The precipitation spatio-temporal trend and variability over the Republic of Moldova territory

La tendance et la variabilité spatio-temporelle des précipitations sur le territoire de la République de Moldavie

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Vol. 36.1 / 2026, 72-82

Received:
19 May 2025

Accepted:
3 November 2025

Published online:
17 November 2025

ABSTRACT: This study analyzes the seasonal precipitation regime in the Republic of Moldova (1961-2024), applying the Mann-Kendall test to identify significant changes necessary for adapting water resource management. The observed trends were validated by comparing them with the regional IPCC SSP projections for Eastern Europe and the Black Sea Basin. The results indicate a substantial shift in the climate regime. A sharp decrease in precipitation was recorded during the spring and summer seasons in both the North and the South. The Southern region, particularly Cahul, is the most severely affected, showing statistically significant aridification. The critical figure is a reduction in summer precipitation of 10.7 mm/decade. In contrast, the autumn season shows a significant increase, indicating a reorientation of the seasonal climate cycle. Furthermore, the analysis reveals a crucial correlation: La Niña events are linked to an increase in the intensity and frequency of severe drought periods. This finding provides a strong scientific basis for developing differentiated climate change adaptation and effective water resource management policies.

KEY WORDS: climate change, precipitation trend, temporal variability, Mann-Kendall test, ENSO (long-distance atmospheric and oceanic impacts), IPCC (Intergovernmental Panel on Climate Change).

RÉSUMÉ : Cette étude analyse le régime pluviométrique saisonnier en République de Moldavie (1961-2024) via le test de Mann-Kendall pour identifier les changements significatifs nécessaires à l'adaptation de la gestion hydrique. Les tendances, validées par les projections GIEC SSP pour l'Europe de l'Est, révèlent une transformation climatique substantielle. On observe une baisse marquée des précipitations printanières et estivales au Nord comme au Sud. Le Sud, notamment Cahul, est le plus durement touché, avec une aridification statistiquement significative. Le chiffre clé est une baisse de 10,7 mm/décennie l'été. À l'inverse, l'automne enregistre une hausse significative, signalant une reconfiguration du cycle saisonnier. L'analyse montre aussi un lien crucial: les épisodes La Niña corrèlent avec une recrudescence des sécheresses sévères. Ces résultats offrent une base scientifique robuste pour élaborer des politiques différenciées d'adaptation au changement climatique et de gestion efficace de l'eau.

MOTS CLÉS: changement climatique, tendance des précipitations, variabilité temporelle, test de Mann-Kendall, ENSO (impacts atmosphériques et océaniques à longue distance), GIEC (Groupe intergouvernemental d'experts sur l'évolution du climat).

How to cite this article:
Botnari, A., Cujba, V. (2025) The precipitation spatio-temporal trend and variability over the Republic of Moldova territory. Georeview, 36, 1, https://doi.org/10.4316/GEOREVIEW.2026.01.05

1. Introduction

Climate change is one of the most severe challenges of the 21st century, with effects that vary significantly depending on the geographical and socio-economic features of each region. States with economies dependent on agriculture, such as the Republic of Moldova, face amplified risks due to increased vulnerabilities to weather variations and reduced adaptive capacity (FAO, 2018; Galwab et al., 2024). Understanding the climatic drivers behind recent drought trends is crucial for effective climate adaptation, not only regionally but also globally (Ficklin et al., 2015). In the context of global climate change, the precipitation regime becomes a critical factor, influencing both water resources and agricultural productivity. The rainfall regime of the Republic of Moldova is determined by the complex interaction between regional and global climatic factors, with direct implications for the water balance and the stability of ecosystems (Bejenaru et al., 2022). A solid understanding of the specific climate of the Republic of Moldova and its regional distribution requires a fundamental climatological basis (Boian, 2015). In this sense, understanding the rainfall regime requires analyzing the influence of major climate teleconnections, such as the North Atlantic Oscillation (NAO) and the El Niño-Southern Oscillation (ENSO), which function as global factors modulating precipitation variability at a regional scale (NOAA/CPC, 2025, ONI).

Atmospheric precipitation, both rain and snowfall, are essential indicators for assessing climate change, providing valuable information in terms of quantity and temporal distribution. Changes in precipitation patterns can have chain effects on water resources, agriculture, and ultimately on food security (Nedealcov, 2020). The authors of the paper propose to analyze seasonal and multiannual changes in precipitation in the Republic of Moldova, through comparing two distinct climate periods: 1961–1992 (the reference period) and 1993–2024 (the period of accelerated climate change). The study of meteorological data and advanced statistical methods, namely including the Mann-Kendall Test, to identify significant trends, and regional variations in the distribution of precipitation. Also, a crucial objective of the study is to validate the observed rainfall trends by comparing them with regional climate change projections developed by the IPCC, especially those based on Shared Socioeconomic Pathways Scenario (SSP), thus ensuring the global relevance of the obtained results (IPCC, 2023, Summary).

The results of the study have practical implications in the development of climate change adaptation strategies, providing essential information for: water resources planning by identifying intervals with increased risk of drought; adaptive agriculture - adjusting the agricultural calendar and crops according to new rainfall patterns; environmental policies - developing regional strategies to combat the effects of climate change etc. The geographical context of the Republic of Moldova, which is historically exposed to a complex array of natural hazards, amplifies the need for such localized climate vulnerability studies (Natural Hazards, 2010). The analysis of the precipitation regime in the Republic of Moldova is complementary to the regional understanding of climate evolution in Eastern Europe, reinforcing findings from similar studies in the neighboring geographical area (Apopei et al., 2023).

2. Study area

The research is based on data collected from three reference meteorological stations, strategically located in the Republic of Moldova:

- ***Briceni Station (North)***– located in an area with more continental climatic influences, the rainfall regime specific to northern temperate regions, where weather conditions are frequently affected by polar air masses.

- ***Chisinau Station (Center)***– located in the central area of the country, it provides representative data for moderate temperate climatic conditions;
- ***Cahul Station (South)***– located in the vicinity of the Danube Basin, it reflects a more arid climate, in some years with subtropical influences. The selection and operational network of these stations are officially documented and managed by the State Hydrometeorological Service (SHS, 2024b; Figure 1).

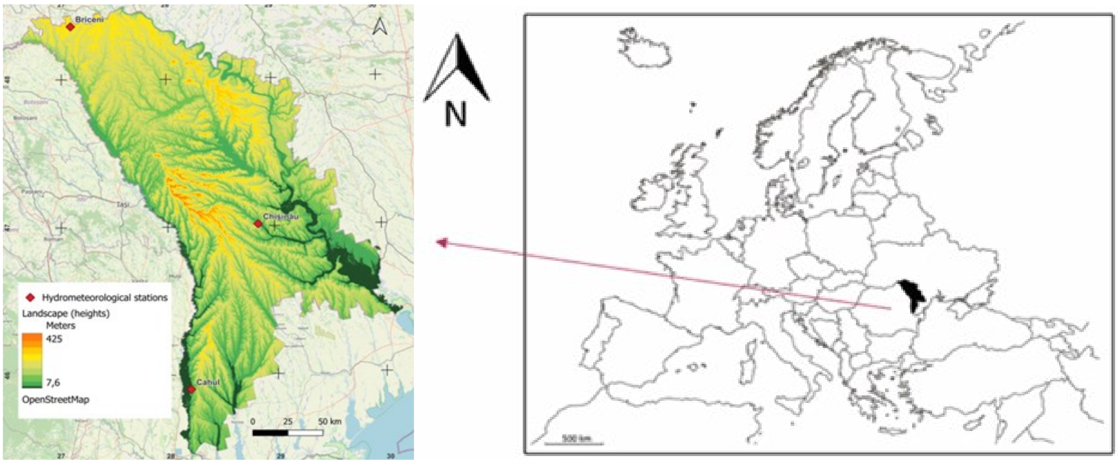

Figure 1 Geographic location of weather stations whose data were used in the trend study
Source: Adapted from the State Hydrometeorological Service (SHS, 2024b).

The selection specifically these weather stations is justified by: a) geographical representativeness – it covers the meridional extent of the Republic of Moldova (≈ 350 km from north to south), allowing the identification of distinct regional climate patterns; b) long data series – all three stations have continuous and reliable meteorological records, covering the analyzed period (1961–2024); c) relevance for agriculture – the areas in which they are located correspond to important agricultural regions, making the analyzed data essential for assessing the climate related risks. The distribution of the stations allows a comparative analysis of rainfall trends by latitude, highlighting: the north-south gradient of precipitation, essential for understanding the impact of climate change on different areas of the country; seasonal variations between regions, which can influence water resources management and agricultural planning; possible climatic mechanisms leading to the observed differences (e.g.: the influence of air masses, changes in atmospheric circulation).

3. Methods

This study analyzes the main precipitation indicators (monthly, seasonal and annual average of atmospheric precipitation) recorded at reference weather stations in the Republic of Moldova (Briceni, Chisinau and Cahul). The analyzed period (1961-2024) was selected according to the recommendations of the World Meteorological Organization (WMO, 2019) for climatological studies, ensuring that the time series are long enough to identify significant trends. The study adhered to the latest global guidelines for high-quality climate data management (WMO, 2023). Source data includes: a) Archive of the State Hydrometeorological Service (primary data); b) Statistical yearbooks of the Republic of Moldova (editions from 2019, 2020, 2024) for data completion and validation; c) database created and processed in Microsoft Excel for organization and preliminary analysis of information.

To analyze data trends, the non-parametric Mann-Kendall Test was applied, a robustness recommended for climate studies and rooted in the foundational statistical works of Mann (1945) and Kendall (1975).

The interpretation of the results of the non-parametric Mann-Kendall Test is achieved through the integrated analysis of three fundamental components: the Z statistic (which indicates the direction of the trend), the Q value (which quantifies the magnitude of the change) and the p significance level (which determines the statistical relevance). Positive values of the Z statistic (accompanied by $Q > 0$) reflect significant increasing trends, while negative values ($Z < 0$, $Q < 0$) indicate relevant decreasing trends. The absolute magnitude of Q reflects the intensity of the changes, and the statistical significance thresholds ($p < 0.05$, $p < 0.01$, $p < 0.001$) validate the robustness of these trends. For Z values close to zero (±1.96 for $\alpha=0.05$) and $p > 0.1$, the absence of a significant statistical trend is concluded.

This approach allows a quantitative and qualitative assessment of the dynamics of climate time series, ensuring a rigorous analysis of rainfall trends and providing reliable results for understanding the impact of climate change in different regions of the Republic of Moldova.

The study complies with international standards of climate analysis and allows for comparability with another similar research in the region (IEG, 2013).

4. Results and discussion

4.1. Analysis of precipitation trends on the territory of the Republic of Moldova

In general, the rainfall pattern of the Republic of Moldova is characterized by spatial and temporal variability, highlighting marked regional differences. In the northern part (Briceni), annual precipitation ranges between 550-600 mm, with a maximum in spring, while the central area (Chisinau) records average values of 500-550 mm, with a relatively balanced distribution over the seasons. The southern region (Cahul) is characterized by amounts below 500 mm annually, with a pronounced summer minimum. The seasonal dynamics present a maximum in spring (30-35% of the annual amount) and a winter minimum (15-20%), with relatively abrupt transitions between seasons.

The analysis of the evolution of precipitation during the period 1961-2024 in the Republic of Moldova, carried out based on data from representative meteorological stations in the north (Briceni), center (Chisinau) and south (Cahul), highlights a general trend of decreasing precipitation amounts, especially in the last three decades. The final year of the data series, 2024, was characterized by specific meteorological conditions documented by SHS (2024a).

The period 1961-1992 is characterized by higher annual average values and reduced interannual variability, indicating a relatively stable precipitation regime. In contrast, the interval 1993-2024 shows a significant increase in variability, with larger oscillations between extremely rainy and dry years, reflecting increased climate instability. This paradigm change in the precipitation regime extends to the impact of climate change on the territory of the Republic of Moldova (IEG, 2021; IEG, 2023). Thus, at the regional level, the changes are much more evident (Figure 2).

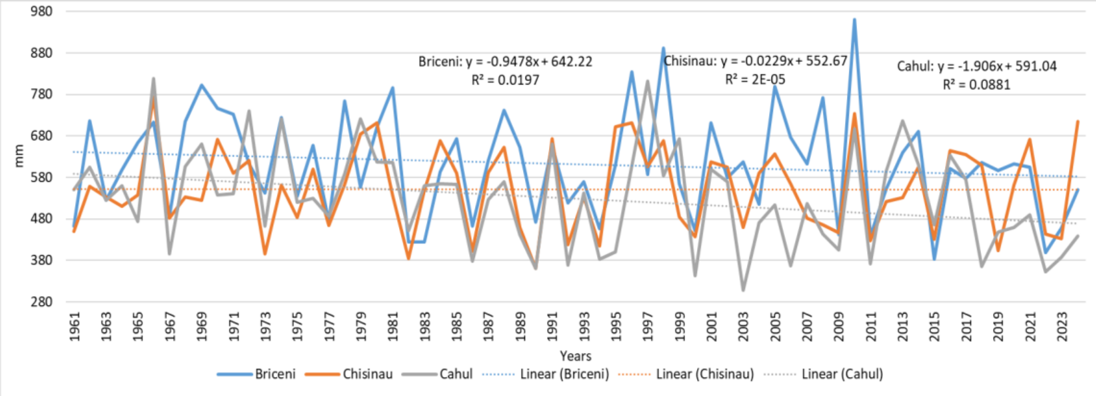

Figure 2 Multiannual precipitation regime (mm/year) in the Republic of Moldova at the Briceni, Chisinau and Cahul weather stations (1961-2024) and its evolution trends.

The Cahul station, located in the southern part of the country, recorded the most pronounced downward trend (-1.906 mm/year), followed by Briceni (-0.947 mm/year) in the north, while Chisinau, in the central area, presented an almost stable evolution (-0.022 mm/year). These geographical differences highlight a north-south gradient of rainfall decline, with different impacts on water resources and economic activities in each region.

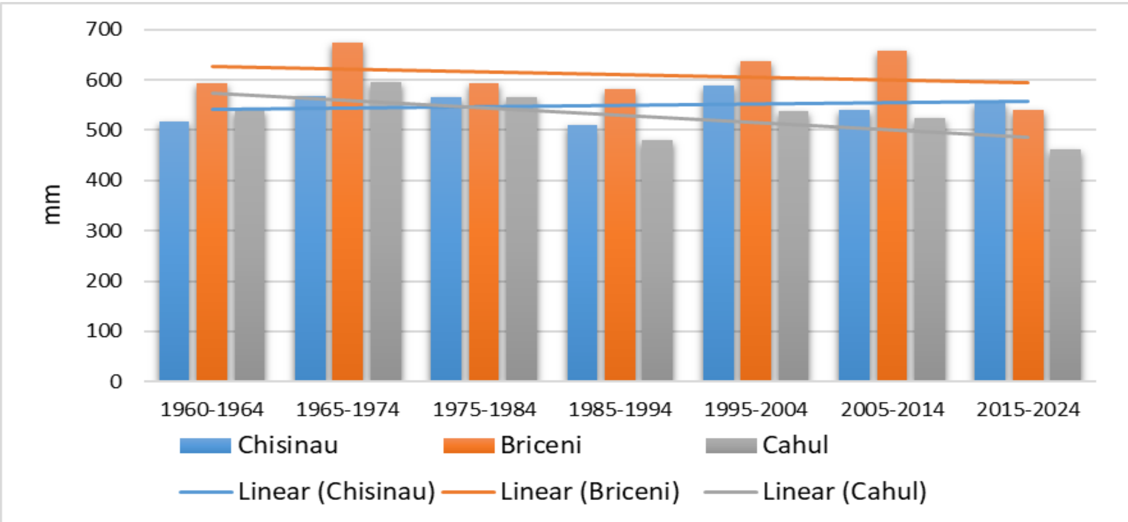

Figure 3 The time series filtering of annual precipitation amount for the period 1960-2024 at the Briceni, Chisinau, Cahul weather stations.

The analysis of the precipitation time series (1961-2024), carried out through data filtering by decades (Nedealcov, 2020), highlights a general slightly downward trend in annual precipitation amounts at the Chisinau and Cahul stations, while the Briceni station records a relatively stable evolution. The study reveals significant regional variations: Briceni (North) presents the highest average values and the widest interdecadal fluctuations, with maxima in the periods 1965-1974 and 2005-2014; Cahul (South) shows the most pronounced downward trend, with constant reductions after 1975, accentuated after 2000, indicating an accelerated aridification process; Chisinau (Center) exhibits moderate variations, but with an observable downward trend after

1995. These results highlight regional differences in precipitation dynamics and the need for continuous monitoring of these trends for adaptation to climate change.

Table 1 Variation in average monthly precipitation (mm) between 1961–1992 and 1993–2024 at the Briceni, Chisinau, Cahul stations.

Stations	**Month**											
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
Briceni	-7	-3	-2	-3	-12	-3	4	-6	8	13	1	-3
Chisinau	0	-8	1	0	-3	-12	-5	4	8	16	5	1
Cahul	-5	-16	-2	-1	-14	-8	-11	-9	5	13	1	-2

Data source: calculated by the authors based on data from the archive of the State Hydrometeorological Service and the National Bureau of Statistics of the Republic of Moldova.

The analysis of monthly precipitation differences between the climatic periods 1961-1992 and 1993-2024 highlights a significant redistribution of the rainfall regime, with important implications for the management of water resources and agricultural activities (Table 1). During the cold season, a decrease in precipitation is observed, more pronounced in the southern region (Cahul: -5 mm in January, -16 mm in February, -2 mm in December), with a negative impact on soil water reserves. Spring is characterized by significant reductions in April and May, with -12 mm in Briceni (North) and -14 mm in Cahul (South), affecting the early development of vegetation. In the warm period of the year, sharp decreases are recorded in July (-12 mm in Chișinău, -11 mm in Cahul) and August (-9 mm in Cahul), thus amplifying the water stress of agricultural crops. In contrast, autumn is marked by significant increases in precipitation, indicating a shift in the rainy regime towards this season (Table 2). This trend has ambivalent effects: on the one hand, it favors the replenishment of soil water reserves, and on the other hand, it can delay the harvest of crops such as grapes or apples.

Table 2 Trends in monthly values of precipitation amounts (mm/decade) for the period 1961-2024 at the Briceni, Chisinau, Cahul weather stations.

The MK Test		**Month**											
		I	**II**	**III**	**IV**	**V**	**VI**	**VII.**	**VIII**	**IX**	**X**	**XI**	**XII**
Briceni	S					+							
	Q	-1.0	-0.7	-1.6	-1.0	-4.4	0.0	-5.0	-2.6	1.1	1.7	-0.2	-0.9
Chisinau	S		*								*		
	Q	0.0	-2.7	0.0	-0.1	0.3	-1.6	-0.6	-1.3	0.0	4.3	0.3	-0.5
Cahul	S		**					*	*		+		
	Q	-0.8	-4.2	0.0	0.0	-1.7	-2.2	-5.5	-3.9	-1.0	3.1	0.0	-1.4

Data source: calculated by the authors based on data from the archive of the State Hydrometeorological Service and the National Bureau of Statistics of the Republic of Moldova.

These changes in precipitation distribution reflect a transformation of the climate regime, with distinct regional variations. The south of the country (Cahul) appears to be the most affected by the reduction in precipitation, while the seasonal redistribution of rainfall, with increases in autumn and reductions in summer, suggests a change in climatic patterns with complex implications for the agricultural sector and water resources management. The study highlights the need for regionally and seasonally differentiated adaptive strategies to mitigate the impact of these changes.

Table 3 Annual and seasonal trends in precipitation amounts (decade mm) at Briceni, Chisinau, Cahul weather stations for the period 1961-2024.

MK test		Spring	Summer	Autumn	Winter	Annual	Cold season	Warm season
Briceni	S	+						
	Q	-4.8	-3.6	4.7	-5.6	-11.1	-4.3	-6.5
Kishinev	S							
	Q	2.1	-1.8	5.0	-4.5	0.6	1.5	-1.0
Cahul	S	*	*			*		*
	Q	-1.7	-10.7	3.2	-6.9	-18.8	-4.4	-13.3

Data source: calculated by the authors based on data from the archive of the State Hydrometeorological Service and the National Bureau of Statistics of the Republic of Moldova.

The analysis of the Mann-Kendall Test applied to the monthly precipitation series for the studied meteorological stations highlighted the following trends: at the Briceni station a significant increase was identified in September (Q_{IX} = +1.1, $p<0.1$), while the months of May and June/July presented insignificant negative trends (Q_V = -4.4, Q_{VII} = -5.0). For the Chisinau station, the increase resulted in a significant decrease in February (Q_{II}=-2.7, $p<0.05$) and a significant increase in October ($p<0.05$). In the case of the Cahul station, significant decreases were observed in February (Q_{II} = -4.2, $p<0.01$), July (Q_{VII} = -5.5, $p<0.05$) and August (Q_{VIII}= -3.9, $p<0.05$), and a decreasing trend in September (Q_{IX}=-1.0, $p<0.1$). The other months did not present significant statistical trends in any of the analyzed stations. These results highlight a seasonal redistribution of precipitation, with distinct regional variations in the territory of the Republic of Moldova (Table 3).

The analysis of the Mann-Kendall test applied to the precipitation series for the period 1961-2024 highlighted distinct regional climate trends in the Republic of Moldova. Throughout the northern part of the country, represented by the Briceni station, a moderate decrease in precipitation is observed (Q=-8.4, $p<0.05$), more pronounced in the cold season, which affects the replenishment of aquifers and the hydrological regime. The southern region, monitored by the Cahul station, records the most pronounced decreases, with statistically significant values both at the annual (Q=-18.8, $p<0.01$) and seasonal levels, especially in summer (Q=-12.3, $p<0.05$), reflecting an accelerated aridification process. These regional differences, also supported by the analysis of the Sen Slope indicating an average decrease of 2.1 mm/year in the South compared to 1.2 mm/year in the north, are the consequences of changes in atmospheric circulation and the increase in the frequency of continental air masses. The North-South gradient of climate vulnerabilities requires differential adaptation approaches, given the impact on agricultural productivity, biodiversity and water resource availability, with major implications for land planning and sustainable development policy. The presented analysis contributes to a deeper understanding of precipitation dynamics over the Republic of Moldova territory, providing a scientific basis for future decisions in the areas of natural resource management, agriculture, and climate change adaptation.

4.2 Validation of Trends with Regional Climate Projections (IPCC)

Global and regional climate projections are crucial for establishing the context and validating long-term trends. This study seeks to validate the changes identified in the rainfall regime over the 1961–2024 period by comparing them with data from the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6), specifically Chapter 13 dedicated to Eastern Europe (IPCC, 2022). The most significant finding from our analysis is the marked, statistically significant drop in precipitation in the southern region of the Republic of Moldova (Cahul Station), particularly during the warm season. This accelerated aridification trend fully concurs with the regional projections developed by the IPCC for Eastern Europe and the Black Sea basin (IPCC, 2023, Summary)

Projections based on the Shared Socioeconomic Pathways (SSP's) - especially high-emissions scenarios like SSP5 - 8.5 **-** point to a sharp decline in total annual average soil moisture in this geographic area, even if global warming were limited to +2℃ or +4℃. This alignment validates the results obtained via the Mann-Kendall test for Cahul (Q = -18.8 annually), confirming that the region is on a trajectory of heightened vulnerability to water deficit, consistent with the latest generation of climate models (IPCC, 2023, Longer Report).

While the overall long-term trend in the South is aridification, our analysis also pinpointed a redistribution of precipitation, characterized by significant increases during the autumn season (notably in October, with Q > +3.1mm/decade in both Cahul and Chișinău). This dynamic matches another key IPCC projection: the global trend towards precipitation intensification - meaning that while the number of rainy days might decrease, the volume of water deposited per rainfall event increases. Consequently, the local results suggest an intensified hydrological cycle with greater variability, where dry seasons (summer, spring) become more arid, yet wet seasons (autumn) face increased risks of heavy rainfall and localized flooding.

4.3 The Influence of Global Climate Oscillations (ENSO)

A complete understanding of the variability in the rainfall regime and the frequency of droughts across the territory of the Republic of Moldova cannot be achieved without considering the influence of major climate teleconnections, particularly the El Niño Southern Oscillation (ENSO). Although ENSO originates in the Equatorial Pacific Ocean basin, its phases (El Niño – the warm phase, and La Niña – the cool phase) modulate global atmospheric circulation patterns, consequently having a significant impact on hydrometeorological conditions in Eastern Europe. The correlation between ENSO and the precipitation regime in this region is established through indirect mechanisms that affect the position and intensity of baric centers and air currents (the Jet Stream), ultimately influencing the advection of moist air masses.

To assess this influence, a comparative analysis was conducted between the average seasonal precipitation anomalies observed in the Republic of Moldova and the years marked by moderate to strong El Niño and La Niña events, according to the Oceanic Niño Index (ONI). It was observed that strong La Niña events (characterized by ONI anomalies ≥ 1.0℃), such as those in 1988/89, 1998/99, 2010/11, and the prolonged 2020–2022 episode, generally coincided with pronounced negative pluvial anomalies, especially during the growing season (spring-summer).

This correlation suggests that the cool phase of ENSO amplifies the risk of agricultural drought across the territory of the Republic of Moldova, a phenomenon particularly evident in the South (Cahul) and North (Briceni) of the country. For example, the major 2020 drought, which had a catastrophic impact on agricultural production, was directly preceded and accompanied by the rapid onset of a La Niña episode, underscoring that ENSO favors the persistence of blocking anticyclones over Eastern Europe. Conversely, years with very strong El Niño events (ONI anomalies ≥ +1.5℃), such as 1997/98, 2015/16, or 2023/24, do not show an equally robust correlation with severe precipitation deficits. This indicates that, in the context of the Republic of Moldova, the ENSO influence is more pronounced and problematic during the cool phase (La Niña), which tends to exacerbate aridification processes and contribute to extreme precipitation variability. This teleconnection analysis validates the necessity of including global climatic factors in water resource management strategies (NOAA/CPC, 2025, ONI; NOAA/CPC, 2025, N3.4).

5. Conclusion

The analysis of precipitation trends based on the Mann-Kendall test, carried out for representative weather stations in the Republic of Moldova, allowed the identification of relevant long-term climate patterns. The results obtained demonstrate the existence regional variations in terms of precipitation distribution.

In the case of the Briceni station, located in the Northern part of the country, a general trend of decreasing precipitation amounts was highlighted, which was more pronounced during cold period of the year. This observation suggests possible changes in the climatic regime specific to the Northern region. The Cahul station, representative of the Southern region, recorded the most significant changes. The analysis revealed statistically significant decreases in all seasons of the year, with significant values of the Q coefficient both at the annual level (-18.8 mm/decade) and for the summer season (-10.7 mm/decade). These results highlight the particular vulnerability of the Southern area to fenomenon related to climate change. The spatial distribution of these trends indicates a clear North-South gradient in terms of precipitation decrease.

In a global approach, the study has allowed a robust validation of the observed trends. The persistent and significant decreases in the South (Cahul) are fully consistent with the regional climate change projections of the IPCC AR6, in particular the SSP scenarios, which indicate a decrease in average soil moisture and a pronounced aridification in the Black Sea region.

At the same time, the analysis highlighted the fact that the interannual variability of precipitation is significantly modulated by climate teleconnections, in particular by the cold phase of ENSO (La Niña). This direct correlation with strong La Niña events explains the amplification of the drought risk, including the severe episode in 2020, and underlines the need to integrate oceanic factors in hydrometeorological forecasts.

From a statistical perspective, all conclusions are supported by significant values ($p < 0.05$), which ensures the robustness of the analysis performed. The negative values of the *Q* coefficient confirm the decreasing of the identified trends. These findings have important implications for the development of climate change adaptation strategies. The regional differences identified suggest the need for differentiated approaches in water resources management and agricultural planning, which take into account complex risks (long-term aridification and extreme cyclical variability). Finally, the study emphasizes the importance of continuous monitoring of climate parameters and periodic updating of trend analyses, in the context in which global climate change appears to be intensifying. The results obtained represent a valuable tool for environmental and sustainable development policies at national and regional levels.

Acknowledgements

This study was carried out under the institutional funding subprogram: Enhancing ecological security and resilience of geo-ecosystems to current environmental changes (code 010801), and the project for young researchers “The impact of climate change on water resources management in the Republic of Moldova“ - (code 24.80012.7007.07TC).

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