Rainfall deficit as a risk phenomenon in the southern region of the Republic of Moldova

Le déficit pluviométrique comme phénomène à risque dans la région sud de la République de Moldavie

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ABSTRACT: Drought and rainfall deficit represent major climatic risks that *increasingly* affect the southern region of the Republic of Moldova. The aim of this study is to identify and characterize the spatial variability and temporal trends of rainfall deficit using three complementary indices - the Percent of Normal Index (PNI), the Decile Index (DI), and the Rainfall Anomaly Index (RAI) - in combination with the Mann–Kendall trend test. The analysis is based on data from five meteorological stations (Leova, Cahul, Comrat, Ceadir-Lunga, and Stefan Voda) covering the 1991-2022 period. The results show that the highest number of months with rainfall deficits occurred at Cahul and Leova, while the overall trends are not statistically significant. However, a seasonal redistribution of precipitation is observed, with drier summers and wetter autumns, along with a slight aridization toward the southwest. The findings confirm the increasing pluviometric instability over recent decades and highlight the need for adaptive measures in water resource management and drought monitoring, both meteorological and agricultural, in the southern part of the Republic of Moldova.

KEY WORDS: drought, Mann Kendall, Moldova, rainfall deficit, risk

RÉSUMÉ : La sécheresse et le déficit pluviométrique constituent des risques climatiques majeurs qui affectent de plus en plus le sud de la République de Moldavie. Cette étude vise à identifier et à caractériser la variabilité spatiale et les tendances temporelles du déficit pluviométrique à l'aide de trois indices complémentaires – l'indice de pourcentage de la normale (IPN), l'indice décile (ID) et l'indice d'anomalie pluviométrique (IAP) – combinés au test de tendance de Mann-Kendall. L'analyse repose sur les données de cinq stations météorologiques (Leova, Cahul, Comrat, Ceadir-Lunga et Stefan Voda) couvrant la période 1991-2022. Les résultats montrent que Cahul et Leova ont enregistré le plus grand nombre de mois déficitaires, tandis que les tendances générales ne sont pas statistiquement significatives. On observe toutefois une redistribution saisonnière des précipitations, avec des étés plus secs et des automnes plus humides, ainsi qu'une légère aridification vers le sud-ouest. Ces résultats confirment l'instabilité pluviométrique croissante observée ces dernières décennies et soulignent la nécessité de mesures d'adaptation dans la gestion des ressources en eau et le suivi de la sécheresse, tant météorologique qu'agricole, dans le sud de la République de Moldavie.

MOTS-CLÉS : sécheresse, Mann Kendall, Moldavie, déficit pluviométrique, risque

1. Introduction

Drought is among the most severe natural hazards worldwide, affecting ecosystems, agriculture, and water resources. Although it is a natural phenomenon, climate change accelerates its onset and amplifies its impacts (Mukherjee et al., 2018; Hao et al., 2018). Depending on duration and intensity, droughts can be classified into four main types: meteorological, agricultural, hydrological, and socio-economic (Salimi et al., 2021).

The rainfall deficit - a temporary imbalance between precipitation and water demand-represents a major climatic feature of continental regions such as the Republic of Moldova, where periods of surplus and deficit frequently alternate (Bojariu, et al., 2021).

In the context of Southeastern Europe, the southern part of the Republic of Moldova is among the regions most exposed to meteorological droughts, mainly due to its continental position and the predominance of anticyclonic regimes, which bring cold or dry air masses. The Siberian anticyclone, which forms over Eastern Europe in October and persists until April, restricts the penetration of moist air from the Mediterranean and Atlantic basins, thus reducing precipitation input (Vlăduț, 2004; Puțuntică, 2018).

At the European scale, numerous studies have investigated the distribution, intensity, and mechanisms of drought (Rebetez et al., 2006; Ionita et al., 2017; García-Herrera et al., 2019; Jaagus et al., 2021; Nistor, 2019; Charalampopoulos et al., 2023). The extreme event of the summer of 2003 represented a turning point, marking the emergence of a new type of compound drought, characterized by the combination of rainfall deficit with prolonged heat waves and a continental-scale extent (Rebetez, Mayer, Dupont, & Schindler, 2006). Subsequent droughts, such as those of 2015 (Ionita, et al., 2017) and 2016-2017 (Garcia-Herrera, et al., 2019), confirmed this trend, affecting up to 90% of Central and Eastern Europe. These episodes were driven by persistent atmospheric blocking, a displacement of the Atlantic jet stream, and abnormally high temperatures in the Mediterranean basin, which enhanced evapotranspiration and favored the persistence of anticyclonic regimes.

Over the long term, Jaagus et al. (2021) revealed a seasonal redistribution of climatic humidity - with wetter winters and drier summers-and a progressive aridization across southern and central Eastern Europe, where increased evapotranspiration amplifies moisture deficits. In Southeastern Europe, Nistor (2019) showed that climate change significantly reduces groundwater reserves, particularly in the lowlands of Romania, Bulgaria, and northern Greece, where aridization processes affect nearly half of the territory. The projections by Charalampopoulos et al. (2023) confirm these tendencies, indicating a tripling of semi-arid areas by the end of the century and a threefold reduction in extremely humid zones, especially within lowland agricultural regions.

Overall, these findings demonstrate that Europe - particularly its southeastern region—is experiencing an intensification of aridization, driven by the interaction between atmospheric warming, decreasing precipitation, and increasing evapotranspiration. The resulting climatic, hydrological, and agricultural consequences highlight the urgent need for coordinated European adaptation policies and sustainable water resource management, given the region’s growing climatic vulnerability.

In Romania, a country with climatic conditions similar to those of the Republic of Moldova, drought variability has been analyzed using both climatic data and satellite-derived products (Cheval et al., 2014; Pelin, 2016; Prăvălie et al., 2019; Angearu et al., 2020; Dobri et al., 2021). These studies indicate a regional aridization trend, particularly affecting the southern and southeastern parts of the country - areas that are climatically comparable to southern Moldova. Using the Standardized Precipitation Index (SPI), Cheval et al. (2014) identified an increase in the frequency and duration of droughts across the Romanian Plain, Oltenia, and Dobrogea - especially after 1980 - with the phenomenon extending into the autumn months. In the northeastern part of the country, Pelin (2016) found, based on the de Martonne, Hârjoabă, and Nedealcov (2012) indices, an increase in the number of dry years after 1990, confirming the climatic continuity between the Moldavian Plain (Romania) and the Moldavian Plateau (Republic of Moldova). Prăvălie et al. (2019) showed a significant decrease - by more than 150 mm in recent decades - in the climatic water balance (CWB = P - PET), reflecting the ongoing aridization of lowland regions. Using MODIS data, Angearu et al. (2020) revealed pronounced aridization toward the end of the agricultural season (July-September), while Dobri et al. (2021) confirmed, through NDDI (2001-2020) analysis, the persistence of drought conditions and the high vulnerability of arable land in southern and southeastern Romania, strongly influenced by the evapotranspiration regime.

In the Republic of Moldova, recent climatological research confirms that drought is among the most frequent and severe natural hazards, with major impacts in the southern regions (Potop, 2011; Potopová et al., 2015; Nedealcov, 2019; Vicente-Serrano et al., 2024). Long-term analyses (1891 - 2020) reveal a steady increase in the frequency and intensity of summer droughts, associated with intensified evapotranspiration and heat waves. Potop (2011) and Potopová et al. (2015) demonstrated that agricultural droughts have become more pronounced after 1990, severely affecting maize, wheat, and sunflower crops - particularly during June - October, when soil moisture deficits explain up to 60% of yield variability. Nedealcov (2019) identified a warming trend of approximately 0.013°C per year and an expansion of severe droughts in the southern part of the country, where economic losses are most substantial. The recent study by Vicente-Serrano et al. (2024) confirms the growing vulnerability of agriculture to rainfall deficits amid rising evapotranspiration, emphasizing the need for agroclimatic adaptation measures focused on soil moisture conservation and the use of drought-resistant species.

Despite this solid scientific background, few studies have combined multiple rainfall deficit indices with statistical trend analysis to identify local drought patterns.

The present study aims to identify and characterize the spatial variability and temporal trends of rainfall deficit in southern Moldova, using three complementary indices - PNI, DI, and RAI - alongside the Mann-Kendall trend test, to assess drought risk and its implications for water management and agriculture.

2. Study area

The analyzed region encompasses the southern part of the Republic of Moldova, which includes several physico-geographical units, namely the Southern Moldavian Plateau and the Bugeac Plain (Figure 1). This area is characterized by low and highly variable annual precipitation, with mean values ranging between 450 and 550 mm, making it one of the most drought-prone regions in the country.

For the analysis, monthly precipitation data recorded at five synoptic stations of the State Hydrometeorological Service - Leova, Stefan Voda, Comrat, Ceadir-Lunga, and Cahul - were used. These stations were selected based on their spatial representativeness and the continuity of observation series (Table 1). Together, they ensure uniform coverage of the southern region of the Republic of Moldova, an area characterized by intensive agricultural land use, thereby enabling a coherent assessment of rainfall variability and of the impact of precipitation deficits on agricultural productivity.

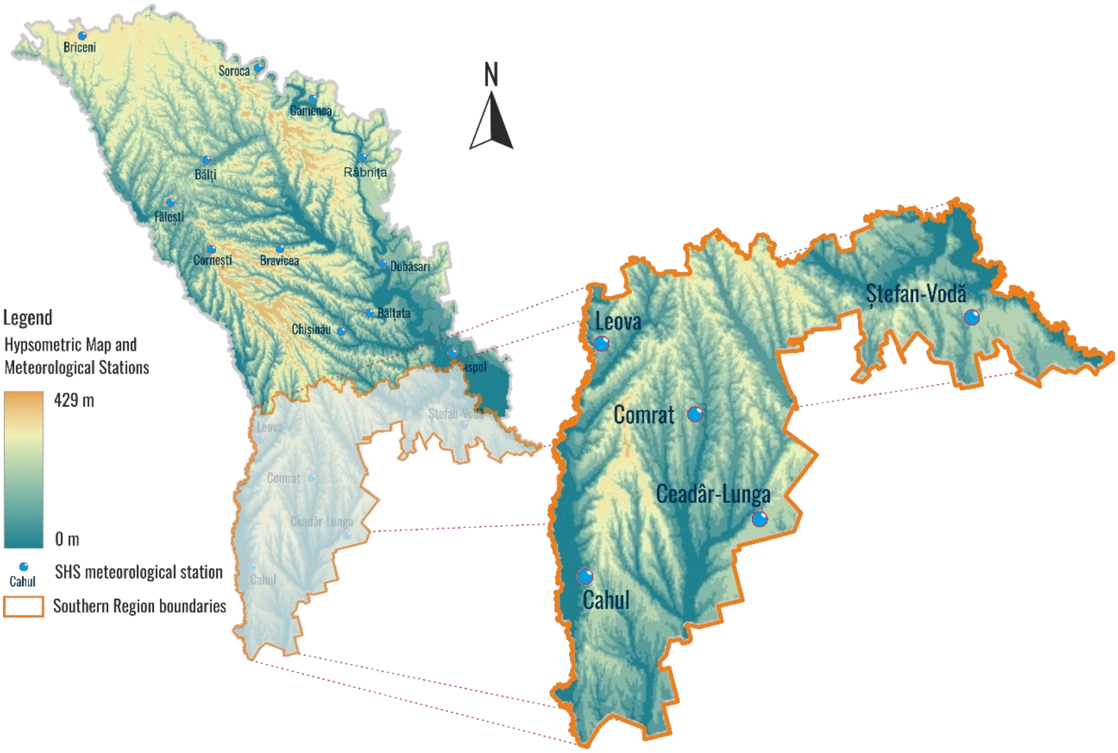

Figure 1 Hypsometric Map and Meteorological Stations of the Republic of Moldova, with Focus on the Southern Region.

Table 1 Geographic characteristics of the synoptic stations used in the study.

Stations	Latitude	Longitude	Altitude
Leova (LV)	46.488	28.283	158
Stefan - Voda (SV)	46.527	29.651	171
Comrat (Co)	46.302	28.629	135
Ceadir-Lunga (CLg)	46.035	28.852	178
Cahul (Ch)	45.899	28.213	113

3. Methods

To highlight recent trends in rainfall deficit, annual averages and the spatial distribution of precipitation were compared for two distinct climatological periods: 1961-1990, considered the standard reference period according to the World Meteorological Organization (WMO), and 1991-2020, representative of current climatic conditions.

The analysis of pluviometric deficit periods was carried out using the Meteorological Drought Monitoring software developed by AgriMetSoft, through the application of three complementary indices: the Percent of Normal Index (PNI), the Decile Index (DI), and the Rainfall Anomaly Index (RAI). The selection of these indices was based on their methodological simplicity and ability to rapidly highlight deviations from the normal rainfall regime, without requiring long time series or specific statistical distributions, as in the case of the Standardized Precipitation Index (SPI).

The Percent of Normal Index (PNI) expresses the ratio between precipitation over a given period and the multiannual mean, allowing an intuitive interpretation of rainfall deficit. It can be computed for monthly, seasonal, or annual intervals and has proven effective for characterizing regional droughts (Salehnia et al., 2017):

$$PNI = P_i/P*100, (1)$$

where Pi represents precipitation during period i (mm), and P is the mean precipitation over the study period.Values below 40% indicate extreme drought, 40-55% a severe drought, 55-70% a moderate drought, and 70-80% a mild drought. The 80-100% range reflects normal conditions, while values above 100% correspond to humid regimes.

The Decile Index (DI) classifies monthly precipitation values into ten ranked categories (deciles), from the lowest to the highest, providing a probabilistic estimate of drought severity and an objective basis for distinguishing between wet and dry periods.

Values from 1 to 4 indicate drought conditions of increasing intensity - from mild drought (4) to extreme drought (1) - whereas values ≥ 5 correspond to normal or wet conditions.

The Rainfall Anomaly Index (RAI) quantifies the intensity of positive and negative deviations from the long-term mean by relating observed precipitation to historical extremes. Monthly precipitation values are ranked in descending order: the mean of the ten highest values defines the threshold for positive anomalies, while the mean of the ten lowest values defines the threshold for negative anomalies. The index is calculated using the following relationships

$$RAI=3*[(p-\overline{p})/(\overline{m}-\overline{p})], (2)$$

$$RAI=-3*[(p-\overline{p})/(\overline{m}-\overline{p})], (3)$$

where p represents annual precipitation (mm); $\overline{p}$ is the long-term mean precipitation (mm); and $\overline{m}$ is the mean of the ten highest (for positive anomalies) or ten lowest (for negative anomalies) precipitation values. Negative values indicate drought conditions, whereas positive values denote wet periods.

According to the intensity scale, values between -0.3 and -1.2 indicate near-normal conditions, -1.2 to -2.1 correspond to moderate drought, -2.1 to -3.0 to severe drought, and values below -3.0 to extreme drought. Conversely, values above +0.3 describe wet periods, from moderate to extreme.

The values of the three indices, together with the trends in monthly precipitation amounts, were computed for the five meteorological stations over the 1991-2022 period. The direction and significance of trends were assessed using the non-parametric Mann-Kendall test, while their magnitude was estimated through the Sen's slope estimator - methods recommended for analyzing discontinuous and non-Gaussian climatic time series.

The combined use of these three indices enables a more detailed and robust characterization of the pluviometric regime, adapted to the specific climatic conditions of southern Moldova, where spatial and interannual rainfall variability is pronounced and exerts a direct impact on agricultural activity.

4. Results

The spatial distribution of mean annual precipitation (Figures 2-3) highlights the persistence of the northeast–southwest pluviometric gradient, characteristic of the southern region of the Republic of Moldova. In both analyzed climatological periods, maximum values (>550 mm) were recorded in the northeastern sector (around the Leova and Stefan Voda stations), while minimum values (<500 mm) occurred in the southwestern area (Cahul and Ceadir-Lunga).

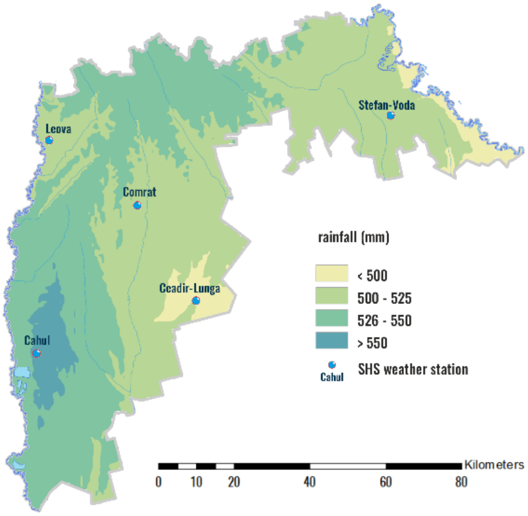

Figure 2 Mean annual rainfall 1961-1990.

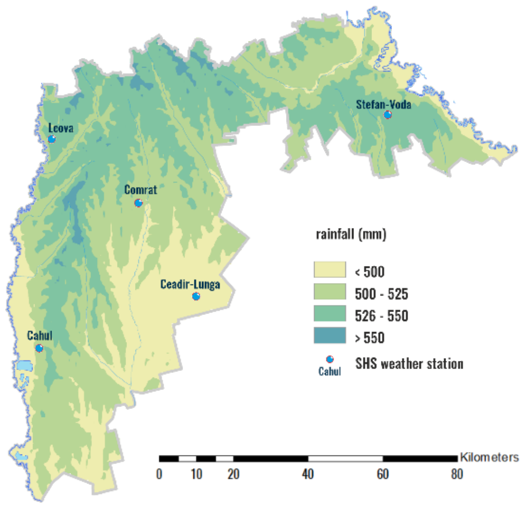

Figure 3 Mean annual rainfall 1991-2020.

A comparison of the two climatological periods reveals that during 1991-2020 there was a contraction of areas receiving more than 550 mm of precipitation and an expansion of zones with values below 500 mm, particularly in the southwestern sector. These spatial changes indicate a slight reduction in mean annual precipitation relative to 1961-1990 and suggest a declining trend in rainfall input across the southernmost part of the region.

The analysis of monthly precipitation series for 1961-2022 (and 1967-2022 for the Stefan Voda station), performed using the Mann-Kendall test and the Sen's slope estimator, revealed monthly and annual trends of low intensity, yet relevant for understanding the climatic dynamics of southern Moldova (Table 2). The Kendall's τ (tau) coefficient indicates the direction of the trend, the p-value denotes its statistical significance, and Sen's slope represents the magnitude of change (mm/year).

At the annual scale, most stations show no statistically significant trends. However, the overall direction is slightly negative toward the southwest, with an almost significant decrease at Cahul ($\tau = -0.169$; $p = 0.053$; Sen = -1.79 mm/year), suggesting a gradual aridization trend. In contrast, Stefan Voda shows a slight but statistically insignificant increase.

Throughout the year, winter and spring months (January-April) show no clear tendencies, with high interannual variability and no dominant direction. In May and June, trends remain weak (Sen between -0.23 and +0.41 mm/year), reflecting normal oscillations of the rainfall regime.

During the summer season (July-August), negative trends become evident, especially at Cahul, where the July decrease is statistically significant ($p = 0.027$; Sen = -0.50 mm/year). These results confirm the reduction of summer precipitation and the intensification of summer droughts. For September, no statistically significant tendencies were detected.

In October, however, a significant increase in precipitation was observed at all stations ($\tau = 0.18$-0.26; $p < 0.05$; Sen = +0.33…+0.50 mm/year), indicating a "wetting" trend in autumn months. This evolution can be attributed to the enhanced cyclonic activity over the Black Sea basin. November and December remain relatively stable, showing no systematic trends.

Table 2 Results of the Mann–Kendall test for the analyzed stations. Period 1961-2022 (Stefan Voda – 1967-2022).

Month	Stefan-Voda			Leova			Comrat			Ceadir-Lunga			Cahul		
	tau	p-value	Sen Slope	tau	p-value	Sen Slope	tau tau	p-value	Sen Slope	tau	p-value	Sen Slope	tau	p-value	Sen Slope
Jan	0.174	0.060	0.000	0.007	0.942	0.360	0.027	0.766	0.031	0.027	0.766	0.035	-0.051	0.564	-0.082
Feb	-0.105	0.258	-0.200	-0.131	0.138	-0.217	-0.183	0.037	-0.296	-0.183	0.037	-0.323	-0.239	0.006	-0.385
Mar	0.068	0.466	0.116	0.068	0.440	0.121	0.042	0.635	0.056	0.042	0.635	0.000	-0.011	0.908	0.000
Apr	0.059	0.529	0.000	-0.013	0.884	0.107	-0.022	0.803	-0.044	-0.022	0.803	0.000	-0.021	0.817	-0.026
May	-0.023	0.810	0.071	0.036	0.688	-0.059	-0.072	0.416	-0.184	-0.072	0.416	-0.231	-0.072	0.412	-0.167
Jun	0.133	0.151	0.000	0.000	1.000	0.412	0.040	0.653	0.105	0.040	0.653	0.077	-0.053	0.547	-0.150
Jul	-0.086	0.354	-0.106	-0.032	0.720	-0.288	-0.124	0.159	-0.333	-0.124	0.159	-0.280	-0.193	0.027	-0.500
Aug	-0.092	0.322	-0.091	-0.031	0.729	-0.245	-0.051	0.564	-0.116	-0.051	0.564	-0.209	-0.135	0.124	-0.333
Sep	0.005	0.966	0.000	-0.009	0.927	0.000	-0.042	0.640	-0.105	-0.042	0.640	0.000	-0.039	0.657	-0.093
Oct	0.195	0.036	0.333	0.179	0.042	0.405	0.257	0.003	0.500	0.257	0.003	0.444	0.194	0.027	0.370
Nov	0.060	0.524	-0.080	-0.038	0.666	0.143	-0.038	0.666	-0.091	-0.038	0.666	0.000	-0.020	0.822	-0.033
Dec	0.015	0.876	0.055	0.025	0.784	0.043	-0.038	0.666	-0.077	-0.038	0.666	-0.103	-0.062	0.481	-0.143
Year	0.085	0.358	-0.077	-0.008	0.932	0.714	-0.060	0.496	-0.556	-0.060	0.496	-1.200	-0.169	0.053	-1.790

From a spatial perspective, an east-west gradient emerges: positive tendencies prevail at Stefan Voda, while toward Cahul, the trends become increasingly negative. Overall, the analysis confirms a seasonal reorganization of the pluviometric regime, characterized by drier summers and wetter autumns. Although the amplitudes of change are moderate, the direction of these trends points to a gradual climatic evolution, with implications for the hydrological balance, agriculture, and drought risk in southern Moldova.

The analysis of monthly RAI values for the period 1991-2022 reveals a pronounced alternation between excess and deficit precipitation periods, a feature typical of regions influenced by transitional climatic regimes. The mean annual RAI values range between -0.19 and -0.24, indicating a slight predominance of months with below-average precipitation. The high standard deviation (≈2.7) confirms strong interannual and intraseasonal variability, while the maximum amplitudes (up to +12.4) reflect short episodes of intense convective rainfall, and the minimum values (-5.1) mark severe drought events.

The distribution of RAI values reveals persistent pluviometric instability, without a clear increasing or decreasing trend in precipitation. In the western sector (Cahul, Leova), positive anomalies dominate, associated with summer convective storms, whereas in the eastern sector (Ștefan Vodă, Ceadîr-Lunga), deficit months occur more frequently. This high variability confirms the oscillatory character of the rainfall regime, with irregular alternations between excess and deficit conditions.

Overall, the RAI index confirms the unstable nature of the pluviometric regime in southern Moldova and the amplification of rainfall contrasts over recent decades. The increased frequency of months with large deviations from the mean suggests a climate increasingly prone to pluviometric extremes- either prolonged droughts or short, intense rainfall episodes.

The analysis of PNI values for the five southern stations (Leova, Cahul, Comrat, Ceadir-Lunga, and Stefan Voda) during 1991-2022 indicates pronounced monthly variability, reflected in high standard deviations (≈70-75%). This oscillation highlights the instability of the pluviometric regime, characterized by rapid alternations between surplus and deficit periods.

The distribution of PNI values shows a strong alternation between wet and dry months, without the dominance of a single climatic condition. Months with PNI < 50% (moderate to severe drought) occur across all stations, being more frequent in the eastern sector (Stefan Voda, Ceadir-Lunga). Conversely, months with PNI > 150% (rainy episodes) prevail in the western stations (Cahul and Comrat), confirming the influence of western frontal systems and local convective rains. The large oscillations of monthly values indicate strong pluviometric anomalies, defining an unpredictable rainfall regime.

The PNI index thus confirms the highly fluctuating and unbalanced character of the rainfall regime in southern Moldova. Short periods of abundance alternate with pronounced drought intervals, particularly during the warm season, directly affecting agricultural water availability and local hydrological risks (flash floods, erosion). Through its wide amplitude range and high standard deviation, PNI faithfully reflects the irregular and uneven nature of precipitation under recent climatic changes, justifying its integration into operational meteorological and agricultural drought monitoring systems.

The Decile Index (DI) expresses the position of monthly precipitation values within the ordered climatological distribution, allowing for a rapid identification of dry months (DI ≤ 3), normal months (DI = 4-7), and wet months (DI ≥ 8).

For the 1991-2022 period, DI values show a general mean of 5.4, common across all five analyzed stations, indicating a general tendency toward near-normal conditions. However, the high standard deviation (≈2.9) highlights substantial monthly variability, confirming the frequent alternation between dry and wet intervals.

The uniform distribution of mean DI values among stations (differences <0.03 units) suggests a regionally homogeneous rainfall behavior. Nevertheless, the range of values (1-10) reveals persistent pluviometric instability, characterized by: a higher frequency of moderate-to-severe drought months (DI ≤ 3), more pronounced in the east (Stefan Voda, Ceadir-Lunga); a greater proportion of wet months (DI ≥ 8) in the west (Cahul, Leova), under the influence of western advections; and the absence of a systematic trend toward either intensification or attenuation of droughts.

The Decile Index confirms that the rainfall regime of southern Moldova is highly contrasting. The relatively balanced distribution of DI values across the lower and upper deciles reflects a transitional climatic regime, sensitive to variations in atmospheric circulation. The high frequency of months falling within the extreme deciles (1-3 and 8-10) emphasizes the risk of hydric imbalance, particularly during the vegetation season, and provides a robust statistical basis for evaluating drought severity and calibrating other indices (RAI, PNI, SPI).

The comparative analysis of the three indices (PNI, RAI, and DI) reveals a rainfall regime marked by high instability and pronounced seasonal contrasts, typical of climatic transition regions. Although mean annual values do not show statistically significant trends, the monthly and interannual amplitudes confirm an increase in the frequency of extreme eventsi-both prolonged droughts and short-term torrential rains.

Spatial differences among the analyzed stations are relatively small; however, the overall direction of variability points to increasing drought severity and duration toward the southwest (Cahul, Ceadir-Lunga), consistent with the declining trend in mean annual precipitation identified through the Mann-Kendall analysis.

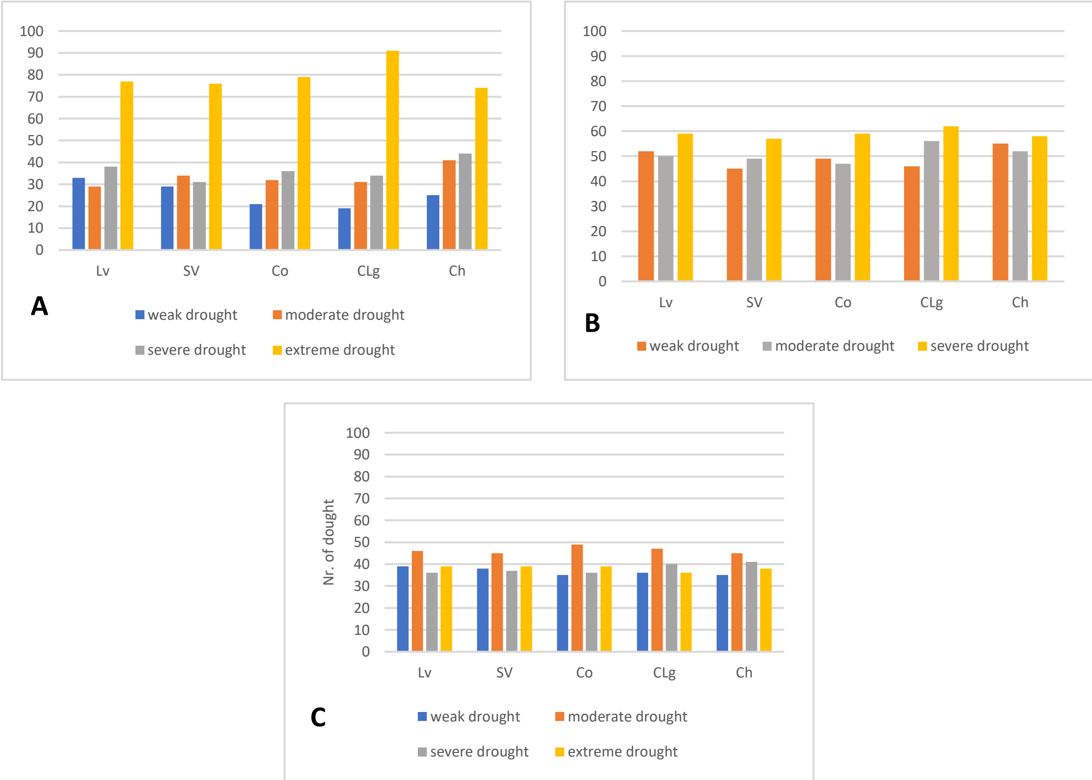

Figure 4 Number of months with rainfall deficit recorded at the five stations analyzed according to the indices PNI (A); RAI (B) și DI (C).

The comparative analysis of the October 1993 - November 1994 period highlights the similarities among the results obtained using the three indices (Table 3). In all three cases, the most pronounced rainfall deficits occurred during February and March 1994, as well as in September of the same year. The most intense and prolonged deficit periods are evident in the results derived from the PNI index, whereas precipitation shortages of lower intensity are reflected in the DI-based analysis.

The same pattern can be observed for other drought episodes, such as those recorded during June 2006 - July 2007 and July 2011 - July 2012, among others. From a spatial perspective, there are no major differences in the number or intensity of rainfall deficit cases, as the phenomenon manifests uniformly across the entire analyzed region.

The trend analysis of monthly precipitation indicates no significant tendency of change in the monthly data for the 1991-2022 period in southern Moldova. For 59 out of 60 analyzed cases, the p-value exceeds 0.05, suggesting the absence of statistically significant trends.

The annual rainfall deficit analysis shows that the highest number of dry years was recorded at Cahul - 25% of the 32 analyzed years - while Ceadir-Lunga had the lowest share (12.5%).

Overall, the combined interpretation of the three indices (PNI, RAI, and DI) reveals: a predominance of months with moderate to severe drought across the entire region; an increasing frequency of extreme droughts in the southwestern sector (Cahul, Ceadir-Lunga); and a more uniform distribution of moderate droughts in the central and eastern parts (Leova, Stefan Voda).

These findings confirm the highly oscillatory and heterogeneous character of the pluviometric regime in southern Moldova and demonstrate that, although annual means do not show significant changes, the intensity and frequency of extreme events are increasing.

Table 3 Pluviometric deficit periods analyzed through the three indices.

Year	Month	PNI						DI						RAI				
		Lv	SV	Co	CLg	Ch		Lv	SV	Co	CLg	Ch		Lv	SV	Co	CLg	Ch
1993	Oct																	
1993	Nov																	
1993	Dec																	
1994	Jan																	
1994	Feb																	
1994	Mar																	
1994	Apr																	
1994	May																	
1994	Jun																	
1994	July																	
1994	Aug																	
1994	Sep																	
1994	Oct																	
1994	Nov																	
			Extremely Dry					Severely Dry						Moderately Dry				

This rainfall behavior indicates that the aridization process in southern Moldova does not manifest through a uniform decrease in precipitation, but rather through an increasing alternation between wet and dry periods, which amplifies the climatic vulnerability of local agricultural and hydrological systems.

Therefore, integrated monitoring based on the simultaneous use of PNI, RAI, and DI provides a solid scientific foundation for the early detection of droughts and for developing adaptive water management measures in the southern region of the Republic of Moldova.

5. Discussion

The spatial distribution of mean annual precipitation (Figures 2-3) confirms the persistence of the classic northeast–southwest pluviometric gradient in southern Moldova, with higher values in the northeastern sector (Leova, Stefan Voda) and minimum values in the southwest (Cahul, Ceadir-Lunga). Compared to the reference period 1961-1990, during 1991-2020 a retraction of areas exceeding 550 mm/year and an expansion of zones below 500 mm/year were observed, indicating a slight reduction in mean pluviometric input within the already drier sub-regions. This trend may accentuate spatial contrasts during drought years, thereby increasing the climatic vulnerability of the country's southern areas.

The statistical analysis performed using the Mann-Kendall test and the Sen's slope estimator (Table 2) reveals generally weak monthly trends, though with robust seasonal signals.

During the summer season (July-August), negative tendencies prevail, with a significant decrease in July precipitation at Cahul ($p = 0.027$; Sen ≈ -0.50 mm/year). This result corresponds to the increased frequency of months with PNI<50% and negative RAI values, indicating intensified summer droughts. Conversely, October shows a significant increase in precipitation across all stations (τ = 0.18-0.26; $p < 0.05$; Sen ≈ +0.33…+0.50 mm yr^{-1}), interpreted as a "wetting" of the autumn season, likely related to enhanced cyclonic activity over the Black Sea basin and recurrent southern advections during the post-warm season.

Winter and spring months (January-April) show no coherent tendencies, as high interannual variability tends to mask trend signals.

Overall, these results converge toward an intra-annual redistribution of precipitation, characterized by drier summers and wetter autumns. Although Sen's slope amplitudes are moderate, the consistency of the trend direction across indices supports the existence of a gradual climatic reorganization of the rainfall regime.

All three indices confirm a high degree of pluviometric instability.

- The PNI shows large standard deviations (≈70-75%) and frequent alternations between very dry (PNI<50%) and wet (PNI> 150%) months, with deficits more common in the east (Ștefan Vodă, Ceadîr-Lunga) and convective excesses in the west (Cahul, Comrat).
- The RAI exhibits slightly negative mean values (-0.19…-0.24) and extreme amplitudes (up to +12.4 / -5.1), emphasizing the episodic and irregular nature of monthly rainfall.
- The DI remains close to normal (mean ≈ 5.4; σ ≈ 2.9) but displays a high proportion of extreme deciles (1-3 and 8-10), suggesting frequent alternation between contrasting climatic states.

The coherence among indices explains the absence of statistically significant long-term trends in monthly series: mean values change slowly, yet variability and extremeness increase, reflecting an intensification of pluviometric oscillations. Thus, the aridization process manifests not through a uniform decline in precipitation, but through greater intermittency and amplitude of anomalies.

At the annual scale, most stations show no significant trends, but the regional pattern is consistent: Cahul displays an almost significant decrease (τ = -0.169; p = 0.053; Sen ≈ -1.79 mm yr^{-1}), indicating a slow aridization process toward the southwest, whereas Ștefan Vodă exhibits a slight, non-significant increase, consistent with the east–west gradient observed. These findings align with the mean-annual precipitation maps (Figures 2–3) and the frequency of dry years (≈25% at Cahul versus ≈12.5% at Ceadîr-Lunga).

The comparative analysis of drought episodes-October 1993-November 1994, June 2006-July 2007, and July 2011-July 2012 (Figure 4, Table 3)-confirms the spatial coherence of drought events. All indices identify the same deficit peaks (February-March and September 1994), with varying intensity depending on the metric: PNI highlights the most prolonged and pronounced dry sequences, DI tends to smooth extremes, while RAI captures the maximum anomaly amplitudes. These differences are methodological (scaling and normalization) rather than spatial or climatic divergences.

The results have important implications for water-resource management and agro-climatic risk reduction. The seasonal redistribution of rainfall-drier summers and wetter autumns-creates an imbalance between water demand and availability, requiring local storage systems, rehabilitation of irrigation infrastructure, and climate-adaptive agricultural water planning. The increased risk of hydric stress during the growing season, combined with short-term torrential events, enhances soil erosion vulnerability, highlighting the need for conservation agriculture practices (minimum tillage, grass strips, mulching).

From a methodological perspective, the combined use of PNI, RAI, and DI allows for early and robust drought detection, providing a basis for operational warning systems and climate-risk communication to farmers and authorities. Although the statistical significance of long-term trends remains low, the spatial and seasonal coherence of signals reinforces the hypothesis of a gradual climatic evolution toward more arid conditions.

The rainfall regime of southern Moldova is thus characterized by high instability, strong seasonal contrast, and vulnerability to extremes. The increasing intermittency and amplitude of rainfall anomalies confirm the need for integrated monitoring and seasonal hydro-agricultural adaptation as essential tools to mitigate drought and extreme-precipitation risks.

6. Conclusion

The comparative analysis of pluviometric deficit indices (PNI, RAI, and DI) based on data from the five meteorological stations in southern Moldova (Leova, Ștefan Vodă, Comrat, Ceadîr-Lunga, and Cahul) reveals an unstable rainfall regime, characterized by high spatial and temporal variability. Although long-term trends are not statistically significant, the overall direction of change indicates a gradual aridization toward the southwestern part of the country, particularly in the Cahul area.

The results confirm the persistence of the northeast–southwest pluviometric gradient, as well as a seasonal redistribution of precipitation, with drier summers and wetter autumns. This internal reorganization of the pluviometric regime suggests a shift in the regional water balance, with direct implications for water resources, agriculture, and ecosystem stability.

The high frequency of months with rainfall deficits, especially at Cahul and Leova, reflects increasing atmospheric instability and an irregular alternation of dry and wet periods. Conversely, the slight increase in mean annual precipitation at Leova, coupled with large monthly amplitudes, confirms an unpredictable rainfall regime dominated by alternating drought and torrential rainfall episodes. These extremes trigger secondary hydrological and geomorphological processes, such as accelerated soil erosion, flash runoff, and rapid floods.

Although multiannual means do not indicate a clear upward or downward trend, the intensity and intermittency of extreme pluviometric events are increasing, thereby amplifying the risk of hydroclimatic imbalance. In the absence of clear signs of trend reversal, it can be anticipated that southern Moldova will continue to experience recurrent rainfall deficit episodes, especially in its southern and southwestern sectors.

In this context, the integration of the PNI, RAI, and DI indices into climate monitoring systems provides a robust foundation for early drought detection and the implementation of adaptive water management measures. Strengthening these systems by incorporating thermo-pluviometric indices (such as SPEI and the hydrothermal coefficient) and correlating them with agricultural and hydrological parameters would contribute to a better understanding and prevention of climate-related risks in the southern region of the Republic of Moldova.

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