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Long-Term Temperature and Precipitation Trends in the Turkish Section of the Euphrates-Tigris Basin

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Abstract—This study examines the long-term trends of key meteorological variables within the section of the Euphrates-Tigris Basin located within Türkiye's national borders. Using data from 18 meteorological stations (1965-2023) and applying methods such as the MMK test, SS, SR, and several homogeneity tests, the analysis identifies notable climatic shifts. The combined use of these methods allows for a more consistent evaluation of both trends and potential structural changes in the time series. Significant decreases in precipitation were detected at three stations, while the remaining stations showed no clear trend. This indicates that precipitation changes are limited and station-specific, reflecting spatial variability within the basin rather than a uniform basin-wide pattern. In contrast, maximum temperatures increased significantly at 77.8% of stations, and minimum temperatures rose at nearly 83%. The widespread increase in temperature across most stations suggests a more consistent warming pattern compared to precipitation. Homogeneity assessments revealed major change points in 1989, 1994, and 1998 for both precipitation and temperature. These years may be associated with variations in atmospheric circulation patterns and regional hydro-climatic influences, including reservoir-related effects. The identification of similar change points by different homogeneity tests supports the consistency of these findings. These results suggest an increasing hydro-meteorological imbalance, likely influenced by rising temperatures and declining or stable precipitation. These changes may have an impact on the hydrological processes within the catchment area and on water-dependent sectors. The findings highlight the urgent need for long-term, adaptive, and integrated water management strategies, supported by basin-specific climate change scenarios.

Keywords: Change point detection, Euphrates-Tigris basin, modified Mann-Kendall test, precipitation trend.

1. Introduction

Climate change presents significant challenges for the sustainable management of water resources by affecting hydro-meteorological processes at both global and regional scales (Intergovernmental Panel on Climate Change (IPCC) 2023). Increasing temperatures, irregular precipitation regimes, and changes in the hydrological cycle are leading to a decline in water potential, more frequent extreme weather events, and the need for a reconfiguration of water management policies (Hamed & Rao, 1998; Sonali & Nagesh Kumar, 2013). These impacts are more pronounced in semi-arid and arid regions, where the long-term identification of hydro-meteorological trends is crucial for the accurate planning of water management strategies (Achite et al., 2024; Bozkurt & Şen, 2013; Nazeri Tahroudi, 2025). Recent assessments indicate that climate-induced variability in temperature and precipitation significantly affects water availability, particularly in semi-arid regions (Intergovernmental Panel on Climate Change (IPCC) 2023; Sonali & Nagesh Kumar, 2013).

The Euphrates and Tigris river system constitutes a major transboundary basin in the Middle East, supporting agricultural irrigation, hydropower production, and drinking water supply across multiple countries (Buyukyildiz, 2023; Ceribasi & Aytulun, 2020). In this study, the analysis is limited to the Turkish portion of the basin, where a significant part of the headwaters originates and where large-scale water management projects, such as the Southeastern Anatolia Project (GAP), significantly influence regional hydrological processes. Previous studies

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have demonstrated that climatic variability in upstream regions directly affects downstream water availability and basin-wide sustainability (Buyukyildiz, 2023; Ceribasi & Aytulun, 2020; Güçlü et al., 2018). Recent fluctuations observed in the basin's hydro-meteorological variables have led to irregularities in precipitation and increases in temperature. This situation is putting pressure on the basin's water potential and necessitates a revision of long-term water management policies. Studies show that these changes have significant effects on water management strategies, particularly strengthening drought trends (Ceribasi & Ceyhunlu, 2021; Güçlü et al., 2018). Recent basin-scale studies further indicate that increasing temperature trends and non-stationary precipitation regimes contribute to intensified hydrological variability and water stress in the region (Ceribasi & Ceyhunlu, 2021; Güçlü et al., 2018; Intergovernmental Panel on Climate Change (IPCC) 2023).

Various statistical analysis methods have been developed to identify trends in hydro-meteorological time series. Non-parametric methods are widely preferred in hydrological analyses since they do not require assumptions about the distribution of data (Ergün et al., 2024; Helsel & Hirsch, 1993; Kundzewicz & Robson, 2004). The Modified Mann–Kendall (MMK) test is one of the most commonly used non-parametric methods for identifying long-term trends in hydro-meteorological variables, offering more reliable results, especially in datasets containing autocorrelation (Hamed & Rao, 1998; Mann, 1945). Sen's Slope Estimator (SS), a widely used method for determining the direction and magnitude of trends, was developed to predict linear trends in time series (Sen, 1968; Theil, 1992). The Spearman Rho trend test (SR), with its non-parametric structure, allows for the identification of nonlinear trends in hydrological and climatic variables (Sonali & Nagesh Kumar, 2013). To detect abrupt changes in meteorological time series, methods such as the SNHT, PT, BRT, and VNT are employed (Buishand, 1982; Pettitt, 1979). These methods are used in this study to identify potential structural changes and abrupt shifts in long-term hydro-meteorological series. Detecting such changes is essential for interpreting hydrometeorological variability in time series and its implications for water resource management (Wagh & Guhathakurta, 2023).

In this study, these methods were selected due to their robustness and widespread applicability in hydro-climatological analyses, particularly for detecting both monotonic trends and potential non-stationary behavior in long-term datasets (Kundzewicz & Robson, 2004; Mann, 1945). Despite the extensive application of these methods, previous studies often focus on limited spatial domains or single-variable analyses and do not adequately address both long-term trends and structural changes simultaneously at the basin scale (Ceribasi & Ceyhunlu, 2021; Güçlü et al., 2018). Previous studies have provided valuable insights into hydro-meteorological variability in the Tigris–Euphrates Basin. However, most of these studies have primarily focused on individual variables, future climate projections, or specific sub-regions of the basin, rather than providing an integrated basin-scale assessment. As a result, the combined evaluation of long-term trends together with potential abrupt changes in observed data remains insufficiently addressed, particularly for the Turkish portion of the basin (Adamo et al., 2020; Daggupati et al., 2017; Özdoğan, 2011). Therefore, there is a clear need for a basin-scale analysis that integrates multiple statistical approaches and evaluates both trend behavior and change points in key meteorological variables within a consistent hydro-climatic framework.

This study conducted a comprehensive analysis using MMK, SS, SR, SNHT, PT, BRT, and VNT tests to detect long-term trends in meteorological parameters in the part of the Euphrates–Tigris basin located within Türkiye. Annual precipitation, maximum temperature, and minimum temperature data from 1965 to 2023 were evaluated in this study. The selected period (1965–2023) provides a sufficiently long dataset to capture multi-decadal variability and potential regime shifts in hydro-meteorological processes, which is essential for reliable trend and change-point detection (Kundzewicz & Robson, 2004; Mann, 1945; Sonali & Nagesh Kumar, 2013). The main objective of the study is to detect trends in meteorological processes, highlight the potential effects of climate change in the region, and develop

strategic recommendations for the sustainable management of water resources.

2. Study Area and Data

2.1. Study Area

Covering the east and southeast of Türkiye, the Euphrates and Tigris rivers are the two rivers with the largest volume of water in the country. The Euphrates originates from Mount Ararat at an altitude of 4500 m, while the Tigris originates near Lake Caspian at an altitude of 1150 m (Fig. 1). The Euphrates and Tigris rivers, which are the transboundary waters of our country, merge within the borders of Iraq and flow into the Persian Gulf at the Shatt al-Arab. The basin lies in the territories of Iraq (46%), Türkiye (22%), Iran (19%), Syria (11%), Saudi Arabia (1.9%) and Jordan (0.03%) (Frenken, 2009). The part of the Euphrates–Tigris basin within the borders of Türkiye is approximately 185,000 km^2 and includes the areas with the highest need for drinking, utility, energy and irrigation water. 20% of the 8.5 million hectares of irrigable land in Türkiye is in the GAP region, which consists of large plains in the Lower Euphrates and Tigris basins. Not only to feed southeastern Türkiye and the Mesopotamian plains, but also The Euphrates and Tigris, which carried erosion products across the southern part of Anatolia and the Arab lands of Türkiye, Syria and Iraq (because they drained the youngest 8 collisions in the Alpine-Himalayan orogenic belt), played an important role in the geological and hydrological

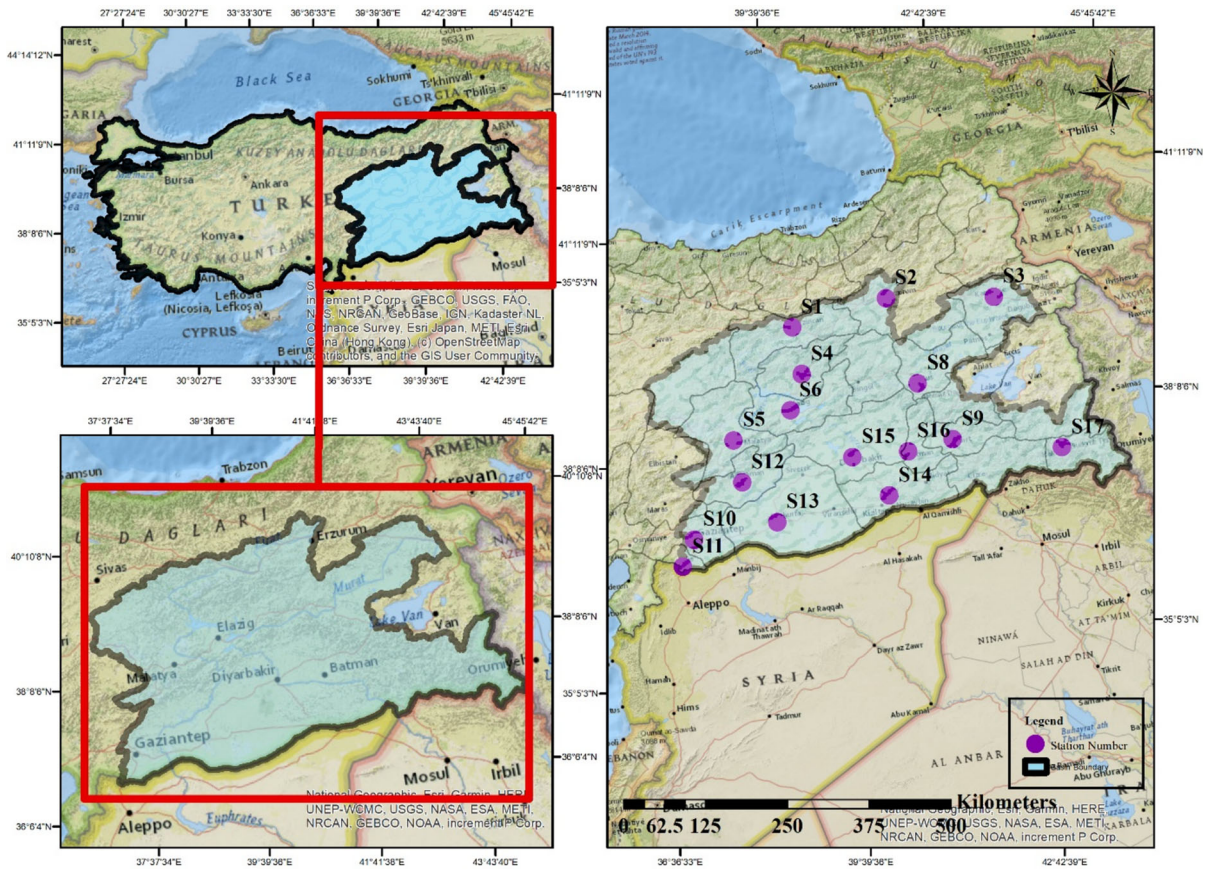


Figure 1
Location map of the study area and meteorological observation stations

Table 1

Information of the stations used in the study

Station ID	# Station	Station name	Latitude	Longitude	Data range
S1	17,094	Erzincan Region	39° 45′ 08″ N	39° 29′ 12″ E	1965–2023
S2	17,096	Erzurum Airport	39° 57′ 10″ N	41° 11′ 22″ E	1965–2023
S3	17,099	Agri	39° 43′ 31″ N	43° 03′ 07″ E	1965–2023
S4	17,165	Tunceli	39° 06′ 20″ N	39° 32′ 26″ E	1965–2023
S5	17,199	Malatya	38° 20′ 12″ N	38° 13′ 02″ E	1965–2023
S6	17,201	Elazıg Region	38° 38′ 39″ N	39° 15′ 21″ E	1965–2023
S7	17,203	Bingol	38° 53′ 04″ N	40° 30′ 02″ E	1965–2023
S8	17,204	Mus	38° 45′ 03″ N	41° 30′ 08″ E	1965–2023
S9	17,210	Siirt	37° 55′ 54″ N	41° 56′ 07″ E	1965–2023
S10	17,261	Gaziantep	37° 03′ 30″ N	37° 21′ 03″ E	1965–2023
S11	17,262	Kilis	36° 42′ 30″ N	37° 06′ 44″ E	1965–2023
S12	17,265	Adıyaman	37° 45′ 19″ N	38° 16′ 39″ E	1965–2023
S13	17,270	Sanlıurfa	37° 09′ 38″ N	38° 47′ 10″ E	1965–2023
S14	17,275	Mardin	37° 18′ 37″ N	40° 43′ 42″ E	1965–2023
S15	17,280	Diyarbakır Airport	37° 53′ 50″ N	40° 12′ 09″ E	1965–2023
S16	17,282	Batman	37° 51′ 48″ N	41° 09′ 22″ E	1965–2023
S17	17,285	Hakkari	37° 34′ 28″ N	43° 44′ 19″ E	1965–2023
S18	17,950	Cizre	37° 19′ 57″ N	42° 12′ 09″ E	1965–2023

characteristics of Mesopotamian civilization (Nicoll, 2010).

GAP, one of Türkiye's most extensive regional development programs, integrates water resources management, energy production, and agricultural development to enhance socio-economic conditions across the Euphrates–Tigris Basin. As of 2023, approximately 91.2% of the energy investments within the project have been completed, resulting in the generation of 20.6 billion kilowatt-hours of electricity per year through operational hydropower plants. Additionally, 58% of the planned irrigation infrastructure has been realized, bringing 633,984 hectares of agricultural land under irrigation. Upon full completion, GAP is expected to control 28% of Türkiye's total water potential, irrigate 1.8 million hectares of farmland, and produce 27 billion kilowatt-hours of electricity annually with a total installed capacity of 7476 megawatts (Devlet Su İşleri Genel Müdürlüğü (DSİ) 2023).

In the northern and eastern parts of the Euphrates–Tigris basin, the elevation reaches up to 4000 m in mountainous areas. As you move towards the south of the basin, the topography changes rapidly and in these parts, where the elevation drops to 300 m, relatively flat and lowland areas dominate. The rivers in the basin are largely fed by the snowfall that falls for long periods throughout the year in the higher parts of the region. Especially in the southern parts of the basin, semi-arid climatic conditions prevail, with relatively low precipitation and high air temperature and consequently high evaporation.

This study examines the Euphrates–Tigris Basin, which is a transboundary basin; however, the analyses carried out are limited to the section of the basin located within Türkiye's borders. For the purposes of enhancing data continuity and the reliability of observations, 18 meteorological observation stations with long-term data records were selected for the study. Within the scope of this study, data from 18 meteorological observation stations used to investigate the effects of climate change are presented in Table 1.

2.2. *Data*

In this study, annual total precipitation (TP), maximum (Tmax), and minimum temperature (Tmin) data obtained from 18 stations in the study area for the period 1965–2023 (59 years) were used for trend analysis and the identification of turning points. Descriptive statistics for the 59-year TP, Tmax, and Tmin parameters of the selected 18 stations are presented in Tables 2, 3, and 4, respectively. For the

Table 2

Descriptive statistics of annual TP (mm)

Station	Mean	SD	Variance	Skewness	Kurtosis	Minimum	Maximum
S1	378.363	77.968	6079.089	0.825	0.893	238.400	626.00
S2	406.479	80.014	6402.192	0.385	− 0.346	253.800	593.500
S3	522.566	103.414	10,694.374	0.254	− 0.277	329.600	779.600
S4	856.253	266.895	71,232.972	2.248	6.629	526.500	1992.800
S5	386.179	80.714	6514.765	0.806	0.498	252.000	597.400
S6	419.774	106.872	11,421.638	0.687	0.791	211.190	734.950
S7	952.053	200.144	40,057.889	0.726	0.808	596.600	1579.100
S8	761.702	145.527	21,178.198	0.063	− 0.347	489.100	1091.180
S9	690.405	160.659	25,811.285	0.392	− 0.419	413.890	1046.400
S10	573.149	140.758	19,812.777	0.544	0.314	330.600	999.390
S11	499.312	133.917	17,933.644	0.674	− 0.075	297.840	833.740
S12	713.239	192.939	37,225.438	0.541	− 0.512	426.750	1173.800
S13	456.997	151.617	22,987.822	0.772	0.414	178.660	856.730
S14	660.606	220.232	48,501.989	0.468	− 0.229	250.680	1200.030
S15	490.009	125.983	15,871.810	0.074	− 0.230	200.470	768.600
S16	487.434	126.819	16,083.024	0.406	− 0.318	246.410	803.790
S17	776.993	165.043	27,239.307	0.455	0.074	450.300	1202.640
S18	673.857	192.743	37,149.813	0.229	− 0.299	242.100	1126.420

Table 3

Descriptive statistics of annual Tmax (°C)

Station	Mean	SD	Variance	Skewness	Kurtosis	Minimum	Maximum
S1	37.364	1.515	2.296	− 0.199	0.131	33.400	40.600
S2	33.007	1.565	2.448	0.002	− 0.289	29.200	36.500
S3	35.268	1.682	2.829	− 0.088	− 0.355	31.600	38.900
S4	39.446	1.659	2.753	0.007	− 0.537	35.600	42.700
S5	39.390	1.516	2.298	− 0.074	− 0.374	36.000	42.400
S6	39.446	1.659	2.753	0.007	− 0.537	35.600	42.700
S7	39.188	1.234	1.524	− 0.101	0.040	36.400	42.000
S8	37.595	1.466	2.150	0.093	0.819	33.800	41.600
S9	41.544	1.472	2.166	0.097	0.813	38.000	46.000
S10	40.290	1.530	2.340	0.301	− 0.078	37.000	44.000
S11	41.293	1.741	3.032	0.814	2.008	37.900	47.600
S12	42.507	1.411	1.991	− 0.011	− 0.283	39.000	45.300
S13	43.151	1.358	1.845	0.183	− 0.048	40.300	46.800
S14	39.893	1.295	1.676	− 0.554	0.423	36.200	42.500
S15	42.809	1.239	1.535	− 0.621	0.025	39.900	44.800
S16	43.746	1.332	1.773	− 0.146	− 0.094	40.300	46.500
S17	35.225	1.615	2.609	− 0.529	0.374	31.000	38.800
S18	46.051	1.373	1.884	0.048	− 0.098	42.400	49.100

18 stations in the study area, 1062 (59*18) annual data sets were used, derived from 12,744 (59*18*12) monthly data records. The total record length of 1062 years and 12,744 months does not represent the continuous observation period of a single station, but rather the sum of the time series lengths of all stations included in the study. On the other hand, missing values, which accounted for 1.02% of the maximum temperature parameter, 0.99% of the minimum

Table 4

Descriptive statistics of annual Tmin (°C)

Station	Mean	SD	Variance	Skewness	Kurtosis	Minimum	Maximum
S1	12.207	1.921	3.688	− 0.128	− 0.731	8.300	16.200
S2	6.273	1.949	3.800	0.260	− 0.462	2.700	11.300
S3	8.309	1.603	2.568	− 0.109	− 0.890	4.800	11.300
S4	14.990	1.274	1.623	− 0.293	− 0.520	12.000	17.300
S5	16.520	1.763	3.108	0.397	− 0.202	12.700	20.700
S6	15.675	1.532	2.347	0.045	− 0.701	12.600	18.600
S7	15.542	1.265	1.601	− 1.021	1.230	11.400	17.800
S8	13.798	1.841	3.391	− 1.023	1.594	8.000	16.700
S9	20.488	1.535	2.356	− 0.263	− 0.349	17.000	23.000
S10	17.564	2.038	4.151	− 0.333	− 0.945	13.400	21.000
S11	18.554	1.447	2.095	− 0.179	− 0.817	15.500	21.200
S12	19.925	1.341	1.798	− 0.118	− 0.681	17.100	23.000
S13	20.690	1.398	1.954	− 0.020	− 0.575	17.800	23.800
S14	20.265	1.867	3.487	0.190	− 0.725	17.000	24.000
S15	17.642	1.359	1.847	0.296	0.698	14.200	21.400
S16	16.564	1.804	3.254	− 0.247	− 0.488	12.500	20.000
S17	15.468	1.614	2.606	0.004	− 0.242	12.000	19.200
S18	21.111	1.394	1.945	0.234	− 1.013	18.600	23.702

temperature, and 0.97% of the total precipitation parameter, were imputed using regression analysis.

Multiple linear regression was used to impute missing data. In this context, station data with missing observations were treated as the dependent variable; measurements from neighboring stations for the same period and relevant meteorological parameters were included in the model as independent variables. The regression analyses were performed using SPSS software, and the accuracy of the results is validated through the software's statistical analysis. In this way, missing values were estimated, making the dataset suitable for analysis.

The TP amounts analyzed in this study provide important information about the hydrological cycle and climate characteristics of the basin. As seen in Table 2 the average precipitation amounts indicate that the basin receives a moderate level of precipitation in terms of the general water regime. However, standard deviation values indicate that precipitation amounts are quite variable between years. The results of the minimum and maximum precipitation amount show that some years are quite dry while other years are much wetter. Inter-quartile values show that precipitation is generally concentrated between 243.17 and 423.54 mm and this range is a typical precipitation regime for the basin.

The Tmax data in Table 3 shows that the Euphrates–Tigris Basin experiences high temperatures in summer periods and has a hot climate in general. Standard deviation values reveal that Tmaxs can vary significantly between years. While the minimum maximum temperature value represents the cooler years of the basin, the maximum temperature value indicates very hot years. Inter-quarter temperature values reveal that extreme values in maximum temperatures are rare.

When the Tmin data in Table 4 are analyzed, the average values show that this basin has a cool climate characteristic at night or in winter. The standard deviation values in the minimum temperature data reveal that the minimum temperatures of the basin vary considerably over the years. The lowest minimum temperature value reflects a very cold climate event. In the light of the minimum temperature values, it can be interpreted that the basin generally has mild night temperatures.

In general, it is understood that precipitation and temperature data in the Euphrates–Tigris Basin show a significant spatial and temporal variability. While the fluctuations in total precipitation data reveal that

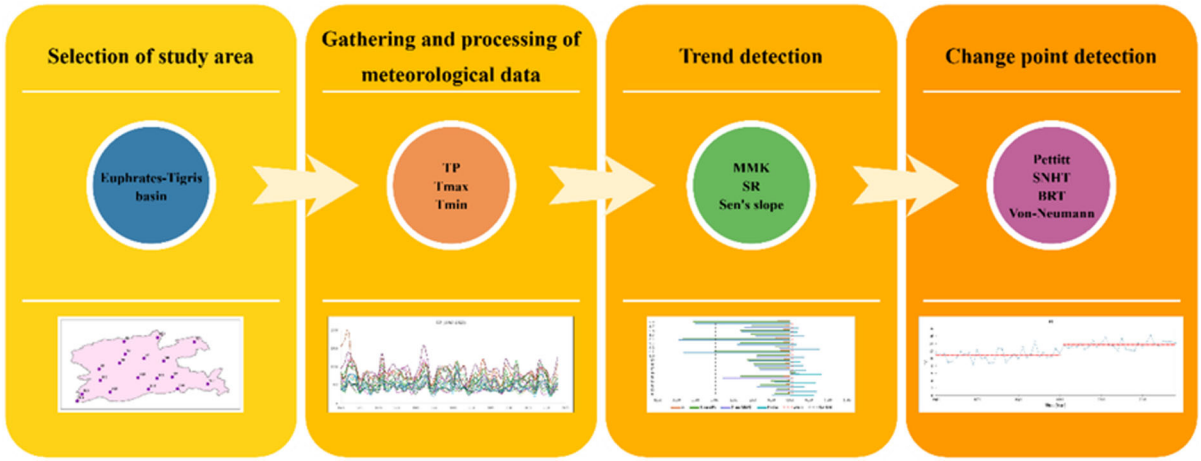


Figure 2
General methodology approach

the basin experiences dry and wet periods in the hydrological cycle, the changes in temperature data indicate that extreme temperatures can be observed especially in summer and cold periods in winter. This situation shows that the basin has a variable climate structure in terms of water resources management and agricultural activities and suggests that it should be carefully examined in the context of future climate change scenarios.

3. *Materials and Methods*

The meteorological data used in this study were obtained from observation stations operated by the General Directorate of Meteorology, a government agency in Türkiye. For the analysis, 18 stations with long-term, uninterrupted data records from 1965 to 2023 were selected. The data are archived with regular measurement intervals and quality control processes, and only reliable and suitable data were selected for the analysis. To ensure the accuracy of climate analysis results, the homogeneity of the data must be examined. In the analysis of hydrometeorological time series, both the identification of trends and the assessment of data set homogeneity are of great importance. In trend analysis, the Modified Mann–Kendall (MMK) test and Spearman's rho (SR) test are widely used in the literature to determine the magnitude of the trend, as they are less affected by non-parametric structures and outliers, along with Sen's slope estimator (Burn & Elnur, 2002; Partal & Kahya, 2006; Yue & Pilon, 2004). However, the Pettitt test (PT), standard normal homogeneity test (SNHT), Buishand range test (BRT), and Von Neumann ratio test (VN) are also commonly preferred in hydrometeorological studies to identify potential breakpoints and data inconsistencies in time series (Costa & Soares, 2009; Wijngaard et al., 2003a).

3.1. *Trend Analysis*

In this study, homogeneity analyses, including the SNHT, PT, BRT, and Von Neumann Ratio Test, were applied to the annual TP, Tmax, Tmin records from 18 stations in the Euphrates–Tigris Basin, covering the period from 1965 to 2023. These analyses were conducted alongside traditional statistical methods such as the MMK test, Sen's Slope estimator, and SR test. The overall methodological framework employed in the study is illustrated in Fig. 2.

3.1.1 *Modified Mann–Kendall (MMK) Trend Test*

Pre-whitening is used to detect the trend of autocorrelation in a particular time series (Burn et al., 2004). Moreover, it is stated that pre-whitening reduces the detection rate of significant trend in the MK test (Yue

et al., 2003). Therefore, the Modified MK test is used to detect the autocorrelated trend of a series (Rao et al., 2003). The MK test is a correlation analysis based on ordinal data and is widely used to identify trends in ordinal data (Hirsch et al., 1982). However, the classical method has some disadvantages; therefore, a modified version was developed. Autocorrelation has a significant impact on the reliability of the results obtained with the MK test.

It uses the variance correction approach, which is also included in the MK test. The autocorrelation of the ranks is calculated at the significance level. First of all, the time series data should be properly prepared. The data should be complete and organized in a specific time period. Furthermore, necessary measures should be taken to reduce the effect of extreme values (Gilbert, 1987). A comprehensive empirical significance level has been established. In particular, the use of adjusted variance offers significant advantages as it accounts for both the autocorrelation function and the normalized data in a consistent manner. The calculation of the adjusted variance can be found in Hamed and Rao (1998) and Yue and Wang (2004) in the MMK test.

In both MK and MMK tests, the alternative hypothesis (H_1) is accepted if the calculated p value is less than or equal to the chosen α level of 0.05 at the specified 5% significance level. This acceptance indicates the presence of a discernible trend in the data. Conversely, if the p value exceeds α (0.05), the null hypothesis (H_0) is preferred, indicating that there is no significant trend in the data set. Significant trend is assessed according to the p value. In this study, the 5% significance level adopted for the MMK analysis follows the conventional threshold widely used in hydrological and hydro-meteorological time series studies (Joshi & Shah, 2022; Oruc, 2021; Sa'adi et al., 2023). Therefore, $\alpha = 0.05$ was selected as the reference significance level, while a sensitivity analysis using alternative significance thresholds was considered beyond the scope of the present study.

3.1.2 Sen Slope Estimator

Sen's slope estimator is a nonparametric method. This method is used to determine the magnitude of the trend in a time series (Gajbhiye et al., 2016; Jain et al., 2013; Sen, 1968). This estimator estimates the rate of change per unit time in a trend and is not affected by outliers in the data. Consequently, it is a highly accurate and reliable tool to develop linear relationships and to be preferred over using slopes in a regression.

$$\beta = median\left(\frac{X_j - X_i}{j - i}\right) \quad (i<j) \tag{1}$$

where X_i and X_j are the consecutive data values of the time series in years i and j, respectively. β is the estimated magnitude of the trend slope of the data in the time series. A positive value of Sen's slope indicates an upward or increasing trend, while a negative value indicates a downward or decreasing trend. In this study, Sen's nonparametric approach is applied using a XLSTAT Excel data analysis add-in.

3.1.3 Spearman Rho (SR) Test

Spearman's Rho test is a method used to determine the correlation between two parameters. Since it is convenient and simple, it is one of the most preferred methods to detect the presence of linear trend (Gümüş & Yenigün, 2006). Spearman's Rho test statistic "rs" is calculated as shown in Eq. (2).

$$r_s = 1 - 6\frac{\left[\sum_{i-1}^{n}\left(R(x_i) - \mathrm{i}\right)^2\right]}{(n^3 - n)} \tag{2}$$

In Eq. (2), the observed numerical values xi (i = 1, …, n) are replaced by the sequence numbers in the array formed by sorting the data from smallest to largest (Gilbert, 1987). The r_s distribution approaches normal when $n > 30$ and the Z value corresponding to the r_s test statistic is calculated as shown in Eq. (3) (Gümüş & Yenigün, 2006).

$$Z = r_s\sqrt{(n-1)} \tag{3}$$

If the Z value calculated by Eq. 3 is greater than the critical Z value ($Z_{kr} = 1.96$) corresponding to the 95% confidence level in the standard normal distribution table, it indicates that there are increasing or decreasing trends. For the results to be significant, if $r_s > 0$, it is concluded that the trend is increasing and if $r_s < 0$, it is concluded that the trend is decreasing (Türkeş 2013). When the Z value is smaller than the

critical Z value (Z_{kr} = 1.96) corresponding to 95% confidence level in the standard normal distribution table, the H_0 hypothesis is accepted and it means that there is no trend in the series (İçağa, 1994; Sneyers, 1991).

3.2. Change Point Detection

3.2.1 Standart Normal Homogeneity Test (SNHT)

This method developed by Alexandersson (1986) has been used in many hydro-meteorological studies to determine the homogeneity of the data set. SNHT is a sensitive method for detecting breaks at the beginning and end of the series (Wijngaard et al., 2003b). T(k) is calculated by Eq. (4). ($\overline{y}$) is the mean of the observed data, y_i is the observed data for each year and s is the standard deviation.

$$T(k) = k\overline{z}_1^2 + (N-k)\overline{z}_2^2 \quad k = 1, 2, 3, \ldots, N \qquad (4)$$

The values of $\overline{z}_1$ and ($\overline{z}_2$), expressed as two parts of the series, are calculated by Eqs. (5) and (6).

$$\overline{z}_1 = \frac{1}{k}\sum_{i=1}^{k}(y_i - \overline{y})/s \qquad (5)$$

$$\overline{z}_2 = \frac{1}{N-k}\sum_{i=k+1}^{N}(y_i - \overline{y})/s \qquad (6)$$

The T(k) test statistic reaches its maximum value in year "k" when the break occurs. In this case, the T_0 test statistic is calculated by Eq. (7).

$$T_0 = maks_{1 \le k \le N} T(k) \qquad (7)$$

Then, the critical value, which varies depending on the number of data, is determined. If T_0 is not more than the critical table value, the H_0 hypothesis is accepted. This means that the series is homogeneous.

Table 5

Trend analysis results of annual total precipitation during 1965–2023

Test	MMK test					Sen's slope	SR test	
Station ID	S	Var(S) (Hamed and Rao)	*P* value	Z	Zcr	Value (mm/year)	r_s	Z
S1	− 70	21,130.371	0.630	− 0.475	1.960	− 0.320	− 0.054	− 0.414
S2	− 50	15,809.905	0.691	− 0.390		− 0.228	− 0.046	− 0.351
S3	− 112	16,134.507	0.378	− 0.874		− 0.605	− 0.102	− 0.780
S4	− 65	23,383.667	0.671	− 0.419		− 0.678	− 0.066	− 0.500
S5	− 208	13,738.149	0.076	− 1.766		− 0.885	− 0.172	− 1.306
S6	27	13,631.631	0.817	0.240		0.116	0.019	0.143
S7	− 123	23,383.667	0.421	− 0.798		− 1.097	− 0.109	− 0.832
S8	− 145	23,383.667	0.343	− 0.942		− 0.998	− 0.127	− 0.967
S9	− 167	23,383.667	0.275	− 1.086		− 1.229	− 0.148	− 1.130
S10	− 137	23,383.667	0.370	− 0.889		− 1.024	− 0.115	− 0.876
S11	− 315	12,473.597	**0.005**	**− 2.811**		− 2.121	− 0.261	**− 1.988**
S12	− 45	23,383.667	0.769	− 0.288		− 0.658	− 0.052	− 0.398
S13	− 213	23,383.667	0.164	− 1.386		− 1.455	− 0.173	− 1.314
S14	− 449	23,383.667	**0.003**	**− 2.930**		− 5.458	− 0.371	**− 2.825**
S15	− 139	23,383.667	0.363	− 0.902		− 1.059	− 0.136	− 1.033
S16	− 197	23,383.667	0.198	− 1.282		− 1.345	− 0.173	− 1.316
S17	− 147	14,771.406	0.226	− 1.201		− 1.238	− 0.133	− 1.010
S18	− 383	23,383.667	**0.012**	**− 2.498**		− 3.712	− 0.336	**− 2.559**

Trend is significant at the 0.05 level for written in bold

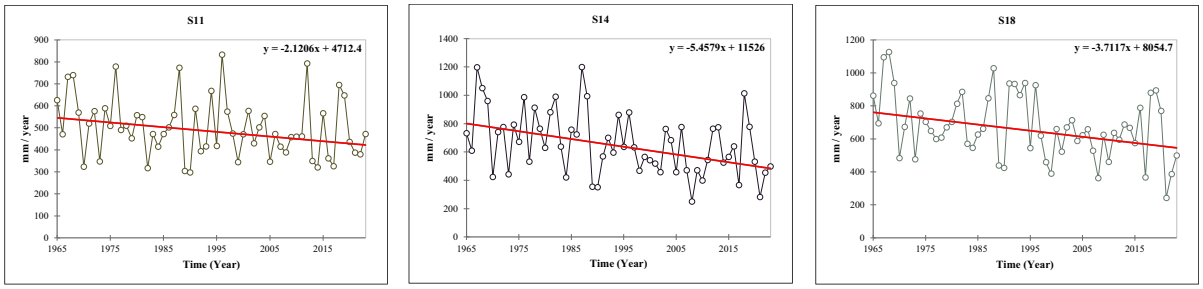


Figure 3
Sen slope graphs of annual total precipitation of **a** S11, **b** S14 and **c** S18 station (The red line represents the Sen's slope.)

3.2.2 Pettitt's Test (PT)

This method was proposed by Pettitt in 1979. The Pettitt test is a more sensitive method to detect breaks in the middle of the series. In this test, which is minimally affted by outliers, the observed values of y_i (y_1, y_2, …, y_N) for each year are ordered as r_1, r_2, …, r_N and the test statistic is "X_k". It is calculated with Eq. (8).

$$X_k = 2\sum_{i=1}^{k} r_i - k(N+1) \quad k = 1, 2, 3, \ldots, N \qquad (8)$$

The test statistic X_k takes its absolute maximum value at year "E" when the break occurs [see Eq. (9)].

$$X_E = maks_{1 \le k \le N}|X_k| \qquad (9)$$

If the calculated X_E is not greater than the critical value obtained depending on the number of data, the H_0 hypothesis is accepted. In other words, the series is homogeneous.

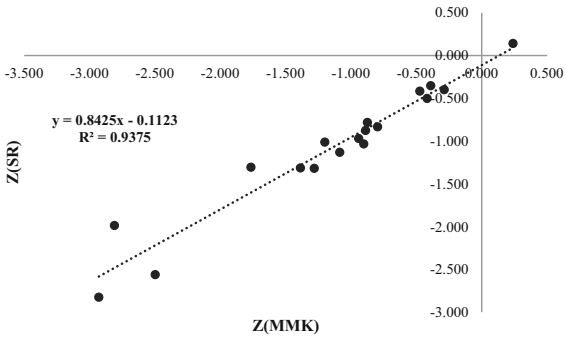


Figure 4
Comparison of Z values obtained as a result of MMK and SR tests applied to TP

3.2.3 Buishand's Range Test (BRT)

In this test developed by Buishand in 1982, R is referred to as the correction value. This value is known as the test statistic. To calculate the test statistic;

$$S^* = 0 \text{ ve } S_k^* \sum_{i=1}^{k}(Y_i - Y) \quad k = 1, 2, 3, 4, \ldots n \qquad (10)$$

equation is used. Where S is the standard deviation and $S0_*$ and S_k^* are the partial sums. The ratio of the difference between the maximum S_k and minimum S_k to the standard deviation is the correction value R (Wijngaard et al., 2003b).

When S_* is equal to 0 in the series, homogeneity exists. Because there is no systematic deviation in the series due to any reason. If the calculated test statistic is not homogeneous, it is explained by the fact that the tested series is greater than the critical values. In this case, the null hypothesis (H_0) is rejected and the alternative hypothesis (H_1) is accepted. In this study, Buishand interval test was calculated from XLSTAT program.

3.2.4 Von-Neumann Ratio Test

This test, introduced by von Neuman (1941), aims to analyze the homogeneity of the series with the statistical value obtained by finding the sum of squares of consecutive (year-to-year) differences and proportioning it to the variance value.

The von Neumann ratio test does not identify or provide information about when homogeneity breaks down and the specific location where homogeneity

Table 6

Trend analysis results of Tmax during 1965–2023

Test	MMK test					Sen's slope	SR test	
Station ID	S	Var(S) (Hamed and Rao)	*P* value	Z	Zcr	Value (°C/year)	r_s	Z
S1	678	20,596.761	**< 0.0001**	**4.717**	1.960	0.050	0.573	**4.364**
S2	582	27,385.028	**0.000**	**3.511**		0.048	0.497	**3.785**
S3	453	7119.054	**< 0.0001**	**5.357**		0.041	0.401	**3.054**
S4	672	21,760.840	**< 0.0001**	**4.549**		0.057	0.555	**4.227**
S5	576	20,910.384	**< 0.0001**	**3.976**		0.043	0.484	**3.686**
S6	672	20,532.951	**< 0.0001**	**4.683**		0.057	0.555	**4.227**
S7	10	25,876.931	0.950	0.056		0.000	− 0.017	− 0.130
S8	548	16,868.200	**< 0.0001**	**4.212**		0.035	0.458	**3.488**
S9	255	23,341.667	0.095	1.663		0.018	0.241	1.834
S10	602	17,745.055	**< 0.0001**	**4.512**		0.044	0.500	**3.808**
S11	391	23,310.333	**0.010**	**2.554**		0.033	0.337	**2.567**
S12	548	26,530.290	**0.001**	**3.358**		0.040	0.473	**3.602**
S13	642	17,770.072	**< 0.0001**	**4.809**		0.041	0.541	**4.120**
S14	620	23,297.333	**< 0.0001**	**4.055**		0.036	0.521	**3.968**
S15	236	23,320.000	0.122	1.539		0.013	0.199	1.513
S16	118	21,773.900	0.424	0.793		0.008	0.106	0.807
S17	324	12,548.811	**0.004**	**2.883**		0.026	0.280	**2.132**
S18	395	21,488.707	**0.007**	**2.688**		0.029	0.340	**2.589**

Trend is significant at the 0.05 level for written in bold

breaks down (Wijngaard et al., 2003b). In this study, the Von-Neuman ratio test was calculated from the XLSTAT program.

4. Results

4.1. Trend Analysis

To determine the trend of the annual TP, Tmax and Tmin data recorded in the study period of the meteorological observation stations located within the borders of the Euphrates–Tigris basin in our country, SR test with MMK was applied and Sen's slope test was applied to determine the magnitude of the trend.

4.1.1 Precipitation (TP)

The results of the trend analysis methods applied to the annual TP data of the stations in the study area are compiled in Table 5. Sen slope graphs of the stations with significant trend and no significant trend are shown in Fig. 3 and Fig. S1, respectively.

The results of the trend analysis applied in the study showed that there was no statistically significant trend in the annual TP recorded by the remaining 15 stations except S11, S14 and S18 stations between 1965 and 2023 at 95% confidence interval (Table 5). Thus, only 3 out of 18 stations showed a statistically significant decrease in annual TP at 95% confidence interval (Fig. S2). This shows that for most of the stations, the changes in precipitation amount are coincidental or far from forming a clear trend. The results of the trend analyses of the MMK test and SR test gave similar results at all stations. The fact that the results of the MMK test and the SR test are compatible shows that these analyses are reliable and increase the consistency of the findings. Both tests yielded similar results, suggesting that the changes in rainfall are statistically supported and methodologically robust (Fig. 4). When the results are evaluated spatially, stations showing a decreasing trend are not evenly distributed across the basin but are concentrated in the lower-lying, drier areas of the basin's southern and southwestern regions (Fig. 10a–d). Although these stations are not physically adjacent,

Table 7

Trend analysis results of Tmin during 1965–2023

Test	MMK test					Sen's slope	SR test	
Station ID	S	Var(S) (Hamed and Rao)	*P* value	Z	Zcr	Value (°C/year)	r_s	Z
S1	919	16,559.098	**< 0.0001**	**7.134**	1.960	0.083	0.750	**5.712**
S2	− 385	70,555.923	0.147	− 1.446		− 0.041	− 0.374	**− 2.848**
S3	861	18,292.913	**< 0.0001**	**6.359**		0.068	0.691	**5.262**
S4	460	23,337.333	**0.003**	**3.005**		0.030	0.418	**3.183**
S5	662	31,183.539	**0.000**	**3.743**		0.057	0.554	**4.219**
S6	312	23,346.000	**0.041**	**2.035**		0.026	0.263	**2.003**
S7	527	15,747.052	**< 0.0001**	**4.192**		0.027	0.455	**3.465**
S8	642	18,265.230	**< 0.0001**	**4.743**		0.050	0.520	**3.960**
S9	721	34,327.596	**< 0.0001**	**3.886**		0.050	0.626	**4.767**
S10	1156	34,790.898	**< 0.0001**	**6.192**		0.103	0.865	**6.588**
S11	1104	23,340.000	**< 0.0001**	**7.220**		0.071	0.835	**6.359**
S12	821	12,888.861	**< 0.0001**	**7.223**		0.053	0.670	**5.103**
S13	865	17,626.928	**< 0.0001**	**6.508**		0.057	0.722	**5.499**
S14	542	23,321.333	**0.000**	**3.543**		0.051	0.480	**3.656**
S15	41	53,113.046	0.859	0.174		0.000	0.032	0.247
S16	97	89,170.394	0.745	0.321		0.009	0.095	0.722
S17	556	15,371.286	**< 0.0001**	**4.476**		0.043	0.471	**3.587**
S18	924	13,047.377	**< 0.0001**	**8.081**		0.064	0.738	**5.620**

Trend is significant at the 0.05 level for written in bold

they can be considered to be located within the same latitudinal band, relatively close to one another, and sharing similar physical environmental conditions. The weakening of the precipitation regime can be attributed to the more pronounced continental and semi-arid climatic conditions in areas near Türkiye's southern border, as well as to the effects of temperature and evaporation. The observation of decreasing precipitation trends only at certain stations can be explained by the fact that climate change is not experienced equally everywhere, and that precipitation is a highly variable spatial parameter. These stations are particularly vulnerable to reduced precipitation because they are located in the southern part of the basin, in low-lying, semi-arid areas where continental influences are more pronounced. Conversely, microclimatic conditions, aspect, and other factors can cause stations to respond differently to the same atmospheric system.

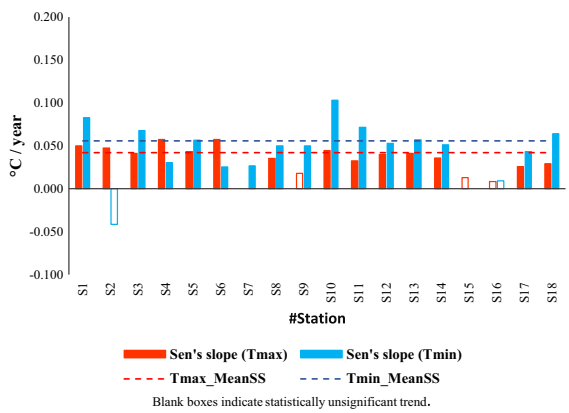


Figure 5
Sen's Slope estimator test for annually Tmax and Tmin from 1965 to 2023

4.1.2 *Maximum and Minimum Temperature (Tmax, Tmin)*

The results of the trend analysis methods applied to the annual Tmax and Tmin data of the stations in the study area are compiled in Tables 6 and 7,

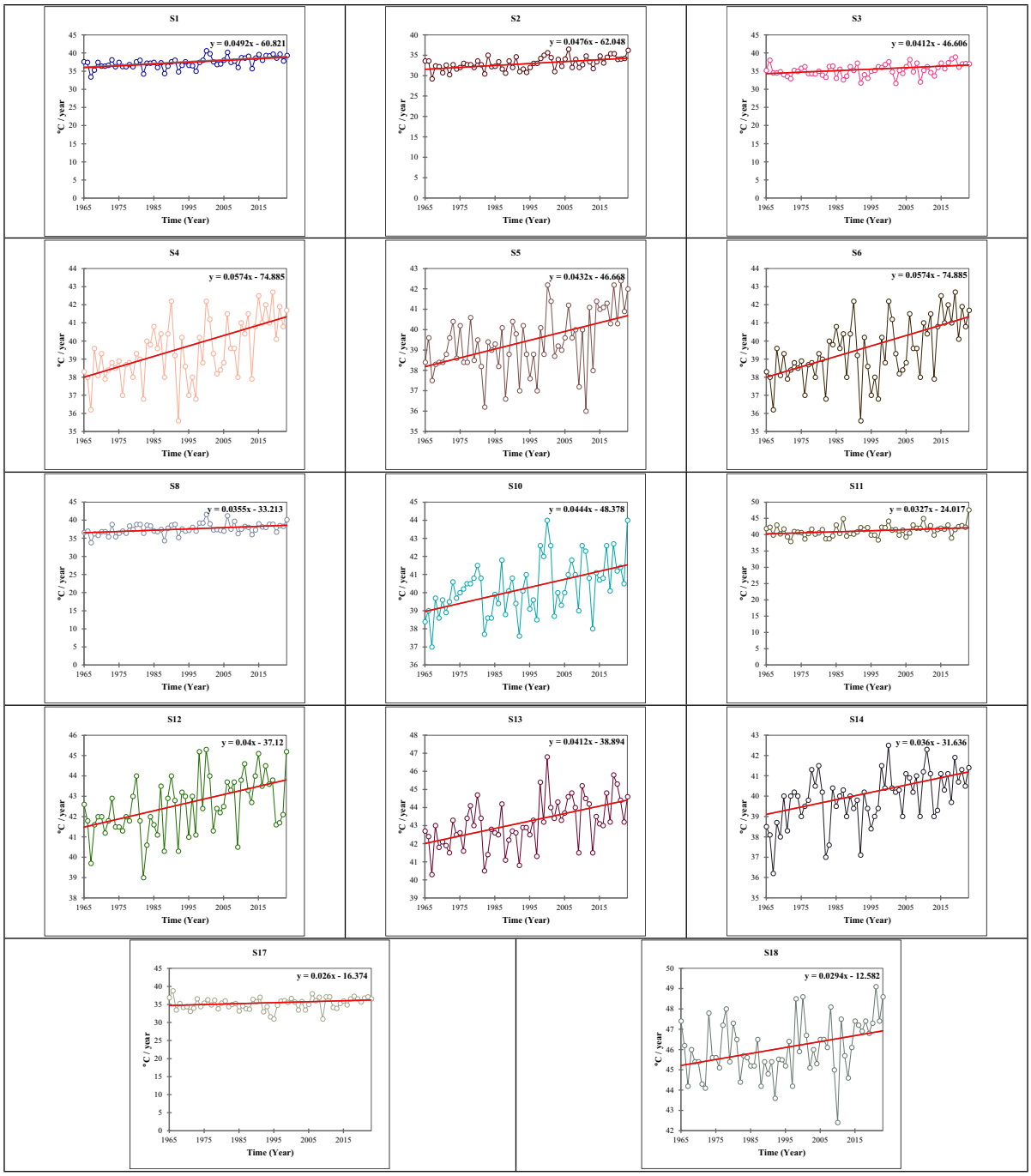


Figure 6
Sen slope graphs of Tmax (The red line represents the Sen's slope.)

respectively. The Sen's slope values for annual Tmax and Tmin are shown in Fig. 5. Sen slope plots of the stations with significant trend are shown in Figs. 6 and 7. Sen slope plots of the stations with no significant trend are shown in Figs. S3 and S4. A statistically significant increasing trend was observed

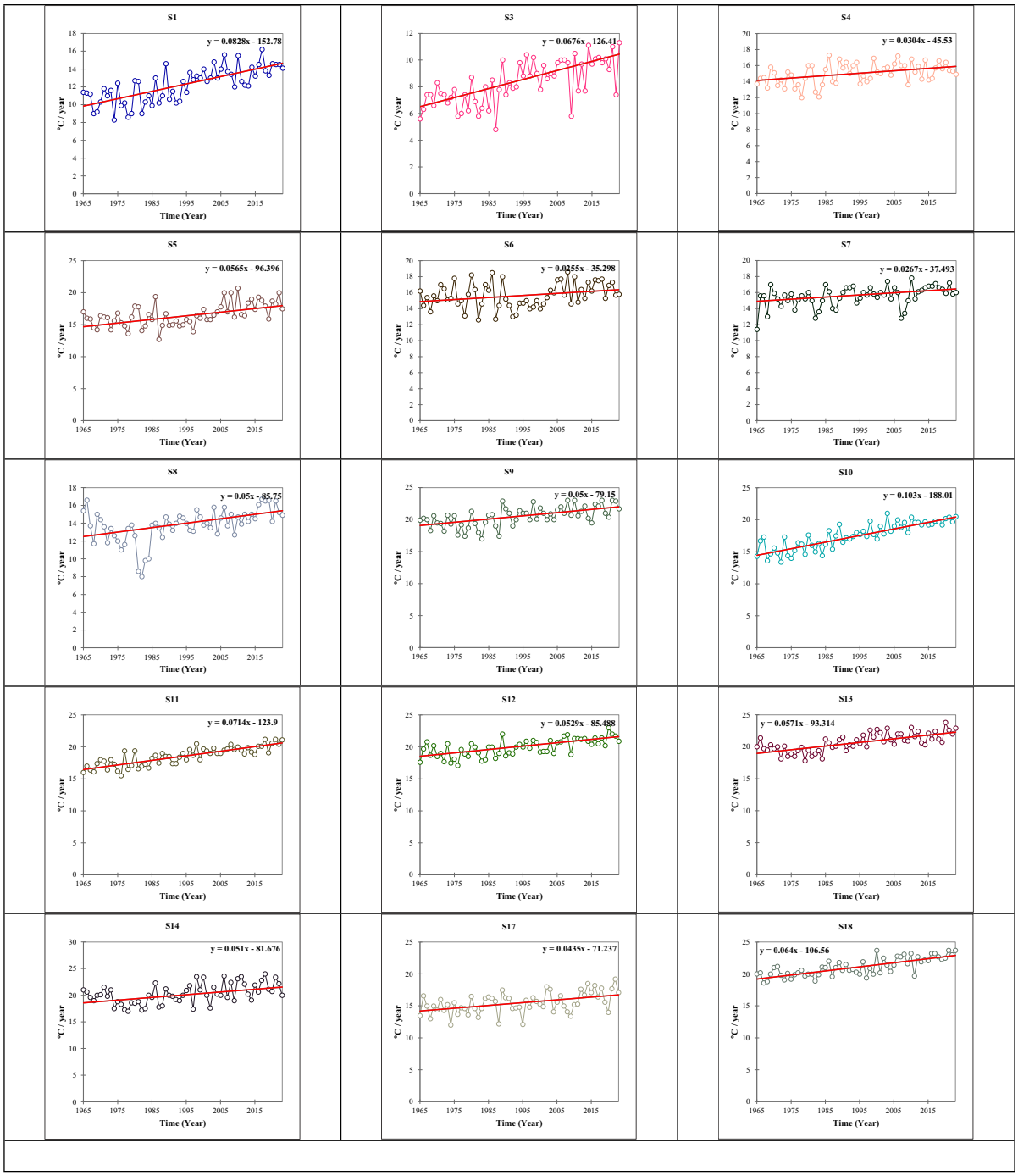


Figure 7
Sen slope graphs of Tmin (The red line represents the Sen's slope.)

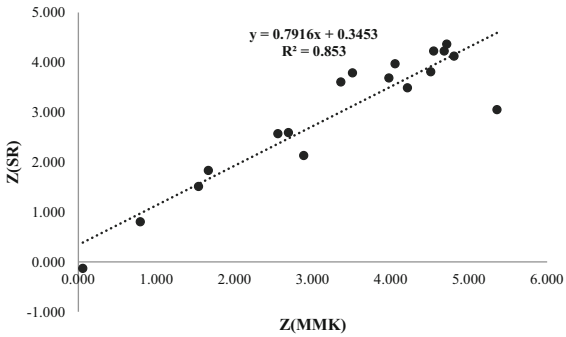


Figure 8
Comparison of Z values obtained as a result of MMK and SR tests applied to Tmax

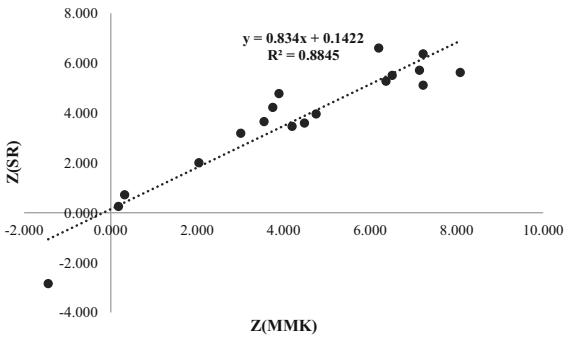


Figure 9
Comparison of Z values obtained as a result of MMK and SR tests applied to Tmin

in the annual Tmax values of 14 out of 18 stations in the study area (Table 6). The upward trend in maximum temperatures recorded at many stations suggests that the increase is not localised, but rather reflects widespread, regional warming across the entire basin. On the other hand, the upward trend observed at both the northern and southern stations indicates that the warming is affecting different topographic units within the basin. However, it is believed that the temperature increase will be more noticeable in the basin's low-lying, distinctly continental areas. Additionally, the anticipated increase in high temperatures is expected to lead to greater evaporation across the basin, potentially putting pressure on water resources.

As in the trend analysis results of annual TP data, MMK test and SR test give similar results in these analyses (Fig. 8).

The trend analysis results of the annual Tmin data reveal that a significant trend is observed at the majority of the 18 stations in the study area (Table 7). In particular, both the MMK and SR tests gave generally consistent results (Fig. 9). However, some differences between the two tests are also noteworthy. Significant trends were found at 15 stations according to the MMK test and 16 stations according to the SR test. This indicates that both tests support each other, but with minor differences. The stations where both tests found insignificant trends were S15 and S16. This indicates that there is no significant change in the annual minimum temperature data at these two stations. The only station with an insignificant trend according to the MMK test is station S2. The fact that the SR test finds a significant trend here suggests that there may be a methodological or data structure-specific difference. Just as maximum temperatures have, minimum temperatures across the basin are also showing an upward trend. This reflects a widespread climatic signal, despite the basin's varied topography. These increases are believed to be leading to more frequent warm nights in the southern part of the basin, which is characterised by low-lying, continental features. Conversely, this increase could have significant implications for agriculture and water resources, potentially leading to changes in evapotranspiration conditions, an extended growing season and fewer frosty days.

The results of the trend analysis applied to the annual TP, Tmax, and Tmin data from the 18 stations examined between 1965 and 2023 are summarized in Fig. 10, which allows for a spatial assessment of the analyses.

4.2. Change Point Detection

In order to perform change point detection analysis, annual data sets including Tmin, Tmax, and TP information were evaluated using statistical tests such as the PT SNHT, BRT and Von-Neumann Ratio test. The final findings showing the homogeneity of TP, Tmax and Tmin series are presented in Tables 8, 9 and 10, respectively. A visual representation of the historical series of climate variables,

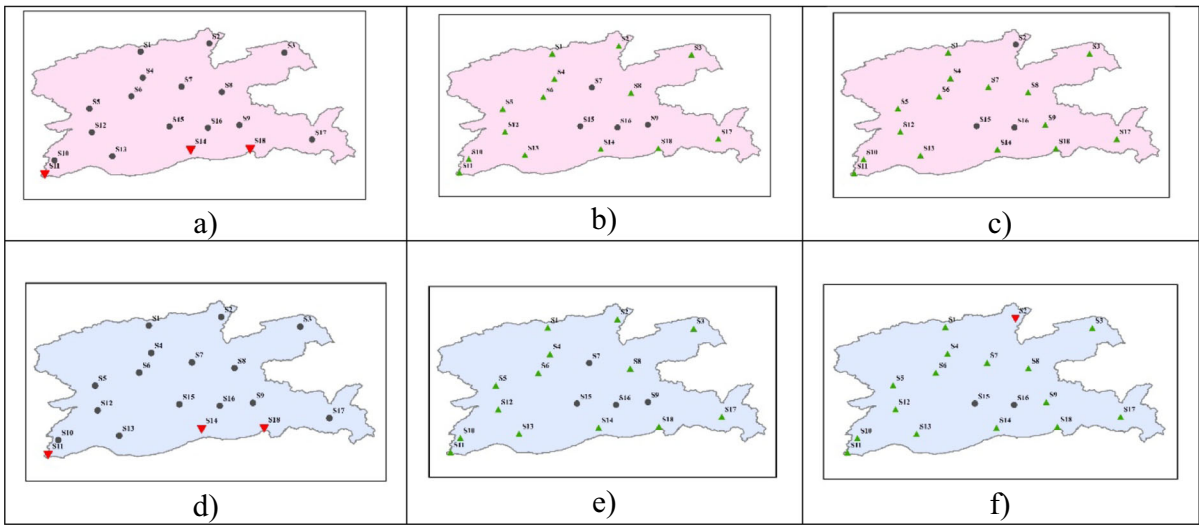


Figure 10
MMK result of **a** TP, **b** Tmax, **c** Tmin data, and SR result of **d** TP, **e** Tmax, **f** Tmin data

with discernible change points, if any, is depicted in Figs. S5, S6 and S7.

4.2.1 Precipitation (TP)

Table 8 provides an overview of the fluctuations in TP data of the stations in the study area and shows the changes on an annual basis. According to four change point detection methods, no change point could be determined in the TP data of 11 stations out of 18 stations. Different studies have identified different years as significant change points. This situation reveals that the sensitivity of different tests to change points may vary and the importance of applying more than one test in homogeneity analysis. Stations S4, S14 and S18 showed significant change in many tests and were finally categorised as 'CP' (Change Point). The analyses showed that there was a significant change point at these stations in 1968, 1989 and 1997 respectively. The fact that the change point has only been identified at these three stations indicates that the disruptions to the precipitation regime across the basin are limited and specific to individual stations, rather than representing a widespread and significant shift in the regime across the entire basin. These limited breaks in the annual precipitation data can be attributed to regional droughts and anomalies observed in the late 1980s and 1990s. They are also the result of natural climate variability and large-scale atmospheric circulation patterns, such as the Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Kadioglu et al., 1999; Keskin et al., 2024). Conversely, the significant results obtained from trend analysis tests at some stations where a break was observed suggest that the points of change identified by homogeneity tests are not statistically independent coincidences.

4.2.2 Maximum and Minimum Temperature (Tmax, Tmin)

Table 9 provides an overview of the fluctuations in Tmax data measured by the stations in the study area during the relevant period and shows the changes on an annual basis. According to the findings, no significant change was detected at 5 stations (Fig. S6). In the remaining 13 stations, change points were identified by various tests. The Pettitt test identified the years 1996, 1998 and 1999; the SNHT test identified the years 1978, 1998, 1999, 2010, 2014, 2015 and 2023 as important moments, while the BRT test identified the years 1997 and 1998 as important change points. Unlike precipitation, it is observed that the breaks in annual maximum temperature values are more widely distributed across the basin, with a particular cluster around the year 1998.

Table 8

Homogeneity tests for annual TP

CP test	PT				SNHT				BRT				Von-Neumann			Final result	
Station ID	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Nature	Year of shift
S1	146	0.325	No	–	5.618	0.237	No	–	3.116	0.985	No	–	1.958	0.431	No	**HG**	–
S2	158	0.451	No	–	3.808	0.509	No	–	4.049	0.884	No	–	2.130	0.692	No	**HG**	–
S3	281	0.290	No	–	5.137	0.284	No	–	8.768	0.101	No	–	1.650	0.092	No	**HG**	–
S4	224	0.733	No	–	36.219	**< 0.0001**	**Yes**	**1968**	10.819	**0.015**	**Yes**	**1970**	0.956	**0.000**	**Yes**	**CP**	**1968**
S5	280	0.294	No	–	7.504	0.089	No	–	10.425	**0.030**	**Yes**	**1989**	1.912	0.369	No	**HG**	**1989**
S6	170	0.603	No	–	7.016	0.152	No	–	5.535	0.573	No	–	1.723	0.146	No	**HG**	–
S7	174	0.660	No	–	5.124	0.299	No	–	5.361	0.604	No	–	1.655	0.092	No	**HG**	–
S8	204	0.973	No	–	6.069	0.173	No	–	6.118	0.451	No	–	1.530	**0.034**	**Yes**	**HG**	–
S9	250	0.493	No	–	6.067	0.166	No	–	7.986	0.169	No	–	1.573	0.057	No	**HG**	–
S10	162	0.518	No	–	3.617	0.524	No	–	4.103	0.871	No	–	2.022	0.538	No	**HG**	–
S11	264	0.393	No	–	5.057	0.281	No	–	6.637	0.350	No	–	2.030	0.554	No	**HG**	–
S12	180	0.741	No	–	6.362	0.145	No	–	5.442	0.595	No	–	1.994	0.499	No	**HG**	–
S13	228	0.684	No	–	5.361	0.260	No	–	5.506	0.567	No	–	2.018	0.537	No	**HG**	–
S14	428	**0.010**	**Yes**	**1989**	12.815	**0.003**	**Yes**	**1989**	13.624	**0.001**	**Yes**	**1989**	1.494	**0.026**	**Yes**	**CP**	**1989**
S15	174	0.663	No	–	5.822	0.187	No	–	4.642	0.772	No	–	1.940	0.408	No	**HG**	–
S16	208	0.907	No	–	9.912	**0.022**	**Yes**	**1970**	6.793	0.330	No	–	1.658	0.098	No	**HG**	**1970**
S17	220	0.780	No	–	5.871	0.230	No	–	6.261	0.414	No	–	1.460	**0.017**	**Yes**	**HG**	–
S18	394	**0.025**	**Yes**	**1997**	10.688	**0.012**	**Yes**	**1970**	12.106	**0.007**	**Yes**	**1997**	1.439	**0.013**	**Yes**	**CP**	**1997**

CP: Change point—A series could indicate the presence of a change point or demonstrate inhomogeneity if the null hypothesis is rejected by more than two tests at a significance level of 5%

HG: Homogenous—A series can be deemed homogeneous if, at a 5% significance level, either no test or just one out of four tests fails to reject the null hypothesis

Table 9

Homogeneity tests for annual Tmax

CP test	PT				SNHT				BRT				Von-Neumann			Final result	
Station ID	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Nature	Year of shift
S1	625	**< 0.0001**	**Yes**	**1999**	22.021	**< 0.0001**	**Yes**	**1999**	17.988	**< 0.0001**	**Yes**	**1998**	1.305	**0.003**	**Yes**	**CP**	**1999**
S2	541	**< 0.0001**	**Yes**	**1996**	17.033	**0.000**	**Yes**	**1998**	15.873	**0.000**	**Yes**	**1998**	1.543	**0.036**	**Yes**	**CP**	**1998**
S3	415	**0.014**	**Yes**	**1996**	13.858	**0.001**	**Yes**	**2015**	11.500	**0.012**	**Yes**	**1997**	1.488	**0.019**	**Yes**	**CP**	**2015**
S4	514	**0.001**	**Yes**	**1998**	18.091	**< 0.0001**	**Yes**	**2010**	15.508	**0.000**	**Yes**	**1998**	1.330	**0.004**	**Yes**	**CP**	**1998**
S5	488	**0.003**	**Yes**	**1998**	18.923	**< 0.0001**	**Yes**	**2014**	13.883	**0.001**	**Yes**	**1998**	1.698	0.123	No	**CP**	**1998**
S6	514	**0.001**	**Yes**	**1998**	18.091	**< 0.0001**	**Yes**	**2010**	15.508	**0.000**	**Yes**	**1998**	1.330	**0.004**	**Yes**	**CP**	**1998**
S7	146	0.317	No	–	3.106	0.679	No	–	5.065	0.676	No	–	1.983	0.477	No	**HG**	–
S8	434	**0.009**	**Yes**	**1998**	12.242	**0.007**	**Yes**	**1978**	12.884	**0.002**	**Yes**	**1998**	1.597	0.056	No	**CP**	**1998**
S9	357	0.066	No	–	5.661	0.262	No	–	9.151	0.080	No	–	1.711	0.135	No	**HG**	–
S10	520	**0.000**	**Yes**	**1998**	15.903	**0.000**	**Yes**	**1998**	15.338	**0.000**	**Yes**	**1998**	1.300	**0.004**	**Yes**	**CP**	**1998**
S11	391	**0.027**	**Yes**	**1998**	13.345	**0.040**	**Yes**	**2023**	11.339	**0.013**	**Yes**	**1998**	1.553	**0.042**	**Yes**	**CP**	**1998**
S12	504	**0.001**	**Yes**	**1998**	14.979	**0.001**	**Yes**	**1998**	14.886	**0.000**	**Yes**	**1998**	1.526	**0.032**	**Yes**	**CP**	**1998**
S13	623	**< 0.0001**	**Yes**	**1998**	20.370	**< 0.0001**	**Yes**	**1998**	17.359	**< 0.0001**	**Yes**	**1998**	1.503	**0.025**	**Yes**	**CP**	**1998**
S14	558	**0.000**	**Yes**	**1998**	16.704	**0.000**	**Yes**	**1998**	15.720	**< 0.0001**	**Yes**	**1998**	1.250	**0.001**	**Yes**	**CP**	**1998**
S15	303	0.198	No	–	4.826	0.335	No	–	8.449	0.127	No	–	1.825	0.251	No	**HG**	–
S16	240	0.573	No	–	3.655	0.569	No	–	6.139	0.443	No	–	1.634	0.079	No	**HG**	–
S17	353	0.069	No	–	6.365	0.200	No	–	8.752	0.107	No	–	1.656	0.089	No	**HG**	–
S18	414	**0.013**	**Yes**	**1998**	12.945	**0.003**	**Yes**	**2015**	11.291	**0.014**	**Yes**	**1998**	1.637	0.081	No	**CP**	**1998**

CP: Change point—A series could indicate the presence of a change point or demonstrate inhomogeneity if the null hypothesis is rejected by more than two tests at a significance level of 5%

HG: Homogenous—A series can be deemed homogeneous if, at a 5% significance level, either no test or just one out of four tests fails to reject the null hypothesis

Table 10

Homogeneity tests for annual Tmin

CP test	PT				SNHT				BRT				Von-Neumann			Final result	
Station ID	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Year of shift	Statistic	*P* value	Shift	Nature	Year of shift
S1	774	**< 0.0001**	**Yes**	**1996**	32.836	**< 0.0001**	**Yes**	**1996**	22.168	**< 0.0001**	**Yes**	**1996**	0.913	**< 0.0001**	**Yes**	**CP**	**1996**
S2	609	**< 0.0001**	**Yes**	**1987**	23.093	**< 0.0001**	**Yes**	**1987**	18.003	**< 0.0001**	**Yes**	**1987**	1.259	**0.002**	**Yes**	**CP**	**1987**
S3	706	**< 0.0001**	**Yes**	**1989**	29.059	**< 0.0001**	**Yes**	**1989**	20.515	**< 0.0001**	**Yes**	**1989**	1.281	**0.002**	**Yes**	**CP**	**1989**
S4	482	**0.001**	**Yes**	**1985**	16.463	**0.001**	**Yes**	**1985**	14.879	**0.000**	**Yes**	**1985**	1.490	**0.022**	**Yes**	**CP**	**1985**
S5	645	**< 0.0001**	**Yes**	**2003**	25.539	**< 0.0001**	**Yes**	**2004**	18.533	**< 0.0001**	**Yes**	**2004**	1.331	**0.005**	**Yes**	**CP**	**2004**
S6	440	**0.008**	**Yes**	**2003**	11.534	**0.007**	**Yes**	**2003**	12.597	**0.005**	**Yes**	**2003**	1.660	0.096	No	**CP**	**2003**
S7	464	**0.003**	**Yes**	**1990**	10.902	**0.037**	**Yes**	**2023**	12.561	**0.004**	**Yes**	**1990**	1.336	**0.007**	**Yes**	**CP**	**1990**
S8	547	**0.000**	**Yes**	**1998**	16.777	**0.003**	**Yes**	**1989**	15.588	**0.000**	**Yes**	**1989**	0.733	**< 0.0001**	**Yes**	**CP**	**1989**
S9	658	**< 0.0001**	**Yes**	**1989**	24.923	**< 0.0001**	**Yes**	**1989**	18.999	**< 0.0001**	**Yes**	**1989**	1.295	**0.002**	**Yes**	**CP**	**1989**
S10	803	**< 0.0001**	**Yes**	**1994**	36.766	**< 0.0001**	**Yes**	**1988**	23.151	**< 0.0001**	**Yes**	**1994**	0.645	**< 0.0001**	**Yes**	**CP**	**1994**
S11	794	**< 0.0001**	**Yes**	**1996**	34.232	**< 0.0001**	**Yes**	**1996**	22.634	**< 0.0001**	**Yes**	**1996**	0.742	**< 0.0001**	**Yes**	**CP**	**1996**
S12	639	**< 0.0001**	**Yes**	**1994**	22.481	**< 0.0001**	**Yes**	**2005**	18.288	**< 0.0001**	**Yes**	**1993**	1.205	**0.001**	**Yes**	**CP**	**1993**
S13	750	**< 0.0001**	**Yes**	**1994**	30.413	**< 0.0001**	**Yes**	**1994**	21.359	**< 0.0001**	**Yes**	**1994**	0.919	**< 0.0001**	**Yes**	**CP**	**1994**
S14	542	**0.000**	**Yes**	**1998**	17.301	**0.000**	**Yes**	**1998**	15.998	**0.000**	**Yes**	**1998**	1.439	**0.012**	**Yes**	**CP**	**1998**
S15	320	0.144	No	–	7.684	0.102	No	–	8.839	0.095	No	–	1.289	**0.001**	**Yes**	**HG**	–
S16	396	**0.023**	**Yes**	**1986**	12.777	**0.004**	**Yes**	**1980**	12.166	**0.007**	**Yes**	**1983**	0.909	**< 0.0001**	**Yes**	**CP**	**1980**
S17	431	**0.008**	**Yes**	**1998**	16.514	**0.000**	**Yes**	**2012**	13.014	**0.003**	**Yes**	**1998**	1.465	**0.019**	**Yes**	**CP**	**1998**
S18	700	**< 0.0001**	**Yes**	**2000**	30.866	**< 0.0001**	**Yes**	**2000**	21.143	**< 0.0001**	**Yes**	**2000**	0.956	**< 0.0001**	**Yes**	**CP**	**2000**

CP: Change point—A series could indicate the presence of a change point or demonstrate inhomogeneity if the null hypothesis is rejected by more than two tests at a significance level of 5%

HG: Homogenous—A series can be deemed homogeneous if, at a 5% significance level, either no test or just one out of four tests fails to reject the null hypothesis

1998 was recorded as a year of a very strong El Niño event on a global scale. It is believed that large-scale climate patterns, such as El Niño, have significant and complex effects on temperature, precipitation, and flow regimes in Türkiye. These extreme phases are thought to lead to shifts in climate variability.

Table 10 provides an overview of the fluctuation in the Tmin data measured by the stations in the study area during the relevant period and shows the changes on an annual basis. In line with the findings, all of the tests detected statistically significant change points at all stations except station S15 (Fig. S7). In some stations, different tests showed changes in different years. This indicates that there is a long-term change process at the station or that the sensitivity of different statistical tests is different. It can be seen that the breaks in minimum temperatures are spread throughout the period from 1985 to 2004, with notable clusters occurring in 1987–1989, 1993–1998 and 2003–2004. Since the early 1990s, hot and dry conditions have been spreading across Turkey, particularly in the inland regions including the Euphrates–Tigris basin (Tunç, 2025). In particular, the simultaneous increase in maximum temperatures observed at numerous stations around 1998, alongside the growing number of inflection points in minimum temperatures after the 1990s, can be largely attributed to regional warming and higher extreme temperature values. On the other hand, given that construction of the Atatürk Dam as part of the Southeastern Anatolia Project altered land cover, the water budget and the surface energy balance in the upper reaches of the basin from the early 1990s onwards, it is plausible that the shifts observed at some stations have been amplified by both regional climate change and project-induced local land use changes. In this context, the regional warming pattern in the Eastern Mediterranean, which is the main cause of temperature anomalies, and the secondary factors related to irrigation and the effects of reservoirs associated with the Southeastern Anatolia Project can be evaluated.

5. *Conclusion*

In this study, the results of trend analyses, including the MMK test, Sen's Slope estimator, and SR test, along with homogeneity tests, were evaluated for the annual TP, Tmax, and Tmin data from 18 meteorological stations in the Euphrates–Tigris Basin for the period 1965–2023. This study comprehensively evaluated long-term trends in meteorological parameters and detected critical shifts in precipitation and temperature patterns across the Euphrates–Tigris Basin, a region of strategic importance for Türkiye's water resources management.

The analyses indicate that, in general, no statistically significant trend was detected in the annual TP data across the study area. However, a statistically significant decreasing trend was observed at stations S11, S14, and S18. The decline in precipitation at these stations suggests potential alterations in the region's hydrological cycle, posing risks to the long-term sustainability of water resources. Homogeneity tests further identified significant breakpoints, particularly in the years 1989, 1994, and 1998, indicating major shifts in both precipitation and temperature series. These breakpoints suggest that the region's hydro-meteorological system is undergoing structural changes, likely influenced by broader climatic factors.

An examination of Tmax data reveals a statistically significant increasing trend at 14 out of the 18 stations. Similarly, trend analyses of Tmin data indicate an increasing trend in the vast majority (83–88%) of the stations. Rising temperatures, combined with largely stable or declining precipitation, indicate a growing meteorological imbalance that could significantly disrupt the seasonal distribution and long-term sustainability of water resources in the basin. Although no substantial changes were observed in precipitation amounts, the rising trends in maximum and minimum temperatures could have profound impacts on the hydrological cycle. Increasing temperatures may lead to higher potential

evapotranspiration, accelerating soil moisture loss and exacerbating drought effects, particularly during the summer months. This, in turn, could elevate plant water consumption, increase irrigation demands, and intensify pressure on water resources.

Furthermore, higher temperatures may accelerate snowmelt, leading to shifts in seasonal flow regimes. While earlier snowmelt could contribute to water abundance in spring, it may also result in reduced streamflows during summer. Consequently, both surface and groundwater recharge could be adversely affected, potentially causing water shortages in drinking water supplies and irrigation systems. In addition to its impacts on agriculture and water supply, the combined effect of rising temperatures and changing precipitation patterns could also lead to fluctuations in hydropower generation capacity, thereby posing further challenges for energy security in the region.

Rising temperatures also enhance atmospheric moisture retention, which may increase the frequency and intensity of extreme precipitation events and sudden floods. Simultaneously, prolonged dry periods may become more frequent, reinforcing drought tendencies. As a result, the spatial and temporal distribution of water resources in the region may become increasingly irregular. To mitigate the effects of rising temperatures, it is crucial to develop sustainable water management strategies, promote agricultural practices that encourage water conservation, and implement adaptation policies based on long-term climate projections. These findings emphasize the urgent need for basin-specific, adaptive water management strategies that integrate climate change projections, account for both regional and local drivers, and balance the competing demands of agriculture, drinking water supply, and energy production. Given the observed temperature increases and precipitation declines at specific stations, the establishment of climate change adaptation policies is of paramount importance. Efficient water resource management, the adoption of drought-resilient agricultural practices, and the development of strategies to mitigate urban heat island effects should be prioritized.

The observed increasing temperature trends in the study area indicate that the effects of climate change are significant at the regional scale. To gain a deeper understanding of how rising temperatures impact ecosystems, water resources, and agricultural production, future studies should conduct more detailed analyses, such as simulations of temperature changes under different greenhouse gas emission scenarios. The precipitation decline detected at stations S11, S14, and S18 is particularly critical for regional water resource management. To assess the impact of these trends on regional hydrology, it is recommended that basin-scale water balance and drought analyses be conducted. Furthermore, the varying breakpoints in Tmin trends across different stations suggest that local factors may play a significant role. Therefore, investigations into the influence of urbanization, industrialization, and land-use changes on temperature trends would be highly beneficial.

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Data Availability

The data that support the findings of this study were obtained from the Turkish State Meteorological Service. Restrictions apply to the availability of these data, which were used under permission for the current study and are therefore not publicly available.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval The paper has been submitted with full responsibility, following due ethical procedure, and there is no duplicate publication, fraud, plagiarism. None of the authors of this paper has a financial or personal relationship with other people or organizations that could inappropriately influence or bias the content of the paper.

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References

Achite, M., Caloiero, T., Wałęga, A., Ceppi, A., & Bouharira, A. (2024). Trend analysis of hydro-meteorological variables in the Wadi Ouahrane Basin, Algeria. *Hydrology, 11*, 77. https://doi.org/10.3390/hydrology11060077

Adamo, N., Al-Ansari, N., & Sissakian, V. K. (2020). Global climate change impacts on Tigris–Euphrates Rivers basins. *Journal of Earth Sciences and Geotechnical Engineering, 10*, 49–98.

Alexandersson, H. (1986). A homogeneity test applied to precipitation data. *Journal of Climatology, 6*, 661–675. https://doi.org/10.1002/joc.3370060607

Bozkurt, D., & Şen, Ö. L. (2013). Climate change impacts in the Euphrates–Tigris Basin based on different model and scenario simulations. *Journal of Hydrology, 480*, 149–161.

Buishand, T. A. (1982). Some methods for testing the homogeneity of rainfall records. *Journal of Hydrology (Amst.), 58*, 11–27. https://doi.org/10.1016/0022-1694(82)90066-X

Burn, D. H., Cunderlik, J. M., & Pietroniro, A. (2004). Hydrological trends and variability in the Liard River basin/Tendances hydrologiques et variabilité dans le basin de la rivière Liard. *Hydrological Sciences Journal, 49*, 53–67. https://doi.org/10.1623/hysj.49.1.53.53994

Burn, D. H., & Elnur, M. A. H. (2002). Detection of hydrologic trends and variability. *Journal of Hydrology, 255*(1–4), 107–122.

Buyukyildiz, M. (2023). Evaluation of annual total precipitation in the transboundary Euphrates–Tigris River Basin of Türkiye using innovative graphical and statistical trend approaches. *Applied Water Science, 13*, 38. https://doi.org/10.1007/s13201-022-01845-7

Ceribasi, G., & Aytulun, U. (2020). Investigation of the effect of climate change on precipitation and temperature data of Susurluk Basin and Van Lake Closed Basin. *International Journal of Global Warming, 22*, 54. https://doi.org/10.1504/IJGW.2020.110212

Ceribasi, G., & Ceyhunlu, A. I. (2021). Analysis of total monthly precipitation of Susurluk Basin in Türkiye using innovative polygon trend analysis method. *Journal of Water and Climate Change, 12*, 1532–1543. https://doi.org/10.2166/wcc.2020.253

Costa, A. C., & Soares, A. (2009). Homogenization of climate data: Review and new perspectives using geostatistics. *Mathematical Geosciences, 41*(3), 291–305.

Daggupati, P., Srinivasan, R., Ahmadi, M., et al. (2017). Spatial and temporal patterns of precipitation and stream flow variations in Tigris–Euphrates river basin. *Environmental Monitoring and Assessment, 189*, 50. https://doi.org/10.1007/s10661-016-5752-y

Devlet Su İşleri Genel Müdürlüğü (DSİ). (2023). 2023 Yılı Faaliyet Raporu.

Ergün, M., Beyza, F., Tuncer, G., & Sönmez, O. (2024). Küçük Menderes Havzasında Mann–Kendall Ve Şen'in Eğimi Yöntemleri Kullanılarak Meteorolojik Değişkenlerin Trend Analizi. *Karaelmas Fen Ve Mühendislik Dergisi, 14*, 1–12.

Frenken, K. (2009). *Irrigation in the Middle East region in figures AQUASTAT Survey—2008*. Food and Agriculture Organization of the United Nations (FAO).

Gajbhiye, S., Meshram, C., Mirabbasi, R., & Sharma, S. K. (2016). Trend analysis of rainfall time series for Sindh river basin in India. *Theoretical and Applied Climatology, 125*, 593–608. https://doi.org/10.1007/s00704-015-1529-4

Gilbert, R. O. (1987). *Statistical methods for environmental pollution monitoring*. Wiley.

Güçlü, Y. S., Şişman, E., & Yeleğen, M. Ö. (2018). Climate change and frequency–intensity–duration (FID) curves for Florya station, Istanbul. *Journal of Flood Risk Management, 11*, S403–S418. https://doi.org/10.1111/jfr3.12229

Gümüş V, & Yenigün K. (2006). Aşağı Fırat Havzası akımlarının trend analizi ile değerlendirilmesi. *Yedinci Uluslararası İnşaat Mühendisliğinde Gelişmeler Kongresi* (pp. 1-10), Yıldız Technical University, Istanbul, Türkiye.

Hamed, K. H., & Rao, A. R. (1998). A modified Mann–Kendall trend test for autocorrelated data. *Journal of Hydrology (Amst.), 204*, 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X

Helsel, D. R., & Hirsch, R. M. (1993). *Statistical methods in water resources*. Elsevier.

Hirsch, R. M., Slack, J. R., & Smith, R. A. (1982). Techniques of trend analysis for monthly water quality data. *Water Resources Research, 18*, 107–121. https://doi.org/10.1029/WR018i001p00107

İçağa, Y. (1994). *Analysis of trends in water quality using non-parametric methods*, Master's Thesis. Fen Bilimleri Enstitüsü.

Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate change 2021—The physical science basis*. Cambridge University Press. https://doi.org/10.1017/9781009157896

Jain, S. K., Kumar, V., & Saharia, M. (2013). Analysis of rainfall and temperature trends in northeast India. *International Journal of Climatology, 33*, 968–978. https://doi.org/10.1002/joc.3483

Joshi, G. S., & Shah, S. (2022). Trend analysis of hydro-meteorological parameters and influence of anthropogenic activities in lower Narmada river basin, India. *Physics and Chemistry of the Earth, Parts a/b/c, 126*, Article 103148. https://doi.org/10.1016/j.pce.2022.103148

Kadioglu, M., Tulunay, Y., & Borhan, Y. (1999). Variability of Turkish precipitation compared to El Nino events. *Geophysical Research Letters, 26*(11), 1597–1600. https://doi.org/10.1029/1999GL900305

Keskin, A. U., Kazembeigi, R., & Zeybekoglu, U. (2024). Evaluation of the relationships between atmospheric indices and rainfall intensities: Black Sea region Türkiye. *Regional Studies in Marine Science, 77*, Article 103627. https://doi.org/10.1016/j.rsma.2024.103627

Kundzewicz, Z. W., & Robson, A. J. (2004). Change detection in hydrological records—a review of the methodology/Revue méthodologique de la détection de changements dans les chroniques hydrologiques. *Hydrological Sciences Journal, 49*, 7–19. https://doi.org/10.1623/hysj.49.1.7.53993

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica, 13*, 245. https://doi.org/10.2307/1907187

Nazeri Tahroudi, M. (2025). Comprehensive global assessment of precipitation trend and pattern variability considering their distribution dynamics. *Scientific Reports, 15*, 22458. https://doi.org/10.1038/s41598-025-06050-5

Nicoll, K. (2010). Landscape development within a young collision zone: Implications for post-Tethyan evolution of the Upper Tigris River system in southeastern Türkiye. *International Geologiy Review, 52*, 404–422. https://doi.org/10.1080/00206810902951072

Oruc, S. (2021). Visual and statistical inference of hourly and sub-hourly extreme rainfall trends Central Anatolia, Turkey Case. *Acta Geophysica, 69*(1), 199–216. https://doi.org/10.1007/s11600-020-00512-2

Özdoğan, M. (2011). Climate change impacts on snow water availability in the Euphrates–Tigris basin, Hydrol Earth. *System Science, 15*, 2789–2803. https://doi.org/10.5194/hess-15-2789-2011

Partal, T., & Kahya, E. (2006). Trend analysis in Turkish precipitation data. *Hydrological Processes: An International Journal, 20*(9), 2011–2026.

Pettitt, A. N. (1979). A non-parametric approach to the change-point problem. *Applied Statistics, 28*, 126. https://doi.org/10.2307/2346729

Rao, A. R., Hamed, K. H., & Chen, H.-L. (2003). *Nonstationarities in hydrologic and environmental time series*. Springer.

Sa'adi, Z., Yusop, Z., & Alias, N. E. (2023). Long-term homogeneity and trend analysis of seasonality and extreme rainfall under the influence of climate change in Johor River basin, Malaysia. *Natural Hazards, 117*(2), 1813–1845. https://doi.org/10.1007/s11069-023-05930-1

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's Tau. *Journal of American Statistical Association, 63*, 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Sneyers, R. (1991). *On the statistical analysis of series of observations*. World Meteorological Organization.

Sonali, P., & Nagesh Kumar, D. (2013). Review of trend detection methods and their application to detect temperature changes in India. *Journal of Hydrology (Amst.), 476*, 212–227. https://doi.org/10.1016/j.jhydrol.2012.10.034

Theil, H. (1992). *A rank-invariant method of linear and polynomial regression analysis* (pp. 345–381). https://doi.org/10.1007/978-94-011-2546-8_20

Tunç, E. (2025). *Analysis and future projections of seasonal shifts in Türkiye* [Master Thesis]. Middle East Technical University.

Türkeş, M. (2013). İklim değişiklikleri: Kambriyen'den Pleyistosene, Geç Holosen'den 21. yüzyil'a. *Ege CoğRafya Dergisi, 22*, 1–25.

von Neumann J (1941). Distribution of the ratio of the meansquare successive difference to the variance. *Ann Math Stat 33*(3), 1187–1192.

Wagh, N., & Guhathakurta, P. (2023). Homogenizing monthly rainfall and temperature data series in Maharashtra & Goa. *Mausam, 75*, 17–34. https://doi.org/10.54302/mausam.v75i1.5886

Wijngaard, J. B., Klein Tank, A. M. G., & Können, G. P. (2003a). Homogeneity of 20th century European daily temperature and precipitation series. *International Journal of Climatology: A Journal of the Royal Meteorological Society, 23*(6), 679–692.

Wijngaard, J. B., Klein Tank, A. M. G., & Können, G. P. (2003b). Homogeneity of 20th century European daily temperature and precipitation series. *International Journal of Climatology, 23*, 679–692. https://doi.org/10.1002/joc.906

Yue, S., & Pilon, P. (2004). A comparison of the power of the t test, Mann–Kendall and bootstrap tests for trend detection/Une comparaison de la puissance des tests t de Student, de Mann–Kendall et du bootstrap pour la détection de tendance. *Hydrological Sciences Journal, 49*(1), 21–37.

Yue, S., Pilon, P., & Phinney, B. (2003). Canadian streamflow trend detection: Impacts of serial and cross-correlation. *Hydrological Sciences Journal, 48*, 51–63. https://doi.org/10.1623/hysj.48.1.51.43478

Yue, S., & Wang, C. (2004). The Mann–Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resources Management, 18*, 201–218. https://doi.org/10.1023/B:WARM.0000043140.61082.60

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