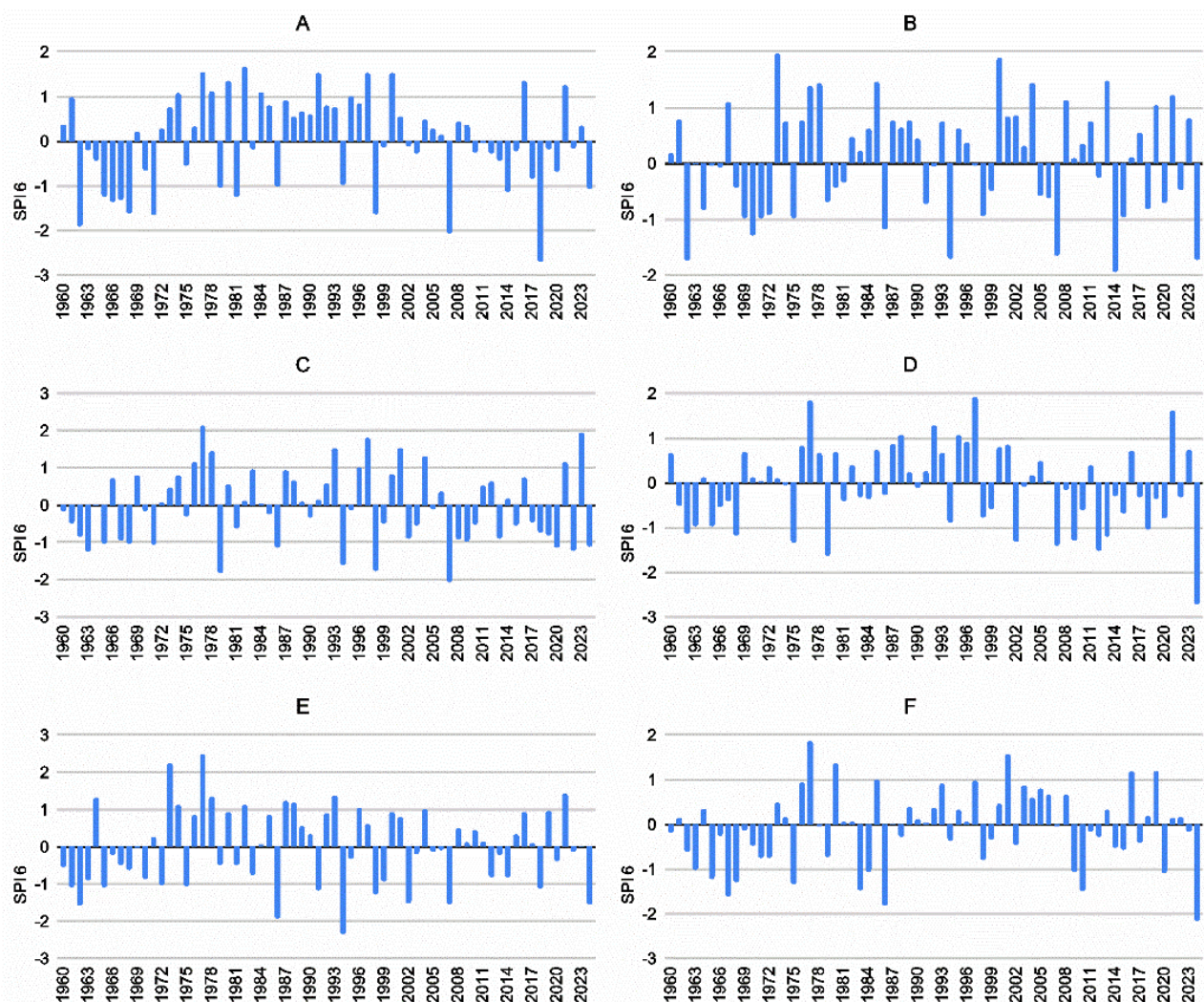


Figure 4. Dynamics of the SPI-6 indicator at the GI (A), RE (B), RD (C), TA (D), TS (E) and CH (F) meteorological stations in the period 1960–2024

In the five-year period 2020–2024, the number of drought events was quite high. However, the main years with drought in the initial period of crop vegetation in the Rostov region occurred in 2024, when extreme (RE, RD, TA, CH) or severe drought (GI, TS) was established throughout the region. It is worth noting that in 2024 for three weather stations at once, namely for RD, TA and CH, the absolute minimum SPI-3 for the entire observation history was noted, and its value amounted to -3.43, -3.01 and -3.1, respectively.

The frequency of drought events according to SPI-6 generally correlates with the frequency of SPI-3 (Table 4). Similarly, the period 1960–1969 had the highest cumulative number of drought events during the entire growing season (Table 4). No extreme drought events were identified during this period, but severe drought was observed for weather stations GI, RE, TS, and CH in some years (Table 4). Moderate drought in this ten-year period was observed for all meteorological stations except RE. However, for weather stations GI, RD and CH, moderate drought during the growing season was observed three times during the decade. The frequency of drought events throughout the growing season also showed a decrease in the following decade. Incidences of extreme drought during the period 1970–1979 were also not observed on SPI-6, but isolated occurrences of severe drought were observed on GI, RD, and TA. At the same time, moderately dry conditions were observed at all weather stations at least once.

Table 3. Number of years per decade with moderately dry (MD), severely dry (SD) and extremely dry (ED) conditions according to SPI-3 at the meteorological stations GI, RE, RD, TA, TS and CH during the period 1960–2024

Period/Meteorological stations		SPI-3		
		MD	SD	ED
1960–1969	GI	1962, 1966, 1968	-	-
	RE	1960, 1968	-	-
	RD	1960, 1969	-	1968
	TA	1962	1969	1968
	TS	1960	-	-
	CH	1967, 1968	1969	-
1970–1979	GI	1971	1979	-
	RE	1972, 1976	-	-
	RD	-	-	-
	TA	1979	-	-
	TS	1971, 1979	1975	-
	CH	-	1975	-
1980–1989	GI	1986	-	-
	RE	-	-	1986
	RD	1986, 1988	-	-
	TA	1984	1986	-
	TS	-	-	1986
	CH	-	1984	1986
1990–1999	GI	1996	-	-
	RE	1996	-	-
	RD	1990	-	-
	TA	1990	-	-
	TS	-	-	-
	CH	-	-	-
2000–2009	GI	-	-	2002, 2003, 2007
	RE	2003, 2007	-	-
	RD	2003	2002, 2007	-
	TA	2002	2007	-
	TS	-	2007	2003
	CH	2003, 2007	-	-
2010–2019	GI	-	-	-
	RE	2015	-	-
	RD	2013	-	-
	TA	-	-	-
	TS	-	-	-
	CH	-	-	-
2020–2024	GI	2020	2024	-
	RE	-	-	2024
	RD	-	-	2024
	TA	-	-	2024
	TS	2022	2024	-
	CH	-	-	2024

The number of drought events in the periods 1980–1989 and 1990–1999 during the growing season in the study region was comparable and quite low over the entire study period. However, in the period 1990–1999, a higher frequency of severe drought events was observed, and for the first time in the study period, extreme drought was observed at weather station TS. The period 2000–2009 was characterized by a further increase in the frequency of drought events, and especially extreme drought events. In this decade, such conditions during the growing season were established at meteorological stations GI and RD. Severe drought in 2000–2009 was also observed at weather stations RE and twice at TS. At the same time at TA for three years moisture conditions were characterized as moderately dry. The 2010–2019 period is also characterized by single occurrences of extreme (GI) and severe (RE and TA) drought. For the five-year period 2020–2024, drought events similarly occurred for the most part in 2024. In this year, moisture conditions during the growing season were characterized as extreme or severely dry for most weather stations.

Table 4. Number of years per decade with moderately dry (MD), severely dry (SD) and extremely dry (ED) conditions according to SPI-3 and SPI-6 at the meteorological stations GI, RE, RD, TA, TS and CH during the period 1960–2024

Period/Meteorological stations		SPI-3		
		MD	SD	ED
1960–1969	GI	1965, 1966, 1967	1962, 1968	-
	RE	-	1962	-
	RD	1963, 1965, 1968	-	-
	TA	1962, 1968	-	-
	TS	1961, 1965	1962	-
	CH	1963, 1965, 1968	1967	-
1970–1979	GI	1979	1971	-
	RE	1970	-	-
	RD	1971	1979	-
	TA	1975	1979	-
	TS	1972, 1975	-	-
	CH	1975	-	-
1980–1989	GI	1981, 1986	-	-
	RE	1986	-	-
	RD	1986	-	-
	TA	-	-	-
	TS	-	1986	-
	CH	1983, 1984	1986	-
1990–1999	GI	1996	-	-
	RE	1996	-	-
	RD	1990	-	-
	TA	1990	-	-
	TS	-	-	-
	CH	-	-	-
2000–2009	GI	-	-	2002, 2003, 2007
	RE	2003, 2007	-	-
	RD	2003	2002, 2007	-
	TA	2002	2007	-
	TS	-	2007	2003
	CH	2003, 2007	-	-
2010–2019	GI	-	-	-
	RE	2015	-	-
	RD	2013	-	-
	TA	-	-	-
	TS	-	-	-
	CH	-	-	-
2020–2024	GI	2020	2024	-
	RE	-	-	2024
	RD	-	-	2024
	TA	-	-	2024
	TS	2022	2024	-
	CH	-	-	2024

Note that the analysis of SPI time series in the monthly approximation for a similar list of meteorological stations in Rostov Region was studied earlier in ([Salmin et al., 2021](#)). For the thirty-year period 1990–2020, the authors found negative trends of monthly SPI in the dynamics of interannual variability. The period 2010–2020, according to the authors, turned out to be a drought period, which partially agrees with the results of our study in terms of SPI-6. At the same time, as in our study, the highest moisture content and a fairly high number of extreme droughts were observed in the period 2000–2009 ([Salmin et al., 2021](#)).

Forecast of moisture conditions

SARIMA model indicators and forecasting horizon

For each station, the optimal SARIMA configuration was selected based on the lowest values of the Akaike Information Criterion (AIC) and minimum error metrics (RMSE, MAE, MAPE) calculated on the validation datasets. Individual sets of model parameters (p, d, q) and (P, D, Q) with seasonal components were defined for each location to ensure the best fit to historical precipitation data and the stability of forecasts.

The forecast was limited to the next two years (2025-2026) because a longer horizon would lead to physically unrealistic precipitation values (e.g., negative) and a significant deviation from the climatic norm. The criteria for selecting such a horizon were: i) reliability of the forecast within the available historical data, ii) absence of anomalies beyond reasonable interpretation of precipitation, and iii) preservation of model stability when seasonal variations are taken into account within the limits of reasonable extrapolation.

Forecasting of dry events

Forecast distribution of SPI-3 and SPI-6 values on the territory of Rostov region, calculated on the basis of modeled precipitation data, are presented in Figures 5 and 6, respectively. According to the obtained models, moisture conditions in the initial growing season according to SPI-3 (March-May) in 2025 in most of the region will correspond to the norm. Drought events are not predicted during this period (Figure 5). As one moves westward into the RD, TA, and CH weather station area, moisture conditions will change to very to extremely wet. In 2026, moderately dry conditions will cover a small portion of the region in the eastern part of the region. At the same time, the isoline from extreme wetness will shift to the east.

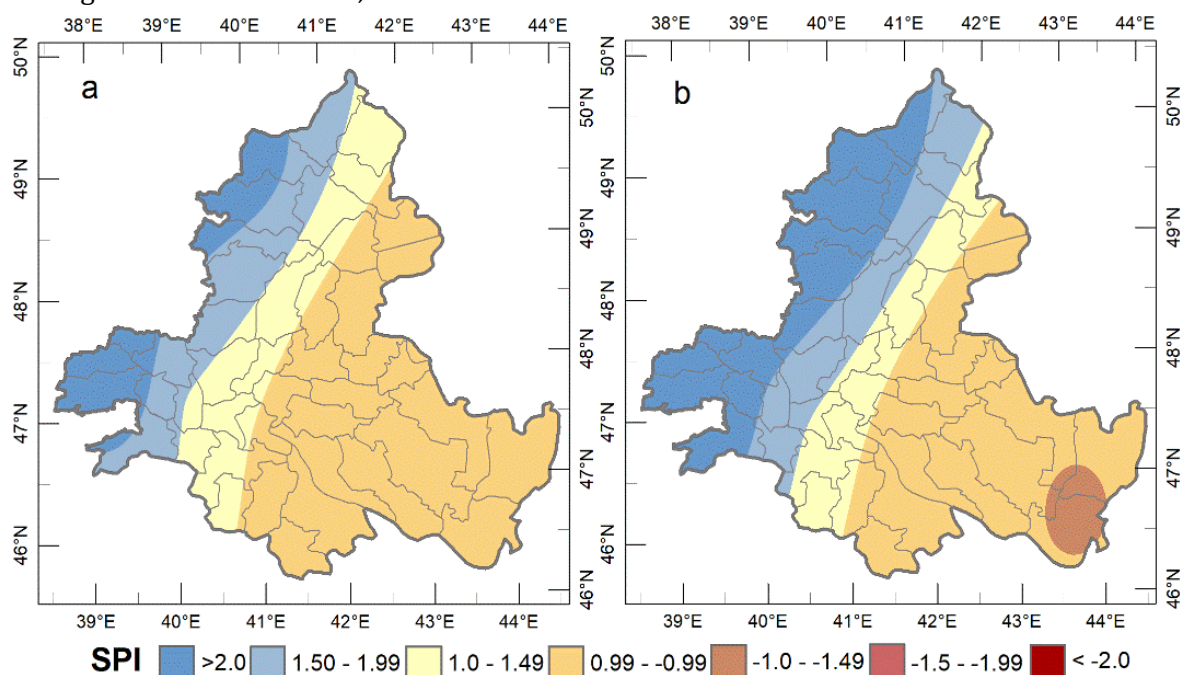


Figure 5. Forecast of the distribution of the SPI-3 (March-May) indicator in the Rostov region for 2025 (a) and 2026 (b)

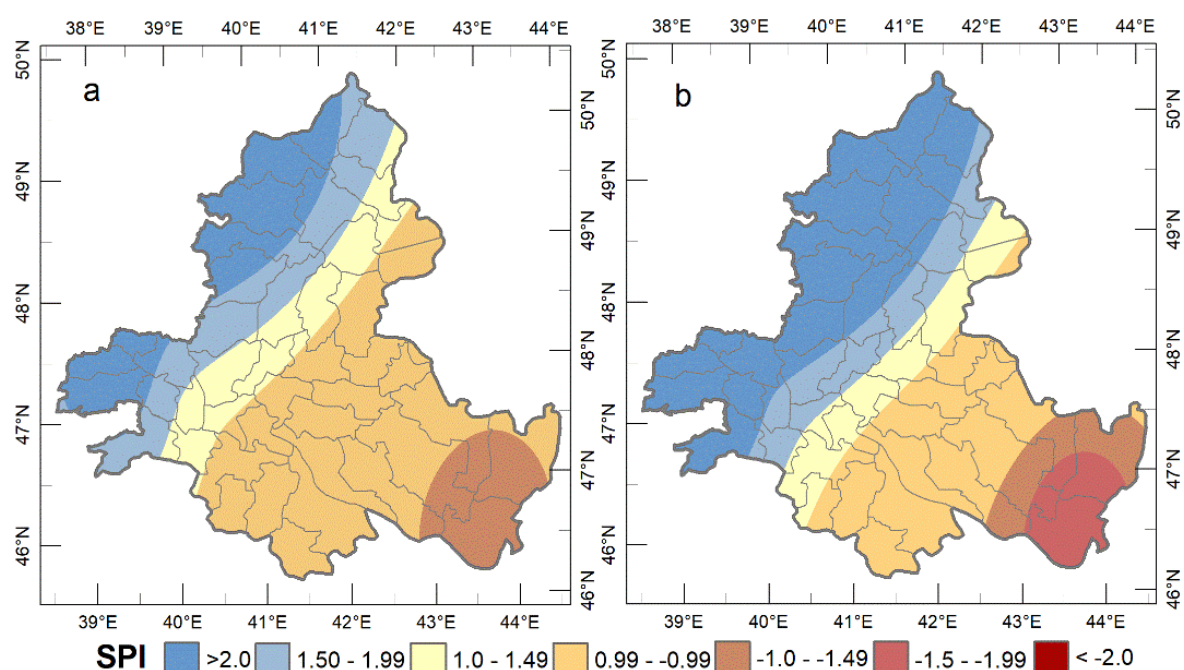


Figure 6. Forecast of the distribution of the SPI-6 (April-September) indicator in the Rostov region for 2025 (a) and 2026 (b)

According to the obtained models, moisture conditions during the entire period of active vegetation of crops according to SPI-6 (April - September) in 2025 in most of the region will also correspond to the norm (Figure 6). However, moderate drought conditions are forecast in the eastern part of the region during this period. Extremely wet conditions are characterized in the areas where the TA and CH weather stations are located. In 2026, according to SPI-6 model data, the eastern part of the Rostov region is characterized by an intensification of moisture deficit to severe drought, as well as a slight expansion of the territory covered by moderate drought. At the same time, the isoline with extreme and very wet conditions will also shift quite significantly to the east of the Rostov Region.

Conclusion

The application of SPI-3 and SPI-6 in this study enabled a comprehensive analysis of drought dynamics in the Rostov Region during two critical phases of crop development: the early vegetation period (March–May) and the full active growing season (April–September). The findings revealed that the highest frequency of drought events for both periods occurred during the initial decade (1960–1969). In the subsequent decades, the frequency of droughts generally declined, particularly during the full growing season, and remained relatively stable across the last three ten-year intervals. However, for the early vegetation period, fluctuations were more pronounced, with periods of low drought frequency followed by intervals marked by more frequent drought occurrences.

Although the overall trend pointed to a slight increase in moisture availability—especially during the early season—this has not entirely mitigated the region’s vulnerability. Of particular concern is the observed rise in the frequency of extreme drought events, which pose significant risks to agricultural productivity. This trend is likely to intensify under ongoing climate change conditions and calls for continued monitoring and adaptive planning.

The SARIMA modeling approach used in this study highlighted both the potential and limitations of time series forecasting for precipitation. While the method proved useful for short-term projections, its predictive capacity diminished over longer horizons due to deviations from climatic norms and the emergence of physically implausible values. For this reason, the forecast horizon was restricted to two years. Despite these limitations, SARIMA can serve as a valuable supplementary tool for forecasting precipitation trends and drought conditions.

The methodological framework presented in this study can be readily adapted for use in other regions facing similar climatic challenges, contributing to a broader understanding of drought dynamics and supporting the development of mitigation strategies in agricultural systems.

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