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Evidence of hydroclimatic change in the upper Dniester basin, Eastern Europe (1975–2025), based on ERA5-Land reanalysis

Volodymyr Salyha[1*], Liudmyla Arkhypova[2]

[1] Department of Ecology, Faculty of Natural Sciences, Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska Str., Ivano-Frankivsk, Ukraine
* Corresponding author's e-mail: volodymyr.salyha-a10124@nung.edu.ua

ABSTRACT

The increasing climate instability in the Carpathian Region of Ukraine highlights the need for a quantitative assessment of long-term changes in precipitation regimes in mountain catchment basins. This study aims to analyse the transformation of the precipitation regime in the Upper Dniester basin (Ivano-Frankivsk Oblast) over 51 years (1975–2025) based on ERA5-Land reanalysis data. The study covers three key aspects: changes in total precipitation and temperature regime; seasonal redistribution of precipitation (DJF, MAM, JJA, SON); and transformation of the snow-to-rainfall ratio. The Mann-Kendall non-parametric test with Sen's slope estimation was applied to detect monotonic trends; sub-period comparisons were conducted for 1975–1999 and 2000–2025. The main results indicate statistically significant warming (+0.058 °C/year, $p < 0.001$) alongside a non-significant decrease in annual precipitation ($p = 0.069$). A significant seasonal redistribution was identified: an increase in winter precipitation (+0.82 mm/year, $p = 0.041$) concurrent with a decrease in summer precipitation (−1.87 mm/year, $p = 0.013$). The winter snow fraction declined from 68.9% to 62.9%, while the annual indicator remains stable (~18–19%). The practical value of the study lies in providing a scientific basis for adaptation measures in the water management and agricultural sectors of the Carpathian Region.

Keywords: climate change, precipitation regime, snowfall fraction, ERA5-Land, Mann–Kendall trend analysis, Ukrainian Carpathians, Upper Dniester Basin.

INTRODUCTION

Climate change is one of the key challenges of our time, significantly affecting the hydrological cycle and precipitation regimes across various regions of the world (Arkhipova, Pernerovska, 2015; Irtyshcheva et al., 2023). According to a global precipitation analysis based on The Global Precipitation Climatology Centre dataset for 1891–2019, precipitation changes are observed in 59% of global regions, most pronounced at latitudes above 30°N, which is explained by two primary mechanisms: the thermodynamic effect (approximately 7% increase in atmospheric moisture capacity per 1 °C of warming according to the Clausius-Clapeyron equation) and dynamic changes in atmospheric circulation, particularly the poleward shift of storm tracks (Nazeri Tahroudi, 2025). At the same time, these changes exhibit pronounced seasonal differentiation: Christidis and Stott (2022), analysing the influence of anthropogenic activity on seasonal precipitation in Europe for 1901–2018 based on Climatic Research Unit time series, version 4.03 (CRU TS4.03) data and CMIP6 models, established a significant increase in winter precipitation in Northern Europe concurrent with a decrease in summer precipitation in the Mediterranean region, with the dominant driver being the increase in greenhouse gas concentrations.

According to Ukraine's First Adaptation Communication to the UNFCCC (2024), over the past 60 years the country's climate has undergone substantial changes: mean annual air temperature has exceeded the 1961–1990 climatic norm by 1.5 °C since 2007. Regarding the precipitation regime, the document notes that, despite overall stability in annual totals, a redistribution of precipitation between seasons is occurring — an increase in autumn and a decrease in winter, and even greater decrease in summer. The irregularity and intensity of precipitation have increased, and drought frequency has nearly doubled over the past 20 years, particularly in the Polissia and forest-steppe zones. For the Carpathian region, irregular snowfall interrupted by rainfall events during winter has been noted, affecting water resources and the tourism sector (Matiyiv et al., 2022; Smyk and Arkhypova, 2025).

The issue of precipitation regime transformation is being actively studied in various European mountain regions. Micu et al. (2021), analysing 16 indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) for the Southern Carpathians (523–2.506 m) for 1961–2018 using the Mann-Kendall test, revealed a combination of significant warming (+0.47 °C/decade) with a tendency towards precipitation decrease and intensification of extremes. Wypych and Ustrnul (2024) studied extreme precipitation and runoff in 8 basins of the Polish Carpathians (1951–2022) and established a strong relationship between extreme precipitation and runoff (R = 0.55–0.76), yet found no significant trends in extremes over the 72-year period. For the Mediterranean region, Yavaşlı (2025), based on ERA5-Land data (1950–2024), identified a zonal precipitation contrast with seasonal redistribution and a determining influence of North Atlantic atmospheric circulation variability.

An important aspect of precipitation regime transformation is the change in the snow-to-rainfall ratio. Ombadi et al. (2023), based on ERA5 data and CMIP6 models for the Northern Hemisphere, showed that the decrease in the snow fraction amplifies liquid precipitation extremes by 15% at elevations above 2.000 m, which is twice the Clausius-Clapeyron effect. Blau et al. (2024), in a global analysis of snow cover across 8 mountain regions (ERA5-Land, 1979–2022), recorded a snow decrease of 7.79% globally and 7.39% in Europe with warming of 1.19 °C. At the regional level, Bozzoli et al. (2024), analysing 100-year snowfall records at 46 Alpine stations (1920–2020), found snowfall depth decreases of 2.3–4.9%/decade, with warming of +0.15–0.16 °C/decade as the primary driver, and most of the decrease occurring after 1980. Blahušiaková et al. (2020), studying 7 mountain catchments in Central Europe (Alps, Šumava, Krkonoše, Low Tatras) for 1966–2012, established that warming of 0.8 °C caused a 22% decrease in the snow fraction and a 1–36% increase in winter runoff alongside reductions in spring and summer flows. For Poland, Somorowska (2024) identified a statistically significant decreasing trends in snow fraction across 59% of the country's territory (−2 to −6.5%/decade) with cold season warming of +0.5 °C/decade, and the snow fraction sensitivity index showed that each degree of warming reduces the snow fraction by 3–13%. Bokwa et al. (2021), studying drought trends in the Polish Carpathians (1991–2020), found significant warming of +0.5–0.7 °C/decade in the absence of significant precipitation trends, with the primary driver of increasing drought identified as rising evapotranspiration due to warming. Regarding the Ukrainian Carpathians, Agayar et al. (2024) studied the climatology of 82 extreme precipitation episodes (≥100 mm/day) across Ukraine (1979–2019) and established that the Carpathians are one of the hotspots for such events, with 75–80% of annual precipitation falling in the warm season.

Despite the substantial body of research on precipitation regimes in the Carpathian region in general, no comprehensive analysis has yet been conducted for the Ukrainian Carpathians, especially on the river basin level, that would simultaneously cover three key aspects: changes in total precipitation, seasonal redistribution, and transformation of the snow-to-rainfall ratio over an extended period. Existing studies for Ukraine either operate at a national scale without sufficient regional detail, cover short time series, or focus on individual aspects of the precipitation regime only. At the same time, the Upper Dniester basin, with its elevation gradient from 200 to 1.800 m and combination of mountain and foothill landscapes, is particularly sensitive to climate change, specifically the transition of precipitation from snow to rain, which has direct implications for water resources, agriculture, and forest ecosystems of the region and as a consequence on the health of the population (Andrusiv et al., 2024). In our previous study (Salyha and Arkhypova, 2025), we investigated the vegetation cover dynamics of this region, where temperature was identified as the primary predictor of NDVI changes, while the role of precipitation required separate in-depth examination. The present study addresses this gap by providing the first comprehensive analysis of precipitation regime transformation at the river basin scale in the Ukrainian Carpathians, simultaneously quantifying changes in total precipitation, seasonal redistribution, and snow fraction dynamics over a 51-year period using high-resolution ERA5-Land reanalysis data.

The aim of this study is to analyse the transformation of the precipitation regime in the Upper Dniester basin (Ivano-Frankivsk Oblast) for the period 1975–2025 based on ERA5-Land reanalysis data. The study is focused on identifying changes in three key aspects: (1) total precipitation and temperature; (2) seasonal precipitation distribution; (3) the snow-to-rainfall ratio (snow fraction).

MATERIALS AND METHODS

The study area encompasses the Dniester River basin within Ivano-Frankivsk Oblast, Ukraine (Figure 1). The region is characterised by a considerable elevation gradient (230–1.800 m a.s.l.) — from the lowland part in the north and east to the Carpathian Mountains in the south and west. This orographic heterogeneity produces marked diversity in climatic conditions and precipitation regimes: in the foothill and mountain zones, annual precipitation substantially exceeds lowland values due to orographic enhancement.

The regional climate is temperate continental with Atlantic influence, which ensures a significant volume of precipitation throughout the year. The hydrographic network of the region is well developed: the Upper Dniester basin within Ivano-Frankivsk Oblast includes the right-bank tributaries — the Limnytsia, Lukva, Bystrytsya, Svicha, Sivka, Vorona, and Hnyla Lypa rivers.

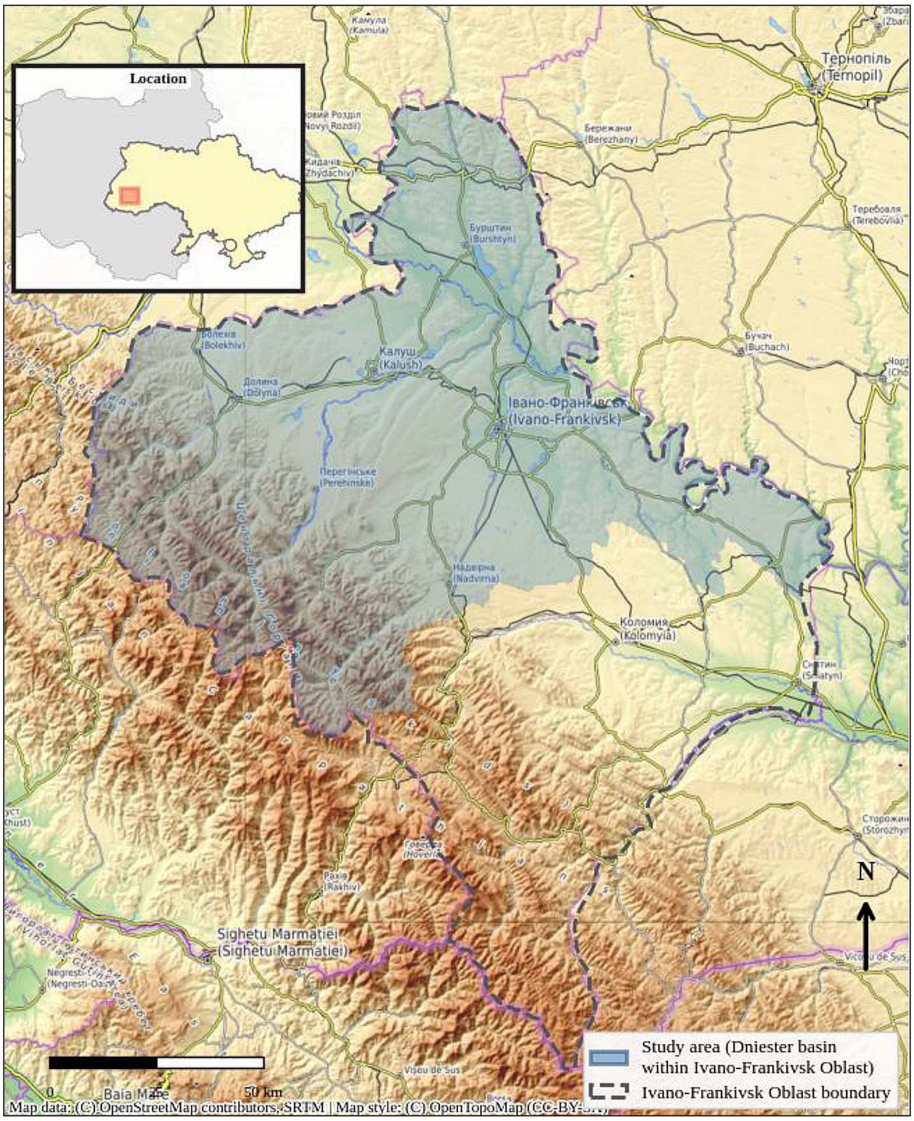

Figure 1. Study area: Dniester River basin within Ivano-Frankivsk Oblast, Ukraine (~8.841 km², elevation 230–1.800 m a.s.l.)

The high density of the river network and substantial mountain runoff make the study of the precipitation regime critically important for water resource management and flood risk assessment. Land use structure is heterogeneous: forests occupy approximately 40–50% of the mountainous part, while agricultural lands predominate in the lowland areas to the north.

ERA5-Land Monthly Aggregated reanalysis data (Google Earth Engine collection identifier: ECMWF/ERA5_LAND/MONTHLY_AGGR), provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), were used for the study. ERA5-Land is a spatially enhanced version of the ERA5 reanalysis with a spatial resolution of approximately 9 km (0.1° × 0.1°), produced by running the land surface model component (HTESSEL, version Cy45r1) forced by atmospheric fields from ERA5 (Muñoz-Sabater et al., 2021). The analysis covers the period 1975–2025 (51 years). The reliability of ERA5 reanalysis for precipitation climate monitoring in extratropical regions has been confirmed by the global validation of Lavers et al. (2022) based on 5.637 stations for 2001–2020: the smallest random errors and the highest skill in distinguishing precipitation types are observed in extratropical regions during winter, with monthly precipitation correlations of 0.94–0.98 for Europe in the winter season. Additional validation of ERA5-Land conducted by Gomis-Cebolla et al. (2023) for Spain (1951–2020) confirmed the reanalysis's ability to reproduce both spatial patterns and temporal precipitation trends with correlations of 0.5–0.9. ERA5-Land was selected as the primary data source because it provides both total precipitation and snowfall as separate monthly variables at ~9 km spatial resolution — a capability essential for calculating the snow fraction, which is one of the key objectives of this study. For the Carpathian region specifically, Bandhauer et al. (2022) evaluated ERA5 precipitation against high-resolution rain-gauge reference datasets in three European subregions, including the Central European Carpathians (Hungary and Slovakia), and confirmed that ERA5 reproduces the major mesoscale spatial patterns of precipitation climatology, though with a tendency to overestimate mean values. ERA5-Land, as the spatially enhanced land surface component of ERA5, inherits these general characteristics while providing improved orographic representation at the basin scale. The practical suitability of ERA5-Land for Ukrainian river basins, including the Dniester, has been further demonstrated by its successful application as climate forcing in a high-resolution hydrological model (Osypov et al., 2025). Collectively, these considerations justify the use of ERA5-Land as a data source for precipitation regime trend analysis in the Upper Dniester basin. The following variables were analysed: total precipitation (total_precipitation_sum, monthly sum, mm), snowfall (snowfall_sum, monthly sum in water equivalent, mm), and air temperature at 2 m height (temperature_2m, monthly mean, °C). Rainfall was calculated as the difference between total precipitation and snowfall, which is consistent with the official ECMWF documentation for these variables. Spatial averaging was performed across the entire study area using a mask defined as the intersection of the Dniester watershed with the administrative boundaries of Ivano-Frankivsk Oblast.

Four meteorological seasons were defined for the analysis of the seasonal distribution of precipitation and temperature, following the standard climatological classification: winter (DJF, December–February), spring (MAM, March–May), summer (JJA, June–August), and autumn (SON, September–November). Seasonal totals for DJF were calculated on a hydrological basis: the winter of a given year includes December of the preceding year and January–February of the current year (for example, winter 1976 comprises December 1975, January and February 1976), ensuring correct aggregation of the winter season and consistency with hydrological approaches.

To detect monotonic trends, the Mann-Kendall non-parametric test (Mann, 1945) with Sen's slope calculation (Sen, 1968) was applied. The test is based on counting the signs of differences between all pairs of observations and assesses the statistical significance of a monotonic trend without assumptions regarding the form of the data distribution. The non-parametric nature of the test ensures its robustness to outliers and departures from normality, which is particularly important for climatic time series with high interannual variability. The null hypothesis of the test is the absence of a trend in the data series; trends were considered statistically significant at $p < 0.05$ (95% significance level). The strength and direction of the monotonic relationship are characterised by Kendall's τ coefficient: $\tau > 0$ indicates an upward trend, $\tau < 0$ a downward trend. The magnitude of the trend was estimated using Sen's slope — the median of slopes between all possible pairs of points in the time series, which is a robust estimator resistant to outlying values. Comparison of climatic characteristics was conducted for two sub-periods: 1975–1999 and 2000–2025.

Prior to trend analysis, lag-1 serial correlation was assessed for all annual time series using Spearman's rank autocorrelation coefficient (rs). Precipitation-related variables (total precipitation, snowfall, rainfall, and snow fraction) exhibited negligible and statistically non-significant lag-1 autocorrelation (rs ranging from −0.10 to −0.05, $p > 0.35$), confirming the independence of observations and justifying the application of the standard Mann-Kendall test. For the temperature series, significant positive lag-1 autocorrelation was detected (rs = 0.65, $p < 0.001$), attributable to the strong underlying warming trend. Application of the Hamed-Rao modified Mann-Kendall test (Hamed and Rao, 1998) yielded identical conclusions, confirming the robustness of the standard test results for this dataset.

Data processing and visualisation were performed using the Google Earth Engine platform (Gorelick et al., 2017) and the Python programming language with the ee, xarray, xee (Google, 2025), pandas, matplotlib, and pymannkendall (Hussain and Mahmud, 2019) libraries.

RESULTS

Time series analysis of mean annual air temperature for the studied territory of the Dniester basin within Ivano-Frankivsk Oblast demonstrates a clear positive trend throughout the 51-year observation period (Figure 2). The mean annual temperature over the entire period was 7.4 °C with a standard deviation of 1.1 °C. The lowest temperature values were recorded in 1980 (5.2 °C) and 1976 (5.3 °C), while the highest were in 2024 (10.0 °C) and 2023 (9.3 °C). The Mann-Kendall test confirmed the statistical significance of the upward trend ($p < 0.001$) with Kendall's $\tau = 0.58$, indicating a strong positive correlation. Sen's slope is +0.058 °C/year, corresponding to a warming rate of +0.56 °C per decade. The total temperature change over the 1975–2025 period amounted to +2.8 °C at a coefficient of determination $R^2 = 0.56$, indicating that the linear model explains 56% of the variance in the temperature data.

Analysis of total precipitation dynamics revealed a tendency towards a decrease over the study period (Figure 3). The mean annual precipitation total was 939.1 mm with a standard deviation of 112.0 mm. The highest precipitation was observed in 1980 (1,199.3 mm), 2010 (1,154.4 mm), and 1998 (1,138.0 mm), while the lowest was in 2011 (717.0 mm), 1994 (751.1 mm), and 2015 (753.2 mm). The amplitude of fluctuations is 482 mm, constituting 51% of the mean value, indicating high interannual precipitation variability. The linear trend shows a decrease of 2.14 mm/year, corresponding to −21.4 mm per decade and a total change of −106.9 mm over 50 years. However, the Mann-Kendall test did not confirm the statistical significance of this trend ($p = 0.069$, $\tau = -0.18$), although the p-value is close to the 0.05 threshold, suggesting a possible decreasing tendency that warrants further observation.

Snowfall dynamics are characterised by considerable interannual variability (Figure 4). The mean annual snowfall total was 176.3 mm with a standard deviation of 50.5 mm, corresponding

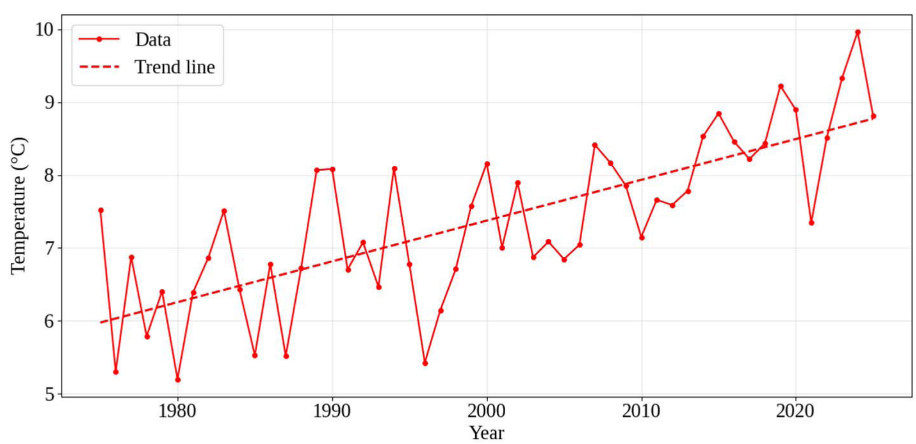

Figure 2. Dynamics of mean annual air temperature in the study area (1975–2025)

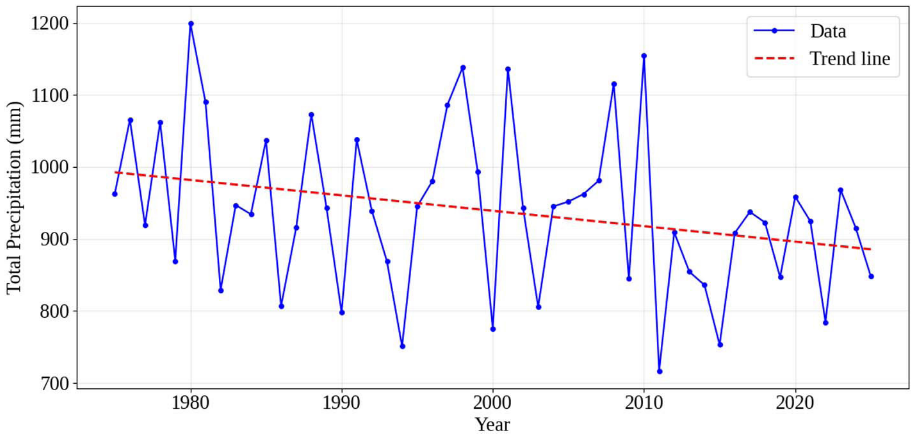

Figure 3. Dynamics of annual total precipitation totals in the study area (1975–2025)

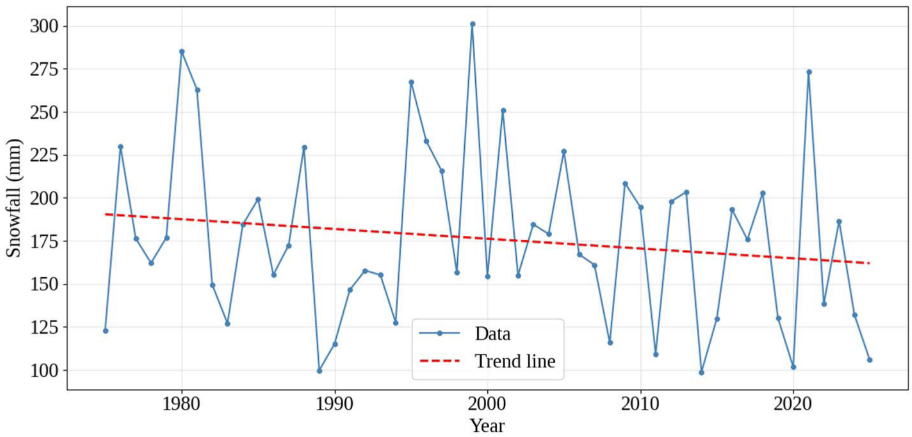

Figure 4. Dynamics of annual snowfall totals in the study area (1975–2025)

to a coefficient of variation of 28.6%. Maximum snowfall values were recorded in 1999 (301.2 mm), 1980 (285.1 mm), and 2021 (273.4 mm), while minimum values were in 2014 (98.9 mm), 1989 (99.8 mm), and 2020 (101.8 mm). The linear trend shows a decrease in snowfall of 0.57 mm/year (−5.7 mm per decade), but the Mann-Kendall test did not confirm the statistical significance of this tendency ($p = 0.32$, $\tau = -0.10$). The high variability of snowfall complicates the detection of long-term trends.

Rainfall also demonstrates a decreasing tendency (Figure 5). The mean annual rainfall total was 762.9 mm with a standard deviation of 98.5 mm. The linear trend shows a decrease of 1.57 mm/year (−15.7 mm per decade), with a total change of −78.5 mm over the period. The Mann-Kendall test did not confirm the statistical significance of the trend ($p = 0.098$, $\tau = -0.16$), although the p-value is close to the significance threshold.

The snow fraction in total precipitation remains relatively stable throughout the entire study period (Figure 6). The mean snow fraction is 18.7% with a standard deviation of 4.6%. Maximum snow fraction values were observed in 1999 (30.3%), 2021 (29.6%), and 1995 (28.3%), while minimum values were in 2008 (10.4%), 1989 (10.6%), and 2020 (10.6%). The linear trend shows a negligible decrease of 0.015%/year (−0.15% per decade), amounting to only −0.7% over 50 years. The Mann-Kendall test confirmed the absence of a statistically significant trend ($p = 0.60$, $\tau = -0.05$). The stability of the snow fraction against the background of substantial warming (+2.8 °C) is an important result, which may be explained by the mountainous character of the study area, where winter temperatures at higher elevations remain below 0 °C even under global warming conditions.

Comparison of the climatic characteristics of the two periods — 1975–1999 and 2000–2025 — revealed substantial changes (Table 1). Mean annual temperature increased from 6.74 °C in the first period to 7.95 °C in the second, representing

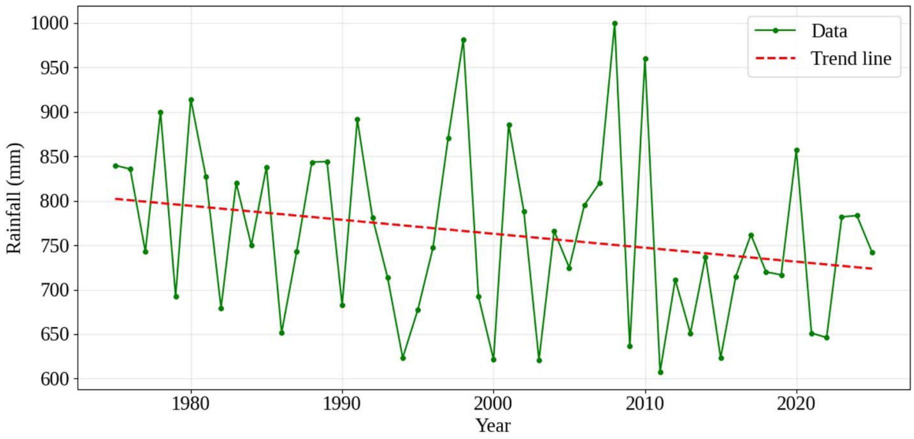

Figure 5. Dynamics of annual rainfall totals in the study area (1975–2025)

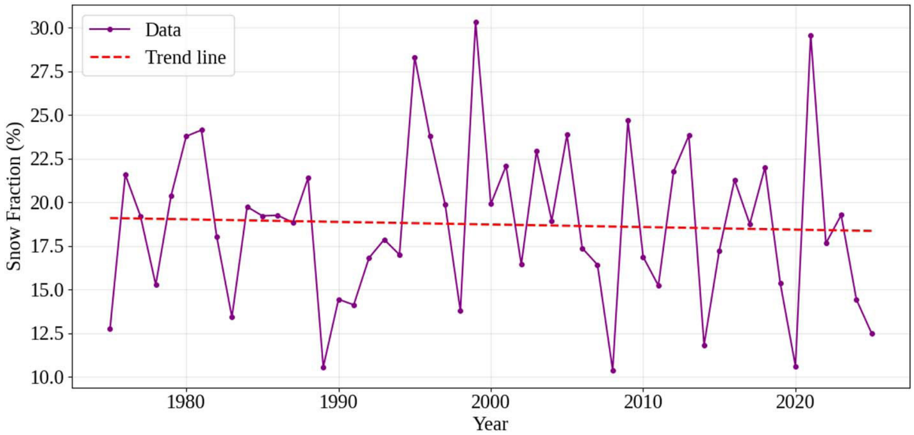

Figure 6. Dynamics of the snow fraction in the study area (1975–2025)

Table 1. Comparison of climatic characteristics for the periods 1975–1999 and 2000–2025

Indicator	1975–1999	2000–2025	Change	Change, %
Total precipitation, mm	971.8	900.7	−71.1	−7.3
Snowfall, mm	185.3	168.4	−16.9	−9.1
Rainfall, mm	787.3	732.3	−55.0	−7.0
Snow fraction, %	19.0	18.5	−0.5	−2.6
Temperature, °C	6.74	7.95	+1.21	+18.0

an increase of 1.21 °C (+18.0%). Total precipitation decreased from 971.8 mm to 900.7 mm (−71.1 mm or −7.3%). Snowfall declined from 185.3 mm to 168.4 mm (−16.9 mm or −9.1%), representing the largest relative decrease among all precipitation types. Rainfall decreased from 787.3 mm to 732.3 mm (−55.0 mm or −7.0%). The snow fraction declined slightly — from 19.0% to 18.5% (−0.5 percentage points or −2.6%).

The results of the trend analysis are summarised in Table 2. Among all the studied indicators, only temperature demonstrates a statistically significant trend. For precipitation (total, snowfall, rainfall) and the snow fraction, the trends are not statistically significant, which may be attributable to the high interannual variability of these indicators.

Analysis of extreme values allowed the identification of years with anomalous climatic conditions. The driest year over the entire observation period was 2011, with an annual precipitation total of 717.0 mm, which is 24% below the mean. This year was also characterised by a low snow fraction (15.2%). The wettest year was 1980

Table 2. Results of trend analysis of climatic indicators (1975–2025)

Indicator	Trend	τ	p-value	Sen's slope	Significant
Temperature	upward	0.58	<0.001	+0.058 °C/year	yes
Total precipitation	downward	−0.18	0.069	−1.87 mm/year	no
Rainfall	downward	−0.16	0.098	−1.65 mm/year	no
Snowfall	downward	−0.10	0.32	−0.60 mm/year	no
Snow fraction	absent	−0.05	0.60	−0.02%/year	no

(1,199.3 mm), which was simultaneously one of the coldest (5.2 °C) and had a high snow fraction (23.8%). The highest snow fraction was observed in 1999 (30.3%), when 301.2 mm of snowfall was recorded alongside a relatively high total precipitation (993.6 mm). The most recent observation years (2019–2024) are characterised by consistently high temperatures (8.8–10.0 °C), confirming the warming trend.

Analysis of seasonal precipitation distribution revealed its uneven distribution throughout the year (Figure 7). The largest amount of precipitation falls in the summer season (June–August): the mean total is 337.6 mm, constituting 36% of the annual total. The spring season (March–May) is characterised by a mean total of 244.1 mm (26%), autumn (September–November) by 196.0 mm (21%), and winter (December–February) by 160.9 mm (17%). The highest interannual precipitation variability is observed in summer (standard deviation 75.8 mm), the lowest in winter (35.5 mm).

The Mann-Kendall test identified statistically significant trends for two seasons (Table 3, Figure 8). Winter precipitation demonstrates a statistically significant upward trend ($p = 0.041$, $\tau = 0.20$) with Sen's slope of +0.82 mm/year, corresponding to an increase of +8.2 mm per decade and a total change of +39 mm over 50 years. Summer precipitation, conversely, demonstrates a statistically significant downward trend ($p = 0.013$, $\tau = -0.24$) with Sen's slope of −1.87 mm/year (−18.7 mm per decade, −94 mm over 50 years). For spring and autumn precipitation, the trends are not statistically significant, although the spring season is close to the significance threshold.

The identified trends indicate a transformation of the seasonal precipitation regime: winters are becoming wetter and summers drier. This change is of considerable importance for the hydrological regime of the territory, as the increase in winter precipitation may lead to more intensive spring flooding, while the decrease in summer precipitation may increase drought risk during the growing season.

Analysis of seasonal temperature trends showed that all four seasons demonstrate statistically significant upward trends (Table 4, Figure 9). The fastest warming is observed in summer: Sen's slope is +0.076 °C/year, corresponding to +0.76 °C per decade and +3.8 °C over 50 years. Winter warming (+0.063 °C/year) is the second most intensive, followed by autumn (+0.041 °C/year) and spring (+0.038 °C/year).

The highest Kendall's τ values for the summer season ($\tau = 0.70$) indicate the most consistent and persistent warming in summer. This is

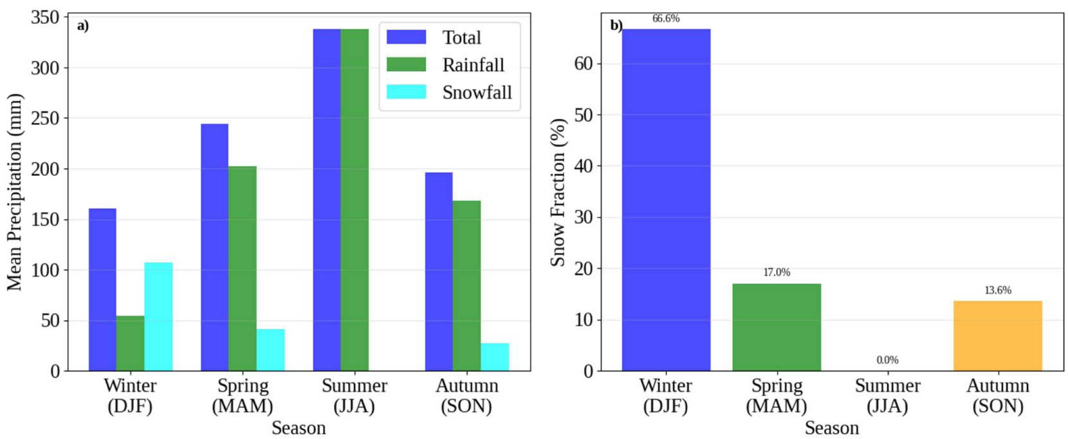

Figure 7. Mean seasonal precipitation distribution in the study area (1975–2025)

Table 3. Results of the Mann-Kendall test for seasonal precipitation (1975–2025)

Season	Trend	τ	p-value	Sen's slope, mm/year	Significant
Winter (DJF)	upward	0.20	0.041	+0.82	yes
Spring (MAM)	downward	−0.18	0.062	−0.91	no
Summer (JJA)	downward	−0.24	0.013	−1.87	yes
Autumn (SON)	absent	0.01	0.935	+0.08	no

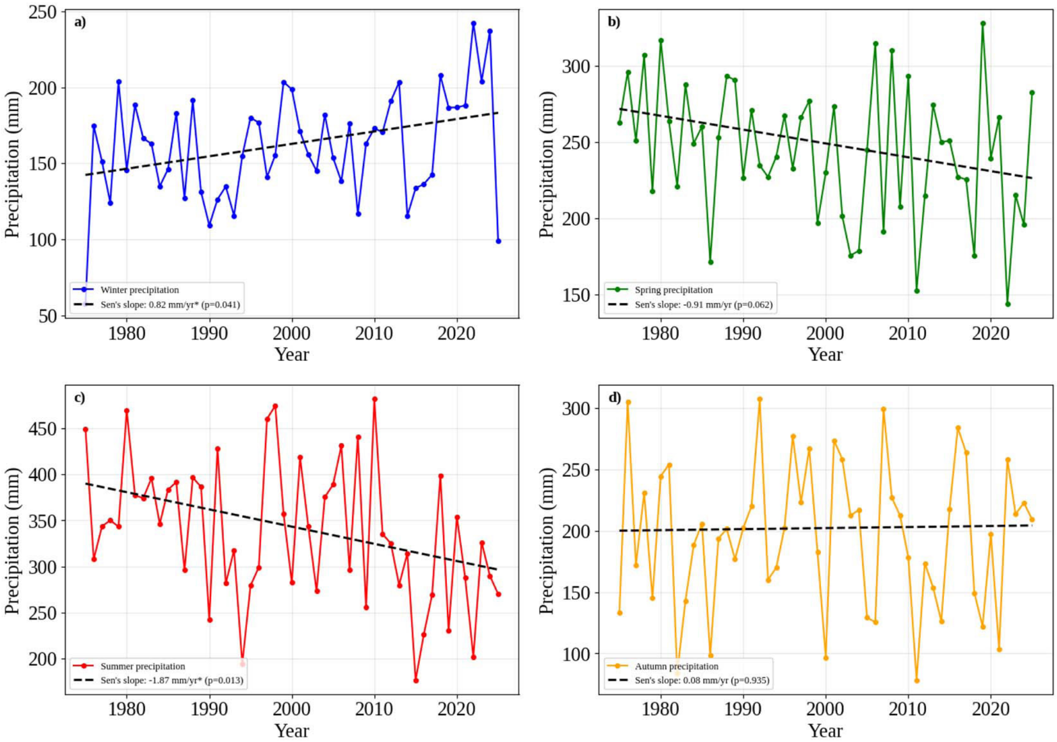

Figure 8. Seasonal precipitation trends in the Upper Dniester basin (1975–2025): (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), (d) autumn (SON). Dashed line — Sen's slope trend; * — $p < 0.05$ (Mann-Kendall test)

Table 4. Results of the Mann-Kendall test for seasonal temperature (1975–2025)

Season	τ	p-value	Sen's slope, °C/year	Sen's slope, °C/decade
Summer (JJA)	0.70	< 0.001	+0.076	+0.76
Winter (DJF)	0.29	0.003	+0.063	+0.63
Autumn (SON)	0.44	< 0.001	+0.041	+0.41
Spring (MAM)	0.29	0.003	+0.038	+0.38

consistent with the downward trend in summer precipitation and may suggest an intensification of summer drought conditions.

Comparison of mean seasonal characteristics between the two sub-periods 1975–1999 and 2000–2025 confirmed the identified trends (Table 5). The largest relative increase in precipitation is observed in winter (+12.2%), while the largest decrease is in summer (−11.1%). Spring and autumn precipitation also decreased, but less substantially (−8.6% and −3.5%, respectively). Between the two sub-periods, the share of winter precipitation in the annual total increased from 15.7% to 18.9%, while the share of summer precipitation decreased from 37.1% to 35.3% (Figure 10).

Analysis of precipitation structure by phase state revealed considerable differences between seasons (Figure 11). In winter, snowfall accounts on average for 65–70% of the total precipitation, in spring — 15–20%, in autumn — 10–15%,

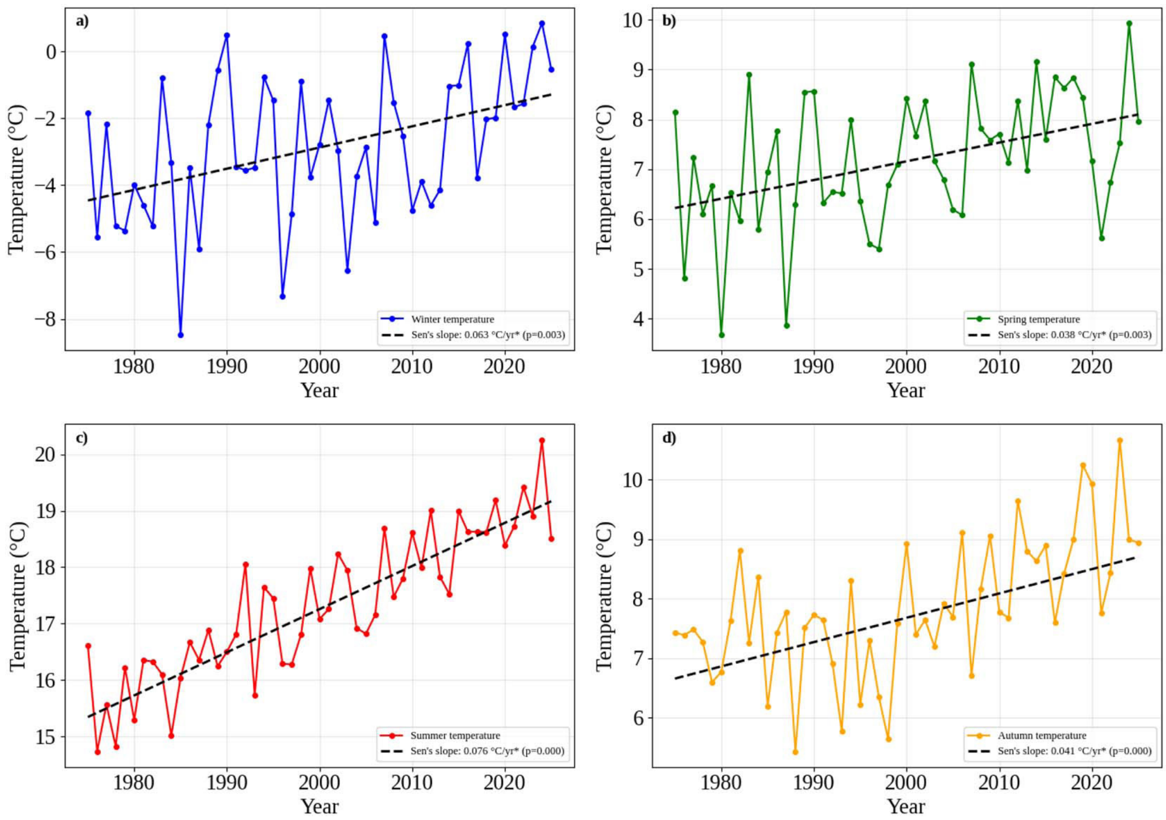

Figure 9. Seasonal mean air temperature trends in the Upper Dniester basin (1975–2025): (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), (d) autumn (SON). Dashed line — Sen's slope trend; * — $p < 0.05$ (Mann-Kendall test)

Table 5. Comparison of seasonal precipitation between the periods 1975–1999 and 2000–2025

Season	1975–1999, mm	2000–2025, mm	Change, mm	Change, %
Winter (DJF)	151.4	169.9	+18.5	+12.2
Spring (MAM)	255.3	233.2	−22.1	−8.6
Summer (JJA)	357.9	318.2	−39.7	−11.1
Autumn (SON)	199.6	192.5	−7.1	−3.5

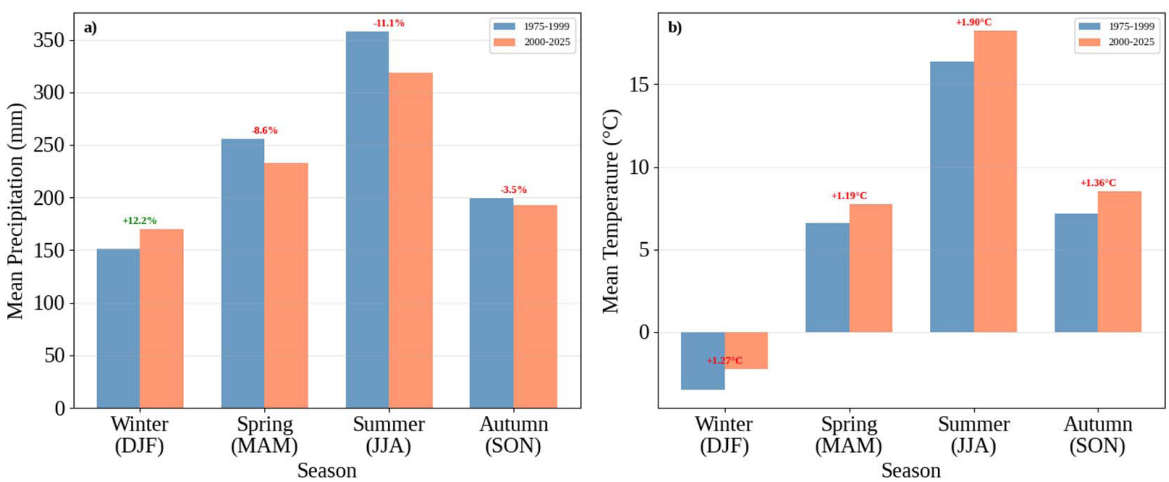

Figure 10. Comparison of seasonal climate parameters between periods 1975–1999 and 2000–2025: (a) mean seasonal precipitation, mm; (b) mean seasonal air temperature, °C. Percentage/absolute change annotated above each bar pair

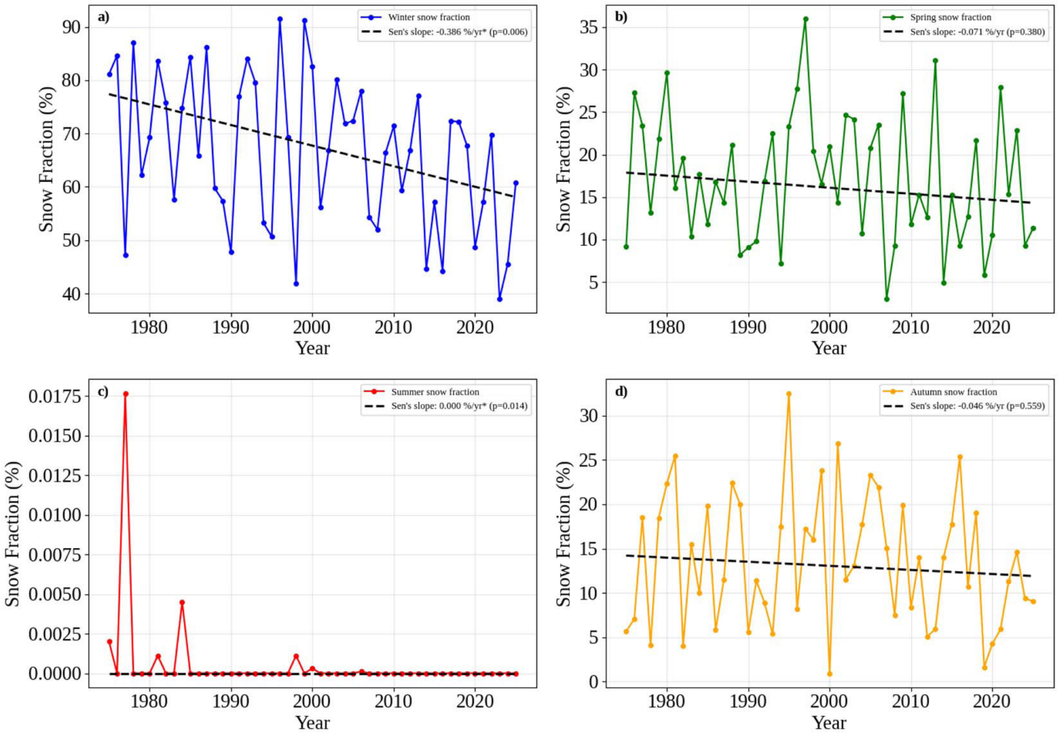

Figure 11. Seasonal snow fraction trends in the Upper Dniester basin (1975–2025): (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), (d) autumn (SON). Dashed line — Sen's slope trend; * — $p < 0.05$ (Mann-Kendall test)

while in summer snowfall is practically absent (< 0.1%). Detailed analysis of the winter snow fraction revealed an important tendency towards a decrease in the solid precipitation share. Comparison of the two sub-periods showed that the mean winter snow fraction decreased from 68.9% in 1975–1999 to 62.9% in 2000–2025, representing a decline of 6.0 percentage points (−8.7%). This indicates a gradual transformation of winter precipitation from predominantly solid to mixed.

Particularly informative is the analysis of years with an anomalously low winter snow fraction (< 50%). Over the entire observation period, there were 8 such years: 1977 (47.2%), 1990 (47.7%), 1998 (41.8%), 2014 (44.6%), 2016 (44.2%), 2020 (48.7%), 2023 (39.0%), and 2024 (45.5%). Of these, 5 out of 8 anomalous years fall within the most recent decade (2014–2024), indicating an acceleration of the transformation process.

The lowest winter snow fraction over the entire observation period was recorded in the winter season of 2023 — only 39.0%. The total winter precipitation for that season was 204 mm, which exceeds the long-term mean (161 mm). This means that over 60% of winter precipitation fell as rain rather than snow. This phenomenon is directly associated with an anomalously warm winter: the mean temperature of the 2023 winter season was +0.13 °C, one of the highest values over the entire study period.

Analysis of the last five winter seasons (2020–2024) demonstrates a persistent tendency towards a declining snow fraction: 48.7%, 57.2%, 69.7%, 39.0%, and 45.5% respectively, with a mean of only 52.0%. This is substantially below the long-term norm (65.5%) and indicates

Table 6. Extreme values of seasonal precipitation

Season	Minimum	Year	Maximum	Year
Winter (DJF)	57.5 mm	1975	242.3 mm	2022
Spring (MAM)	143.9 mm	2022	328.2 mm	2019
Summer (JJA)	176.6 mm	2015	481.8 mm	2010
Autumn (SON)	78.3 mm	2011	307.4 mm	1992

that approximately half of winter precipitation in recent years falls as rain.

Analysis of the last five winter seasons (2020–2024) demonstrates a persistent tendency towards a declining snow fraction: 48.7%, 57.2%, 69.7%, 39.0%, and 45.5% respectively, with a mean of only 52.0%. This is substantially below the long-term norm (65.5%) and indicates that approximately half of winter precipitation in recent years falls as rain. The relationship between winter temperature and snow fraction is clear: years with a positive mean winter temperature (1990, 2007, 2016, 2020, 2023, 2024) are characterised by a low snow fraction (< 55%). The increasing frequency of such "warm winters" is a direct consequence of the overall warming trend (+0.63 °C per decade for the winter season).

Analysis of extreme values allowed the identification of seasons with anomalous conditions (Table 6). The driest summer season (2015, 176.6 mm) coincided with one of the warmest years on record, confirming the relationship between warming and the decrease in summer precipitation. The wettest summer season (2010, 481.8 mm) was associated with catastrophic flooding in the Carpathian region.

DISCUSSION

The results of the precipitation regime analysis in the Upper Dniester basin (Ivano-Frankivsk Oblast) for the period 1975–2025 allow three key patterns of climatic change to be identified: (1) significant warming concurrent with a non-significant decrease in annual precipitation; (2) a statistically significant seasonal redistribution of precipitation — an increase in winter alongside a decrease in summer; (3) a decrease in the winter snow fraction with overall stability of the annual indicator. These results are consistent with findings from adjacent and analogous mountain regions of Europe.

The identified significant warming (+0.058 °C/year, $\tau = 0.58$, $p < 0.001$) concurrent with a non-significant trend in total precipitation ($\tau = -0.18$, $p = 0.069$) is consistent with the results of Bokwa et al. (2021) for the Polish Carpathians (1991–2020), where warming of +0.5–0.7 °C/decade was recorded in the absence of significant precipitation trends across all 12 stations. The authors established that the primary driver of increasing drought is warming itself through increased evapotranspiration, rather than a decrease in precipitation. The warming rate in our region (+0.58 °C/decade) is practically identical to the results for the Polish Carpathians, confirming the spatial coherence of climate change across both regions. At the same time, the decrease in summer precipitation identified in our study (−1.87 mm/year, $p = 0.013$) may create additional pressure compared to the Polish Carpathians where the precipitation trend is non-significant, forming a dual effect: increased atmospheric moisture demand and decreased supply.

An analogous pattern of warming without significant precipitation changes was recorded by Micu et al. (2021) for the Southern Carpathians of Romania (1961–2018), where substantial warming (+0.47 °C/decade) was combined with a coupled warming-drying signal and intensification of precipitation extremes. The absence of a significant total precipitation trend in our study ($p = 0.069$) may be a result of compensation: a significant increase in winter precipitation partially offsets the significant decrease in summer precipitation, which ultimately masks the annual tendency.

The identified seasonal redistribution of precipitation — a significant increase in winter ($\tau = 0.20$, $p = 0.041$, +0.82 mm/year) concurrent with a significant decrease in summer ($\tau = -0.24$, $p = 0.013$, −1.87 mm/year) is one of the principal results of the study. This pattern is fully consistent with the conclusions of Christidis and Stott (2022), who based on CRU TS4.03 data and CMIP6 models (1901–2018) established the dominant influence of anthropogenic greenhouse gases on seasonal precipitation changes in Europe, particularly the increase in winter precipitation in mid-latitudes.

Yavaşlı (2025), analysing 11 ETCCDI precipitation indices for the Mediterranean region using ERA5-Land data (1950–2024), also recorded a seasonal redistribution of precipitation, though with significant trends for fewer than 5% of grid cells. The higher significance of trends in our study may be explained by the more pronounced climatic signal in mountain regions compared to lowland territories.

Sub-period comparison (1975–1999 vs 2000–2025) quantitatively confirms the seasonal redistribution: winter precipitation increased by +12.2% (from 151.4 to 169.9 mm), while summer precipitation decreased by −11.1% (from 357.9 to 318.2 mm). The share of winter precipitation in the annual total increased from 15.7% to 18.9%, while the share of summer precipitation decreased from 37.1% to 35.3%. This redistribution is consistent with the concept of amplified seasonality, which De Winter et al. (2024) confirmed through both mid-Pliocene palaeoclimatic reconstructions and CMIP6 models: under global warming, the weakening of mid-latitude atmospheric circulation causes an increase in intense winter precipitation and prolonged summer droughts. Ukraine's Official Adaptation Communication to the UNFCCC (2024) qualitatively describes an analogous pattern for the entire country: "While total annual precipitation has not changed, there has been a redistribution of precipitation levels among the different seasons." Our results quantitatively confirm this assessment at the regional level and establish the statistical significance of the identified seasonal changes. Although, authors identified decreasing trends in winter precipitation, while our study shows the opposite result for our study area.

The stability of the annual snow fraction (~18–19%, τ = −0.05, p = 0.60) against the background of substantial warming (+2.8 °C over 50 years) appears at first glance to be an unexpected result. However, detailed analysis of the winter season revealed a significant transformation: the winter snow fraction decreased from 68.9% (1975–1999) to 62.9% (2000–2025), that is by −6.0 percentage points (−8.7%). The stability of the annual indicator is explained by the fact that snow falls predominantly in winter (65–70% of winter precipitation), and changes in other seasons are minimal.

Somorowska (2024) for Poland (1981–2020) identified a significant decrease in snow fraction across 59% of the country's territory (−2 to −6.5%/decade) with cold-season warming of +0.5 °C/decade, a value practically identical to ours (+0.58 °C/decade). The snow fraction sensitivity index proposed by the author showed that each degree of warming reduces the snow fraction by 3–13%, depending on the region. The decrease in the winter snow fraction in our region (−6.0 pp with warming of ~1.2 °C between sub-periods) corresponds to the lower bound of this range, which may be explained by the mountainous character of the territory, where winter temperatures remain below 0 °C at higher elevations.

Blahušiaková et al. (2020), studying 7 mountain catchments in Central Europe (Alps, Šumava, Krkonoše, Low Tatras) for 1966–2012, showed that warming of 0.8 °C caused a 22% decrease in the snowfall fraction at medium elevations (1.000–1.500 m) and a 1–36% increase in winter runoff alongside reductions in spring and summer flows due to earlier snowmelt. Our results demonstrate an analogous seasonal redistribution: a significant increase in winter precipitation alongside a decrease in summer, while the decrease in the winter snow fraction confirms the operation of the snow-to-rain transition mechanism at mid-latitudes of the Ukrainian Carpathians.

Bozzoli et al. (2024), analysing 100-year snowfall records at 46 Alpine stations (1920–2020), established that snowfall depth decreases by 2.3–4.9%/decade, with the largest losses at low-elevation stations. In our study, the snowfall trend is also negative but statistically non-significant (τ = −0.10, p = 0.32), which may be explained by the shorter observation period, the use of ERA5-Land reanalysis instead of station data, and the increase in total winter precipitation, which partially compensates for the decrease in the snow fraction. The common mechanism, however, is shared: warming transforms precipitation from snow to rain while total winter precipitation increases.

Li et al. (2020) for the Tian Shan mountains (1960–2017) concluded that changes in the snowfall fraction are predominantly associated with a decrease in snowfall (R = 0.4) rather than a change in total precipitation (R = 0.1), with the largest changes observed at low and medium elevations. Our region corresponds precisely to that elevation zone where snow-to-rainfall ratio changes are most pronounced, but in our study changes in the snowfall fraction were mostly caused by change in the total precipitation, rather than the drastic decrease in snowfall itself.

The identified changes are of considerable practical significance for the Upper Dniester basin. The decrease in the winter snow fraction (from 68.9% to 62.9%) combined with a significant decrease in summer precipitation may affect the hydrological regime: winter rainfall is likely to generate more rapid surface runoff instead of the gradual melting of a snow cover, suggesting increased spring flood risk. Blahušiaková et al. (2020) established that summer hydrological droughts in mountain basins are closely associated with reduced winter snow storage, while Bokwa et al. (2021) showed that the foothill zone (200–400 m) is most vulnerable to increasing drought. Given that our region encompasses this elevation range and the decrease in summer precipitation creates additional pressure, the results indicate the necessity of adaptation measures in the water management and agricultural sectors (Prykhodko et al., 2023).

According to projections by Somorowska (2024), by the 2050s the area of snow-dominated zones in Poland may contract from 86% to 6–30% of the territory. Given comparable warming rates in our region, an analogous transformation may be expected in the Upper Dniester basin as well, which would have significant consequences for water supply, hydropower, and the recreational sector of the Carpathian region.

Several limitations of the conducted study should be noted. First, the use of ERA5-Land as the sole data source may introduce systematic biases. While global validation confirms high ERA5-Land skill in extratropical Europe (Lavers et al., 2022) and ERA5 shows reasonable skill in reproducing mesoscale precipitation patterns in the Central European Carpathians (Bandhauer et al., 2022), a direct station-based validation of ERA5-Land precipitation for the Ukrainian Carpathians has not yet been published, which represents a limitation of the present study. For ERA5-Land specifically in complex mountain terrain, Dalla Torre et al. (2024) identified a systematic overestimation of precipitation (~40 mm/month at annual scale) and underestimation of temperature (~2.1 °C) in the Alpine region (South Tyrol, Italy), and concluded that these biases significantly affect absolute hydrological simulations. However, for the trend analysis conducted in the present study, such systematic biases are of lesser concern: provided that the bias remains stationary over the study period, it does not affect the detection of temporal changes in relative terms. The identified decreasing trend in annual precipitation would therefore represent a conservative estimate if ERA5-Land overestimates absolute values. Second, spatial averaging across the entire basin does not account for intra-basin variability associated with the considerable elevation gradient. Third, the partitioning of precipitation into snowfall and rainfall in ERA5-Land is based on model parameterisations, which may differ from observational data. Finally, the standard Mann-Kendall test assumes independence of observations. Lag-1 serial correlation was assessed using Spearman's rank autocorrelation coefficient and confirmed the absence of significant serial correlation in all precipitation-related annual time series (rs ranging from −0.10 to −0.05, $p > 0.35$), validating the application of the standard test. For the temperature series, significant positive lag-1 autocorrelation was detected (rs = 0.65, $p < 0.001$), attributable to the underlying warming trend; however, application of the Hamed-Rao modified Mann-Kendall test (Hamed and Rao, 1998) yielded identical conclusions, confirming the robustness of the reported trend significance.

CONCLUSIONS

The conducted analysis of precipitation regime transformation in the Upper Dniester basin (Ivano-Frankivsk Oblast) over 51 years (1975–2025) based on ERA5-Land reanalysis data allowed three key patterns of climatic change to be established. First, statistically significant warming was recorded (+0.058 °C/year, $\tau = 0.58$, $p < 0.001$), amounting to +2.8 °C over the study period. Significant warming encompasses all four seasons, being most intensive in summer (+0.076 °C/year) and winter (+0.063 °C/year). Second, total annual precipitation demonstrates a non-significant decrease ($\tau = -0.18$, $p = 0.069$), and between the two sub-periods it declined by 7.3% (from 971.8 to 900.7 mm). Third, a statistically significant seasonal redistribution of precipitation was recorded: winter precipitation is increasing (+0.82 mm/year, $p = 0.041$), while summer precipitation is decreasing (−1.87 mm/year, $p = 0.013$). Between sub-periods, winter precipitation increased by 12.2% (from 151.4 to 169.9 mm), while summer precipitation decreased by 11.1% (from 357.9 to 318.2 mm).

Regarding precipitation phase structure, the annual snow fraction remains stable (~18–19%, $\tau = -0.05$, $p = 0.60$), which against the background of substantial warming is explained by the mountainous character of the study area, where winter temperatures at higher elevations remain below 0 °C. At the same time, the winter snow fraction decreased from 68.9% (1975–1999) to 62.9% (2000–2025), by 6.0 percentage points (−8.7%), indicating a gradual transformation of winter precipitation from predominantly solid to mixed. This transformation has accelerated in the most recent decade: 5 of the 8 winter seasons with an anomalously low snow fraction (< 50%) fall within 2014–2024.

The identified changes are of considerable practical significance for water resource management and adaptation planning in the Carpathian region. The decrease in the solid component of winter precipitation combined with an increase in total winter amounts may generate more rapid surface runoff instead of gradual snowmelt, suggesting increased spring flood and flash flood risk. The simultaneous decrease in summer precipitation combined with enhanced evapotranspiration due to warming may increase growing-season drought risk, with implications for the agricultural and forestry sectors of the region.

REFERENCES

1. Agayar, E., Aemisegger, F., Armon, M., Scherrmann, A., Wernli, H. (2024). Precipitation extremes in Ukraine from 1979 to 2019: Climatology, large-scale flow conditions, and moisture sources. *Natural Hazards and Earth System Sciences, 24*(7), 2441–2459. https://doi.org/10.5194/nhess-24-2441-2024
2. Andrusiv U, Zelinska H, Kupalova H, Bezuhla L, Bieloborodova M, (2024). The influence of the ecological situation in Ukraine on the life expectancy and health of the population. *Ekológia (Bratislava), 43*(2), 219. https://doi.org/10.2478/eko-2024-0023
3. Arkhipova L., Pernerovska S. (2015). Forecasting water bodies hydrological parameters using singular spectrum analysis. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2*(146), 45–50.
4. Bandhauer, M., Isotta, F., Lakatos, M., Lussana, C., Båserud, L., Izsák, B., Szentes, O., Tveito, O. E., Frei, C. (2022). Evaluation of daily precipitation analyses in E-OBS (v19.0e) and ERA5 by comparison to regional high-resolution datasets in European regions. *International Journal of Climatology, 42*(2), 727–747. https://doi.org/10.1002/joc.7269
5. Blahušiaková, A., Matoušková, M., Jenicek, M., Ledvinka, O., Kliment, Z., Podolinská, J., Snopková, Z. (2020). Snow and climate trends and their impact on seasonal runoff and hydrological drought types in selected mountain catchments in Central Europe. *Hydrological Sciences Journal, 65*(12), 2083–2096. https://doi.org/10.1080/02626667.2020.1784900
6. Blau, M. T., Kad, P., Turton, J. V., Ha, K.-J. (2024). Uneven global retreat of persistent mountain snow cover alongside mountain warming from ERA5-land. *Npj Climate and Atmospheric Science, 7*(1), 278. https://doi.org/10.1038/s41612-024-00829-5
7. Bokwa, A., Klimek, M., Krzaklewski, P., Kukułka, W. (2021). Drought trends in the polish carpathian Mts. in the years 1991–2020. *Atmosphere, 12*(10), 1259. https://doi.org/10.3390/atmos12101259
8. Bozzoli, M., Crespi, A., Matiu, M., Majone, B., Giovannini, L., Zardi, D., Brugnara, Y., Bozzo, A., Berro, D. C., Mercalli, L., Bertoldi, G. (2024). Long-term snowfall trends and variability in the Alps. *International Journal of Climatology, 44*(13), 4571–4591. https://doi.org/10.1002/joc.8597
9. Christidis, N., Stott, P. A. (2022). Human influence on seasonal precipitation in Europe. *Journal of Climate, 35*(15), 5215–5231. https://doi.org/10.1175/JCLI-D-21-0637.1
10. Dalla Torre, D., Di Marco, N., Menapace, A., Avesani, D., Righetti, M., Majone, B. (2024). Suitability of ERA5-Land reanalysis dataset for hydrological modelling in the Alpine region. *Journal of Hydrology: Regional Studies, 52*, 101718. https://doi.org/10.1016/j.ejrh.2024.101718
11. De Winter, J, Tindall, J., Johnson, A. (2024, May 15). Amplified seasonality in western Europe in a warmer world. *Science Advances*. https://doi.org/10.1126/sciadv.adl6717
12. Gomis-Cebolla, J., Rattayova, V., Salazar-Galán, S., Francés, F. (2023). Evaluation of ERA5 and ERA5-Land reanalysis precipitation datasets over Spain (1951–2020). *Atmospheric Research, 284*, 106606. https://doi.org/10.1016/j.atmosres.2023.106606
13. Google. (2025). Xee/docs at main · google/Xee. GitHub. https://github.com/google/Xee/tree/main/docs
14. Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment, Big Remotely Sensed Data: Tools, Applications and Experiences, 202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031
15. Government of Ukraine. (2024). Ukraine's Climate Change Adaptation Communication to UNFCCC. https://unfccc.int/sites/default/files/2025-05/Ukraine%201st%20Adaptation%20Communication.pdf
16. Hamed, K. H., Ramachandra Rao, A. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology, 204*(1), 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X
17. Hussain, M. M., Mahmud, I. (2019). pyMann-Kendall: A python package for non parametric Mann Kendall family of trend tests. *Journal of Open Source Software, 4*(39), 1556. https://doi.org/10.21105/joss.01556
18. Irtyshcheva, I., Popadynets, N., Sytnyk, Y., Andrusiv, U., Khromyak, Y., Kramarenko, I., Sakharnatskyi, V. (2023). Management of the environmental potential of freshwater resources in the conditions of sustainable development. *Ecological Engineering & Environmental Technology, 24*(4), 229-235. https://doi.org/10.12912/27197050/162910
19. Lavers, D. A., Simmons, A., Vamborg, F., Rodwell, M. J. (2022). An evaluation of ERA5 precipitation for climate monitoring. *Quarterly Journal of the*

Royal Meteorological Society, 148(748), 3152–3165. https://doi.org/10.1002/qj.4351

20. Li, Z., Chen, Y., Li, Y., Wang, Y. (2020). Declining snowfall fraction in the alpine regions, Central Asia. *Scientific Reports, 10*(1), 3476. https://doi.org/10.1038/s41598-020-60303-z
21. Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica, 13*(3), 245–259. https://doi.org/10.2307/1907187
22. Matiyiv, K., Klymchuk, I., Arkhypova, L., Korchemlyuk, M. (2022). Surface water quality of the Prut River basin in a tourist destination. *Ecological Engineering & Environmental Technology, 23*(4), 107-114. doi: 10.12912/27197050/150311.
23. Micu, D. M., Amihaesei, V. A., Milian, N., Cheval, S. (2021). Recent changes in temperature and precipitation indices in the Southern Carpathians, Romania (1961–2018). *Theoretical and Applied Climatology, 144*(1), 691–710. https://doi.org/10.1007/s00704-021-03560-w
24. Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data, 13*(9), 4349–4383. https://doi.org/10.5194/essd-13-4349-2021
25. Nazeri Tahroudi, M. (2025). Comprehensive global assessment of precipitation trend and pattern variability considering their distribution dynamics. *Scientific Reports, 15*(1), 22458. https://doi.org/10.1038/s41598-025-06050-5
26. Ombadi, M., Risser, M. D., Rhoades, A. M., Varadharajan, C. (2023). A warming-induced reduction in snow fraction amplifies rainfall extremes. *Nature, 619*(7969), 305–310. https://doi.org/10.1038/s41586-023-06092-7
27. Osypov, V., Bawa, A., Osadcha, N., Osadchyi, V., Shevchenko, O., Bonchkovskyi, A., Kostetskyi, O., Nikoriak, V., Ahafonov, Y., Matviienko, Y., Mossur, H., O'Donncha, F., Jacobs, M., Srinivasan, R., Arnold, J., White, M. J. (2025). A high-resolution hydrological dataset for ukrainian river basins with an interactive web interface. *Geoscience Data Journal, 12*(4), e70027. https://doi.org/10.1002/gdj3.70027
28. Prykhodko, M., Arkhypova, L., Fomenko, N., Syrovets, S., Varianichko, V., Osypov, D. (2023). Economic value of ecosystem services in the land scapes of Ukraine. In *17th International conference monitoring of geological processes and ecological condition of the environment* (pp. 1–5). Kyiv: European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.2023520221
29. Salyha, V., Arkhypova, L. (2025). Vegetation cover dynamics of the Dniester basin under climate change influence in the 21st century. *Ecological Safety and Balanced Use of Resources, 2*(16), Article 16(2). https://doi.org/10.63341/esbur/2.2025.19
30. Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association, 63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934
31. Smyk, I., Arkhypova, L. M. (2025). Environmental assessment of water resources in the tourist zones of Ivano-Frankivsk region: A case study. *Ecological Engineering & Environmental Technology, 26*(9), 263–277. https://doi. org/10.12912/27197050/209739
32. Somorowska, U. (2024). Assessing the impact of climate change on snowfall conditions in Poland based on the snow fraction sensitivity index. *Resources, 13*(5), 60. https://doi.org/10.3390/resources13050060
33. Wypych, A., Ustrnul, Z. (2024). Precipitation and hydrological extremes during the warm season in response to climate change: The example from the Polish Carpathians. *Regional Environmental Change, 24*(2), 90. https://doi.org/10.1007/s10113-024-02252-1
34. Yavaşlı, D. D. (2025). Spatio-temporal trends in precipitation indices over mediterranean using ERA5-Land data (1950–2024). *International Journal of Climatology, 45*(13), e70049. https://doi.org/10.1002/joc.70049