УДК 551.583

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СТАТИСТИЧЕСКИЙ АНАЛИЗ И ОЦЕНКА ИЗМЕНЕНИЯ КЛИМАТА В БАССЕЙНЕ РЕКИ ВАРЗОБ (ПЕРИОД 1981–2025 ГГ.)

Аннотация: *В данной статье анализируется тенденция изменения климатических параметров-температуры и атмосферных осадков, в период 1981-2025 гг. с использованием данных NASA POWER. В исследовании применялись непараметрические статистические методы: тест ММК, тест Сена и тест Петтита. Результаты показывают, что среднегодовая температура воздуха значительно повысилась, а ее точка излома приходится на 1999 год. Несмотря на статистическую незначимость тренда осадков, наблюдается положительная тенденция. Результаты годового и сезонного статистического анализа указывают на интенсификацию процесса потепления в речном бассейне, что приводит к увеличению числа экстремальных гидрологических катастроф, таких как оползни и лавины.*

Ключевые слова: *бассейн реки Варзоб, изменение климата, модифицированный тест Манна-Кендалла, тест Петтита, тест наклона Сена, температура, осадки.*

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STATISTICAL ANALYSIS AND ASSESSMENT OF CLIMATE CHANGE IN THE VARZOB RIVER BASIN (PERIOD 1981-2025)

Abstract: *The article analyzes the trend of changes in climatic parameters - temperature and atmospheric precipitation in the period 1981-2025 using NASA POWER data. In this study, non-parametric statistical methods-MMK test, Sen's slope test and Pettit's test were used. The results show that the annual air temperature has increased significantly, and its change point occurred on 1999. Despite the non-significance of precipitation's trend, it has a positive trend. The results of annual and seasonal statistical analyses indicate an intensification of the warming process in the river basin, which leads to an increase in extreme hydrological disasters, such as mudslides and avalanches.*

Keywords: *Varzob River basin, climate change, modified Mann-Kendal test, Pettit's test, Sen's slope test, temperature, precipitation.*

Introduction. Urbanization, industry, and population explosions have exposed humanity to climate change, which has affected all components of the water cycle (hydrology). Even significant hydrological changes have been reported as consequences of climate change.

Water has not been left untouched by climate change, and is considered one of the most vulnerable natural resources, leading to natural disasters and political conflicts between its users. Central Asia is one of these regions. The level of impact of climate change on Central Asian countries varies depending on their location and the industry on which the country's economy is most dependent.

According to existing literature, 60% of Central Asian water resources are located in Tajikistan, and according to [1], 55.4% of the region's water is formed within the current territory of Tajikistan. According to climate forecasts, Tajikistan is expected to experience an increase in air temperature and changes in atmospheric precipitation, depending on its geographical location. The process of climate change will have a negative impact on all sectors of Tajikistan, leading to water shortages and the emergence of interstate conflicts.

Changes in the volume and quantity of water in Tajikistan mean changes throughout the region. It goes without saying that due to population growth, the demand for water is increasing, requiring modern technologies.

The Varzob River is the largest tributary of the Kofarnihon River [2] and is considered one of the country's strategic rivers, playing an important role in the development of the national economy. This river is used to provide the population of the capital with drinking water, generate electricity, and provide irrigation water to the Hisor Valley. The Varzob River supplies irrigation water to some of the cities and districts of the Hisor Valley through the large Hisor Canal, and then joins the Qarotogh River.

The Varzob River basin is located in the southwestern part of Tajikistan and originates in the southern part of the Hisor Range. It gets its name from the confluence of the Zideh and Maykhura rivers. The length of the river is 71 km, and its area is 1,250 km2. Various indicators are given in the literature regarding the morphometric characteristics of the Varzob River. For example, if we look at [3], the length of the river is 97 km and the area occupied by the Varzob River basin is 1900 km2.

According to [2], the Varzob is the largest tributary of the Kafarnihan River and is itself rich in tributaries, such as Maykhura, Siyoma, Takob, Dimalik, Kharangon etc.

According to [4], the Varzob River is a type of river fed by glacial and snowmelt. Therefore, changes in meteorological parameters can lead to accelerated melting of glaciers.

The glaciers of the Varzob River basin are not very high and are scattered. According to the analysis of the literature, it was determined that they belong to the karavi and valley types. In particular, in the valley of the Kofarnihan River, to which the Varzob River belongs, karavi and valley glaciers are widespread, occupying 30%

of the basin area. The firn line in the Varzob River basin is located at an altitude of 3690 m above sea level, and the glaciers are receding from east to west [5].

If we look at the current state of the glaciers, as noted in [2] and [4], the glaciers of the mentioned river basin are unstable and are in the process of receding. The glacier tongues are shortening and their thickness is also decreasing, and some of the smaller glaciers have completely disappeared. According to the conducted studies, Tajikistan will lose 20% of the area and 25% of the volume of its glaciers by 2050, with the most severe situation in the Kofarnihon River basin, most of which are located in the Varzob River basin.

This work is aimed to determining the trends in the climatic parameters of the Varzob River and its consequences.

Methodology. Various methods were used to determine and obtain results.

Data collection and data processing. Data on meteorological parameters - air temperature and atmospheric precipitation at a height of 2 meters above the ground surface were obtained from the NASA POWER DAV platform [6], for the period 1981-2025.

MS Excel and Rstudio programs were used to process data on atmospheric precipitation and air temperature. MS Excel was used to determine the average value of air temperature, atmospheric precipitation amount and visualize the monthly distribution of parameters, and Rstudio was used to process data using the MMK, Sen slope and Pettit tests, as well as to visualize multi-year and seasonal data.

Modified Mann-Kendall Test. To determine the presence of a trend for the data of the listed parameters in the Varzob River basin, the MMK statistical test proposed by Hamed and Rao [7] was used. The MMC trend test is a nonparametric method widely used in earth sciences such as hydrology and climatology. One of the important features of this test is that it does not require a normal distribution of the data and controls for the effect of autocorrelation in the data used.

The calculation of the C statistic is the beginning of the MMC trend method and is calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$$

Here, n is the data set, $x_j$and x_i are the data values at time j and i, and $sgn(\theta)$ is the sign of the function, which can take the values -1, 0, and 1, depending on the analysis. The sign of the function is defined as follows.

$$sgn(\theta) = \begin{cases} -1, & if\ \theta < 0 \\ 0, & if\ \theta = 0 \\ +1, & if\ \theta > 0 \end{cases}$$

In connection with the presence of 45 data rows, i.e. in this case $n > 10$, to determine the variance of S $(V(S))$ we use the following formula:

$$V(S) = \frac{n(n-1)(2n+5)}{18}$$

Hamed and Rao (1998) proposed the MMC test to take into account the effect of autocorrelation, which includes a correction factor depending on the data type and is written as follows.

$$V^*(S) = V(S) \cdot \left(\frac{n}{n^*}\right)$$

$\left(\frac{n}{n^*}\right)$-here is a correction factor that corrects the variance depending on the significance of the autocorrelation lag, and the standardized test statistic Z is calculated using the following formula.

$$Z = \begin{cases} \frac{S-1}{\sqrt{V^*(S)}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \frac{S+1}{\sqrt{V^*(S)}}, & if\ S < 0 \end{cases}$$

The Z value determines whether there is a positive or negative trend. A negative value indicates a negative trend, while a positive value indicates a positive trend. This value has an interval of -1.96 to +1.96, and when this value is located between this interval, there is no clear trend.

Therefore, the null hypothesis H_0 "no trend" is rejected when the significance level is $\alpha = 0.05$, and if $|Z| > 1.96$ or $p < 0.05$, the hypothesis is not rejected, otherwise.

Sen's slope test. The Sen slope test was used to determine the magnitude [8] and trend of air temperature and precipitation. One of the advantages of this test is that it remains stable even when some data are missing. The Sen slope test is calculated as follows:

$$Q_i = \frac{x_j - x_k}{j - k} \quad for\ i = 1, \dots, N$$

x_j and x_i are the data values at time j and k. The Sen slope estimator is the median of the N values of Q_i A positive value indicates an increase, and a negative value indicates a decrease.

Pettit's test. To determine the point of break or change in air temperature and atmospheric precipitation, the Pettit test was used. Through this test, the point of change or transition of the regime of climatic parameters to a new state is determined.

The test statistic K_n is determined as the maximum value of $U_{t,n}$ in the presence of a break or sudden change in the data series. The test is calculated as follows:

$$K_n = max\left|U_{t,n}\right|$$

$$U_{t,n} = U_{t,n-1} + \sum_{j=1}^{n} sgn(x_i - x_j) \quad for\ t = 2, \dots, n$$

Here n is the length of the time series, and if $U_{t,n}$ shows a decreasing trend over time, then there is a change in the data series, but if it shows an increase over time, then the series has no breakpoint or abrupt change. Using the following formula, the significance probability $K_n$is calculated when $p \leq 0.05$:

$$p = 2exp \cdot \left(\frac{-6K_n^2}{n^3 + n^2}\right)$$

Results. The Varzob River basin has a unique orography, which plays a significant role in the formation of the region's climate. The monthly distribution of climatic parameters - precipitation and air temperature in this basin is as follows (Figure 1):

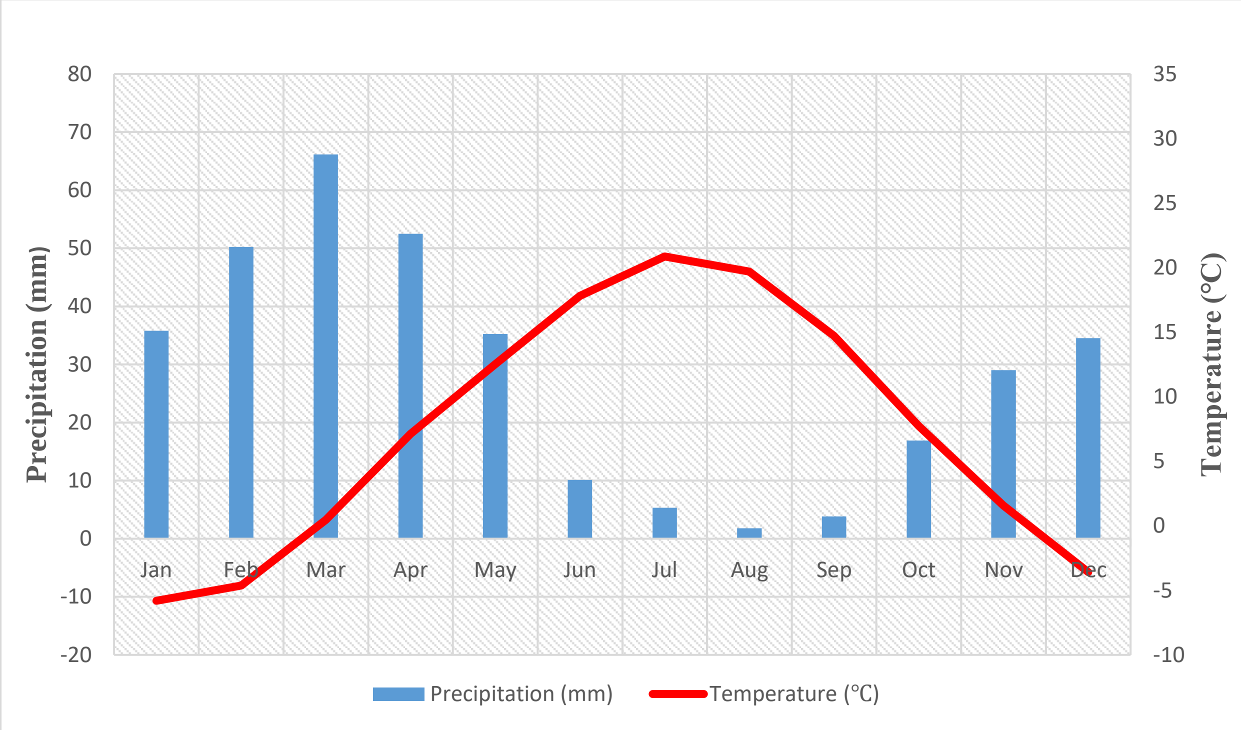

Figure 1. Monthly distribution of atmospheric precipitation and air temperature in the Varzob River Basin

According to Figure 1, the distribution of precipitation and air temperature in the basin is different, with the maximum precipitation in March and the minimum in August. The air temperature reaches its maximum value in July and the lowest in January. The maximum and minimum precipitation values are 66.1 mm and 1.7 mm, respectively, and the air temperature is 20.9 and 5.8 °C. In June-September, a significant decrease in atmospheric precipitation and an increase in air temperature are observed, which is considered a dry period in the river basin.

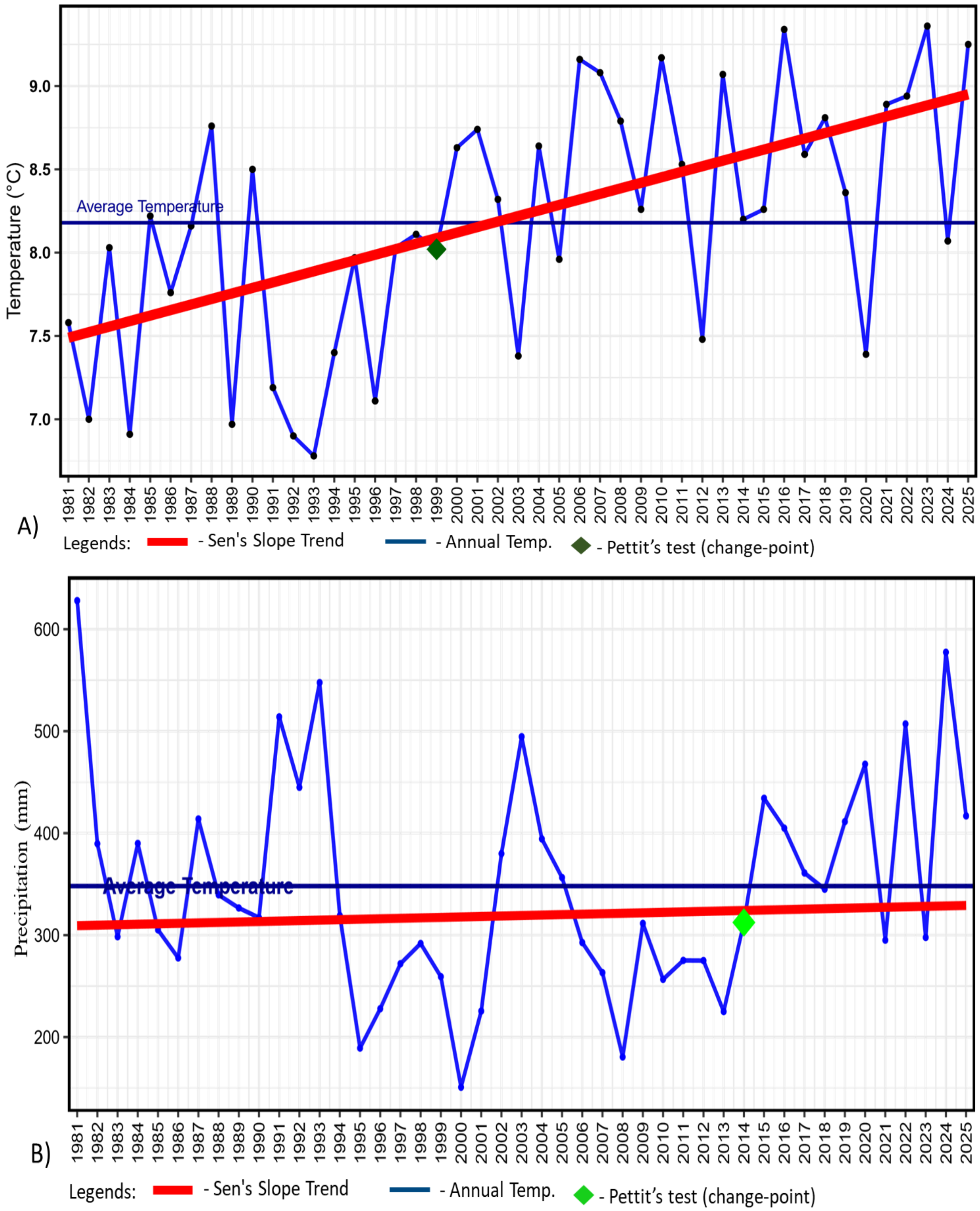

Figure 2. Analysis of trends in (A) air temperature and (B) precipitation in the Varzob River Basin

Table 1.

Results of annual analysis of temperature and precipitation using the MMK, Sen slope and Pettit tests in the Varzob River basin

Test	Annual T (°C)	Annual P (mm)
MMK z-score	4.06	0.24
MMK p-value	0.00	0.81
Sens's Slope	0.033	0.45
Pettitt's test	1999	2014
Pettit's p-value	0.0004	0.17
Average	8.18	348.1
Significance Level	Significant	Not significant

From Figure 1 (A and B), it can be seen that the air temperature and atmospheric precipitation are in a process of increase. The tendency of increasing temperature relative to atmospheric precipitation is very large and indicates a change in the temperature regime in the basin. Based on the collected data in Table 1, the Z-value of the MMC test, which is equal to 4.06, indicates that the air temperature has a positive trend, and its p-value, which is $p<0.05$, indicates that the trend is statistically significant. According to the results of the Sen test, the air temperature increases by more than 0.3 °C per year. The p-value of the Pettit test also indicates that the temperature change point is not random, and indicates that the year 1999 was a turning point or a turning point. The average annual temperature in the Varzob River Basin is 8.18 °C.

The analysis using the MMC did not show a statistically significant trend, the results of the z and p values, which are 0.24 and 0.8, respectively, are greater than the significant level indicators, i.e. $p>\alpha$. On average, 348.1 mm of atmospheric precipitation reaches the Earth's surface per year in this basin. According to the results of the Sen test, atmospheric precipitation increases by 0.45 mm per year, which is equal to 202.5 mm during the observed period.

Pettitt test analysis shows a breakpoint in 2014, but its p-value is 0.17, which does not reject the null hypothesis, since p>α. Based on the results obtained for precipitation from the above test, in the Varzob River basin, the identified volatility in the average values before and after 2014 remains at the natural level of interannual variability.

Table 2.

Results of seasonal analyses of MMK, Sen slope and Pettit tests in the Varzob River basin

Test	Winter	Spring	Summer	Autumn
MMK z-score	2.2505	3.4827	2.3424	1.6141
MMK p-value	0.0244	0.0005	0.0192	0.1065
Sen's slope	0.0281	0.0569	0.0205	0.0187
Pettitt's test	1996	1999	2005	2001
Pettit's p-value	0.1168	0.0000	0.0991	0.3390
Average T	-3.91	7.52	20.35	8.76
Significance Level	Significant	Significant	Significant	No-Significant

To better understand the trend of climatic parameters, a seasonal analysis was conducted in the Varzob River Basin, the results and visualization of which are presented in Figure 2 and Table 2.

The values obtained using the MMC test indicate that there is a positive trend in all seasons of the year, which is statistically significant in winter, spring and summer, and loses its significance in autumn. The most significant trend among the seasons belongs to spring, with a p-value of 0.005, which is a very small significance level.

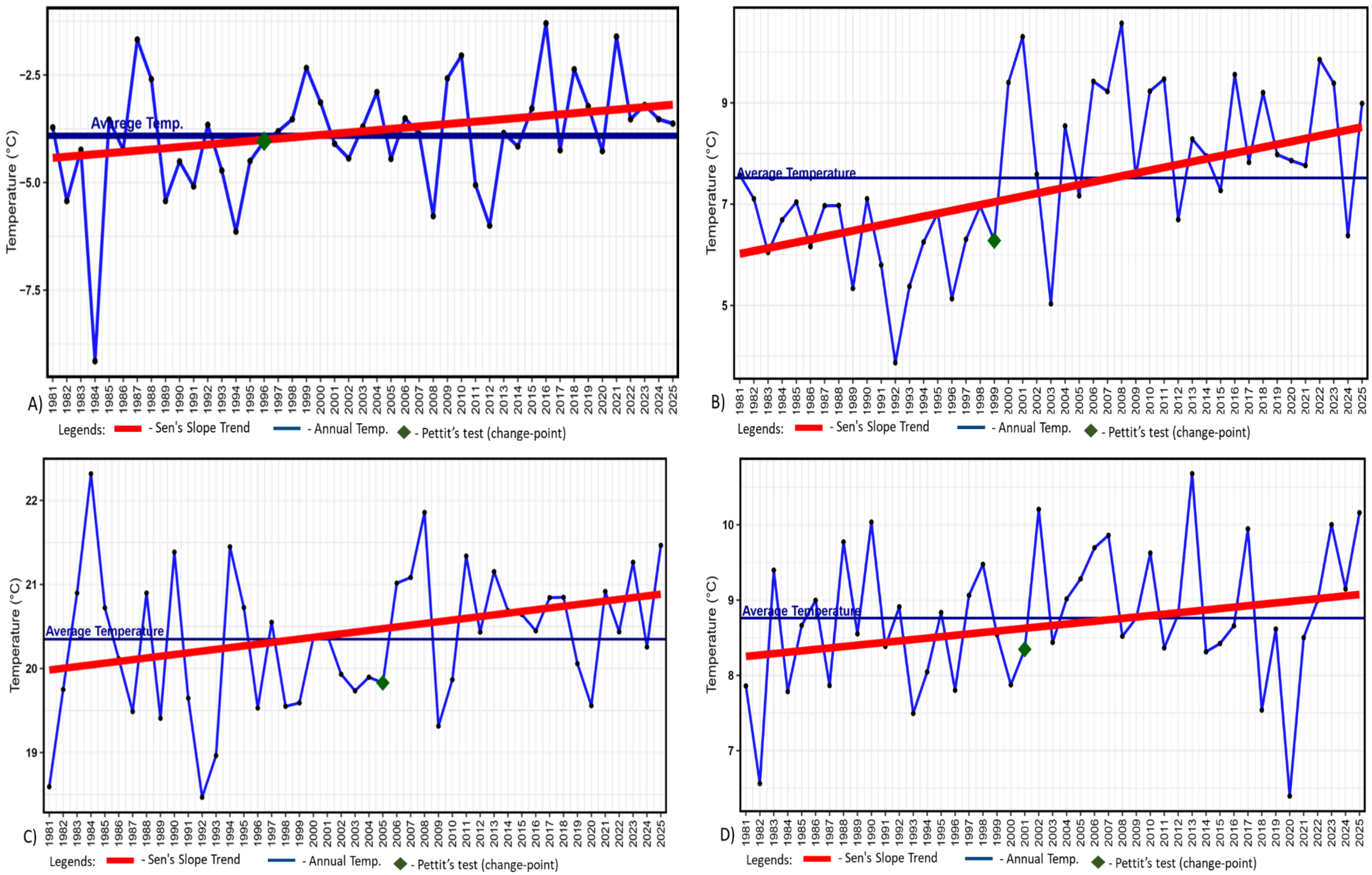

Figure 3. Analysis of seasonal trends in air temperature-winter (A), spring (B), summer (C) and autumn (D) using the MMK, Sen slope and Pettit tests in the Varzob River basin

According to the results obtained from the Sen slope test, the air temperature increases differently in each season of the year. The highest value of the increase in air temperature falls on spring, which is approximately 0.06 times. Therefore, the air temperature increases in winter compared to summer and autumn, which is approximately 0.03 °C per year. The increase in air temperature in the summer and autumn seasons is approximately equal to each other, being 0.02 and 0.018, respectively.

Analysis of the average atmospheric precipitation data using the Pettit test assessed the occurrence of a turning point or change in each season for the years 1996, 1999, 2005 and 2001, respectively. If we look at the results of the p-values in the spring and summer seasons, it indicates that there is a clear moment of change in the mode or arithmetic mean value in the data series, which cannot be explained by simple random variation. The average seasonal air temperature in the winter season, which has the lowest value, is -3.91 °C, in the spring season it is 7.52 °C, in the summer season it is 20.35 °C, and in the autumn season it is 8.76 °C.

Table 3.

Results of atmospheric precipitation analysis using the MMK, Sen slope and Pettit tests in the Varzob River basin

Test	Winter	Spring	Summer	Autumn
MMK z-score	-0.9193	0.3228	2.156	0.9
MMK p-value	0.3579	0.7468	0.0311	0.3734
Sen's slope	-0.1607	0.2649	0.3367	0.3808
Pettitt's test	1994	2014	2013	2013
Pettit's p-value	0.6291	0.3537	0.0335	0.1684
Average P	120.6	153.9	17.23	49.71
Significance Level	No-Significant	No-Significant	Significant	No-Significant

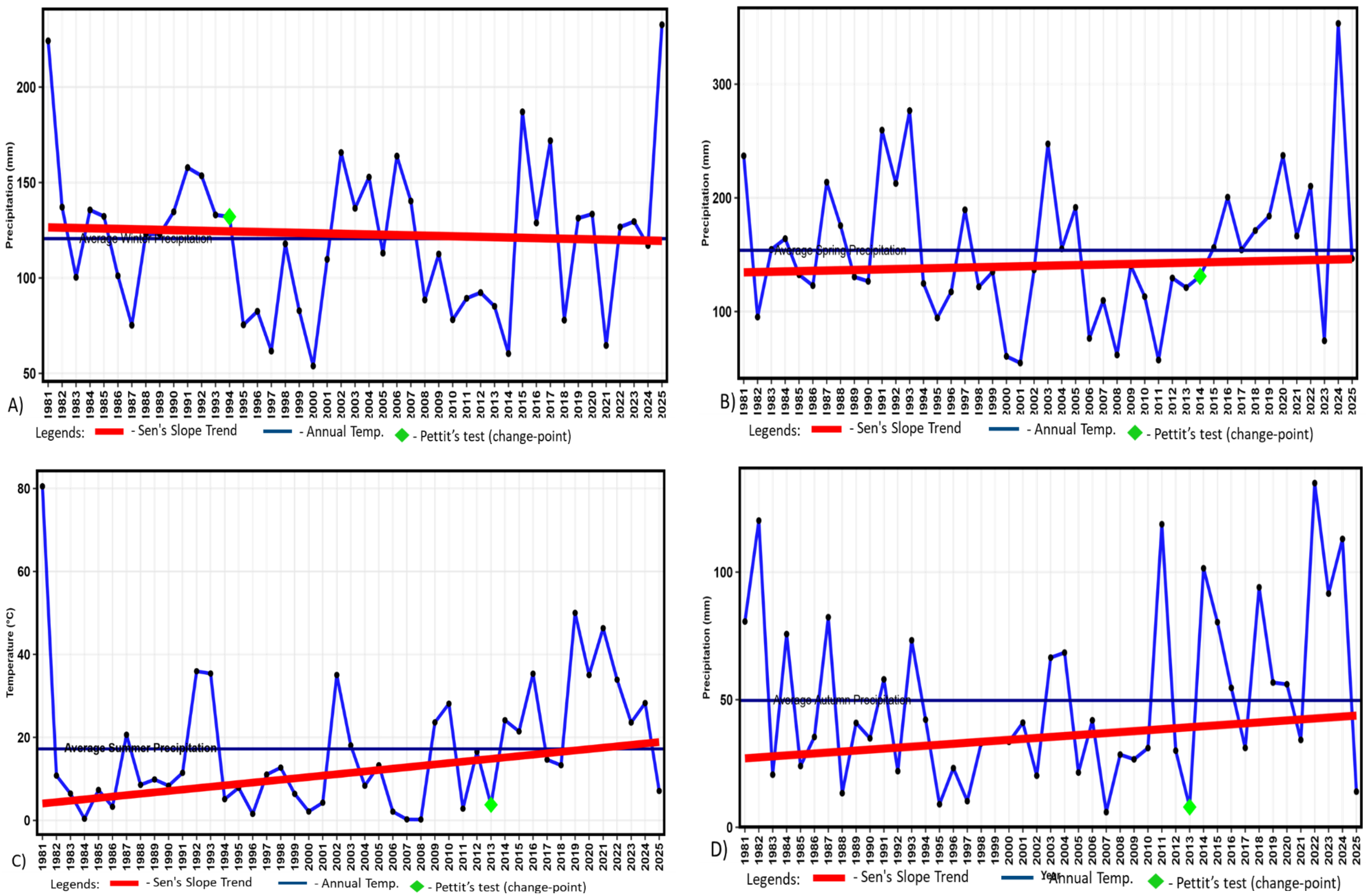

Figure 4. Analysis of seasonal trends in precipitation (A), spring (B), summer (C) and autumn (D) using the MMK, Sen slope and Pettit tests in the Varzob River basin

The seasonal analysis of precipitation is considered very interesting. If we look at the MMC values, it is clear that the precipitation trend in spring is negative and remains positive in other seasons. Regardless of the trend, the p-value results confirm that they are not statistically significant in winter, spring and autumn. The change in precipitation in summer is significant, its z-score is 2.156 and p-value is 0.03, which are higher and lower than the significance level, respectively. Therefore, the increase in precipitation in summer is statistically significant.

The Sen slope test of -0.16 mm per year confirms the decrease in precipitation in winter. The indicators for spring, summer and autumn are positive, and they are 0.26, 0.34 and 0.38 mm per year, respectively.

Pettit's test indicators for determining the turning point indicate that the turning point occurred in the winter of 1994, in the spring of 2014, and in the summer and autumn of 2013. However, it is worth noting that the turning point or change of regime in the summer is not random and cannot be explained by simple variation. The average value of atmospheric precipitation in the winter is 120.6 mm, in the spring it is 153.9 mm, in the summer it has a minimum value of 17.23 mm, and in the autumn it is 49.71 mm. **Discussion.** The results obtained confirm the existence of the theory of global climate change in Tajikistan. The presence of a temperature shift in 1999 is consistent with the results of other studies in the Pamir-Alai mountain systems. This shift point indicates that the Varzob mountain ecosystems are extremely vulnerable to global changes in atmospheric circulation.

As a result of the analysis of meteorological data for the Varzob River basin, a significant increase in the average annual temperature and a statistically insignificant increase in the amount of annual precipitation were observed. According to the results of [9], the average annual temperature in the basin has increased significantly, but precipitation has a downward trend.

As we mentioned above, the Varzob River is included in the group of rivers whose source is snow and glaciers. Changes in precipitation and temperature can have adverse consequences for the hydrological regime of the river. While [2] and

[4] have assessed the glaciers of the region as unstable glaciers, the changes introduced may lead to a further decrease in the number and volume of glaciers.

The increase in air temperature and atmospheric precipitation will not only have a negative impact on glaciers, but also lead to the occurrence of various natural disasters in the region. If we look at the reports of the Committee for Emergency Situations and Civil Defense under the Government of the Republic of Tajikistan [10], [11], [12], [13], [14], the available maps of avalanches indicate that the Varzob River basin is the epicenter of avalanches. Therefore, the increase in these parameters may lead to an increase in avalanches in the study area.

The results of seasonal analyses indicate that air temperatures are increasing significantly in winter, spring and summer. Although not statistically significant, there is also a positive trend in autumn. Atmospheric precipitation, on the other hand, tends to decline in winter, but is not statistically significant. Despite the statistically insignificant trend in precipitation in the spring and autumn seasons, it has an increasing trend. The summer season has a statistically significant positive trend. Based on the evidence presented in [2] and [4] and these results, it is likely that the level of accumulation from ablation in this basin is very low.

The increase in air temperature and the decrease in atmospheric precipitation in winter are favorable conditions for the decline of glaciers, since precipitation reaches the basin surface not in solid form, but rather in liquid form, which accelerates the melting of the snow cover. In such cases, avalanches are unlikely. According to [15], the increase in air temperature and rainfall create favorable conditions for the formation of wet avalanches, which is confirmed by the results obtained in the Varzob River Basin.

Rising temperatures and decreasing amounts of solid precipitation (snow) can lead to avalanches in the warmer months of the year due to old snow. They may be relatively small, but they contain rocks of different sizes, which can cause more damage.

Also, rising temperatures, especially in spring and summer, can cause earlier melting of snowpack and glaciers in the basin. This process can also be a significant factor in making the basin glaciers more unstable. Increased liquid precipitation increases the likelihood of mudflows, disrupting the river's water balance and, to some extent, affecting water quality.

The seasonal results are most interesting, since precipitation increases significantly in the summer. This may be due to the intensification of convective processes associated with surface warming. The insignificant increase in atmospheric precipitation with increasing air temperature in the river basin indicates an increase in evaporation. Of course, this has a negative impact on the basin, as it can lead to drying of the soil in the lower reaches of the basin.

Conclusion. As a result of the analysis and statistical study of climatic parameters in the Varzob River basin, the following conclusions were drawn (for the period 1981-2025):

1) Based on statistical methods, a significant trend of increasing annual air temperature is observed in the river basin ($z=4.06$, $p<0.05$). The Sen value shows that the annual air temperature is 0.033. The Pettit test shows the temperature break point in 1999. This result indicates the transition of the existing climate in the basin to a relatively warmer climate.

2) Despite the presence of a positive trend in the amount of annual atmospheric precipitation, it is not statistically significant. According to the results of the Sen test, its increase is 0.45 mm.

3) Seasonal analyses have shown a significant increase in atmospheric precipitation in the summer. The parallel increase in atmospheric precipitation with air temperature in the summer increases the risk of mudflows and floods in the Varzob River basin.

4) A significant increase in air temperature in the spring and winter seasons accelerates the process of glacier degradation. The presence of this change

in the region's climate leads to a decrease in snow cover, which can lead to water shortages in the summer.

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