Non-monotonic trend analysis using Mann-Kendall with self-quantiles

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Abstract

Recently, climate change makes itself felt at increasing levels due to rising temperatures, irregular precipitation patterns and changing weather events. Although the frequently used Mann-Kendall (MK) method has disadvantages such as needing serial independence, it helps to detect monotonic trends to investigate climate change effects on a given time series. Climate change may have different features on different levels such as the lows and highs of a given time series, leading to non-monotonic trends. Innovative trend analysis (ITA) as an innovative trend analysis method detects non-monotonic trends, which MK cannot. In this study, MK method is improved to detect non-monotonic trends (non-monotonic MK) and applied for Murat River basin, a branch of Euphrates River, precipitation series at Bingöl, Muş, and Ağrı meteorological stations. Although classical MK method cannot detect any trend on the river basin, non-monotonic MK (NMK) method detects two important decreasing (increasing) trends on the low (high) values of Bingöl and Muş (Bingöl) stations. Also, stationarity analysis is applied through the statistical significance level concept for the river basin precipitation series using the NMK method. Bingöl station has a non-stationary precipitation series with a value of 3.07 and 95% confidence level, while Muş station has a remarkable value of 1.58, Ağrı station conserves its stationarity characteristic on the precipitation series. It is hoped that the newly developed NMK method will help to understand the effects of climate change on hydro-meteorological historical records and predict future events for more efficient hydraulic structure designs.

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Non-monotonic trend analysis using Mann-Kendall with self-quantiles

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Abstract: Recently, climate change makes itself felt at increasing levels due to rising temperatures, irregular precipitation patterns and changing weather events. Although the frequently used Mann-Kendall (MK) method has disadvantages such as needing serial independence, it helps to detect monotonic trends to investigate climate change effects on a given time series. Climate change may have different features on different levels such as the lows and highs of a given time series, leading to non-monotonic trends. Innovative trend analysis (ITA) as an innovative trend analysis method detects non-monotonic trends, which MK cannot. In this study, MK method is improved to detect non-monotonic trends (non-monotonic MK) and applied for Murat River basin, a branch of Euphrates River, precipitation series at Bingöl, Muş, and Ağrı meteorological stations. Although classical MK method cannot detect any trend on the river basin, non-monotonic MK (NMK) method detects two important decreasing (increasing) trends on the low (high) values of Bingöl and Muş (Bingöl) stations. Also, stationarity analysis is applied through the statistical significance level concept for the river basin precipitation series using the NMK method. Bingöl station has a non-stationary precipitation series with a z_{NMK} value of 3.07 and 95% confidence level, while Muş station has a remarkable z_{NMK} value of 1.58, Ağrı station conserves its stationarity characteristic on the precipitation series. It is hoped that the newly developed NMK method will help to understand the effects of climate change on hydro-meteorological historical records and predict future events for more efficient hydraulic structure designs.

Keywords: Climate change, Mann-Kendall, hydro-meteorology, trend, non-monotonic.

Introduction

Climate change affects hydro-meteorological events with increasing temperatures dependent on greenhouse gases level increments in the atmosphere. Hydro-meteorological series have trend components as well as random features. To calculate trends on a time series, linear regression analysis (Haan, 1977), Mann-Kendall (Kendall, 1975; Mann, 1945), Sen slope estimator (Sen, 1968), Spearman's Rho (Spearman, 1987), and lastly Şen innovative trend analyses (ITA) methods are used in the literature (Şen, 2012). Although Mann-Kendall (MK) method is the most widely used method in the literature, it has some restrictive assumptions such as normality and independence of time series variable. Dependent series may tend to give significant trend components in the MK method even if there is no trend (Bayazit and Önöz, 2007; Cox and Stuart, 1955; Hamed and Ramachandra Rao, 1998).

Non-monotonic trends (low and high values have different positive or negative trend directions in a time series) are lastly come into question with Şen ITA method (Şen-ITA). Some researchers (Alifujiang et al., 2021; Berhail et al., 2022; Dabanli et al., 2021; Şan et al., 2021; Saplıoğlu and Güçlü, 2022; Şişman and Kizilöz, 2021) claim that Şen-ITA method is superior to MK because of that MK method cannot detect non-monotonic trends on time series while Şen-ITA can. Research results support these claims using visual evaluations on a 1:1 graph. Also, Faulkner et al., (2020) examined flood flows in Great Britain using a non-stationary distribution, and MK methods, the non-stationary distribution is preferred at 68 out of 166 stations where MK cannot detect a trend. Nigussie and Altunkaynak, (2019) apply MK method to detect trends of extreme rainfall indices. Although the rainfall indices have increasing trends, MK method does not find significant trends even at 0.10 significance levels.

Under the light of increasing carbon content of the atmosphere, it is often questioned whether hydro-meteorological variables, whose trends are not classified as monotonic and non-monotonic, have stationary properties. This discussion cannot be conducted effectively without the aforementioned trend classifications. Some researchers argue that stationarity is dead and not valid for future event predictions (Khaliq et al., 2006; Milly et al., 2008; Vogel et al., 2011). The other researchers reject this idea and defend stationarity because it is more understandable and applicable (Bayazit, 2015; Lins and Cohn, 2011; Matalas, 2012; Montanari and Koutsoyiannis, 2014; Serinaldi and Kilsby, 2015). In the non-monotonic trend conditions, the explanations of the first research group are reasonable because non-monotonic trends distort distribution parameters of variables and estimation of these parameters is hard for future events. The comments of the second group are accepted for the monotonic trend conditions because monotonic trends change distribution parameters regularly and these changes can be guessed for future events and relatively easier than non-monotonic trend calculations. Non-monotonic trends cannot be detected by classical trend methods because there are different effects climatic impacts on low and high hydro-meteorological variables. Alashan, (2018) proposes non-stationary cumulative functions to forecast future hydro-meteorological events effectively. Generally, non-monotonic trends do not change total amount of hydro-meteorological variables. Burić and Doderović, (2021) stated that the climate of Podgorica (Montenegro) is getting more arid but total precipitation has not significant trends. Trends may not be a sign of non-stationarity (Oruc, 2021; Serinaldi et al., 2018).

In this study, classical MK method is revised to detect non-monotonic trends (NMK), which enables more effective use of the classical MK method. NMK method separately detects trends on low and high values of a time series according to statistical significance levels. The same method can group series as stationary and non-stationary using basic MK processes. It is a novel and helpful approach to detect distorted hydrologic series by the climate change.

Methodology

Mann-Kendall (MK) is a non-parametric method that cannot detect non-monotonic trends on hydro-meteorological data (Kendall, 1948; Mann, 1945). A new non-monotonic Mann-Kendall (NMK) method is launched in the literature to use the traditional MK effectively in this study. The revised method can be used simply to detect non-monotonic hidden trends in low and high values of a time series. NMK method has the following steps.

- A time series (X) is separated into two times sub-series such as low sub-series *(X_{low})* and high sub-series *(X_{high})* with a rank number. For example, a time series (X) consists of x_1, x_2, ……, and x_n. If x_1 is greater than the mean of the time series, it is classified as a high value otherwise a low value. This process is repeated throughout the time series (Figure 1).
- These low and high values are recorded into a low (X_{low}) and high *(X_{high})* sub-series with their rank numbers.
- If the low and high sub-series can be considered independent and thus the classical MK can be applied to these series. If they are dependent, pre-whitening, over-whitening, and variance correction can be applied despite some of their disadvantages.
- The data numbers of the low and high sub-series are n_l and n_h. MK test statistics, S_{low}, can be calculated with Eq. 1, where, $j > i$ and i from 1 to $n_l - 1$ and j from $i + 1$ to n_l. The sgn function in Eq. 2 represents the signal function. If $X_{low,j} > X_{low,i}$ then $sgn(X_{low,j} - X_{low,i}) = 1$, if $X_{low,j} < X_{low,i}$ then $sgn(X_{low,j} - X_{low,i}) = -1$, otherwise 0. The same processes are applied to the high sub-series and all series.

$$S_{low} = \sum_{i=1}^{n_l-1} \sum_{j=i+1}^{n_l} sgn(X_{low,j} - X_{low,i}) \qquad (1)$$

$$sgn(X_{low,j} - X_{low,i}) \begin{cases} 1 & for \quad X_{low,j} > X_{low,i} \\ -1 & for \quad X_{low,j} < X_{low,i} \\ 0 & for \quad X_{low,j} = X_{low,i} \end{cases} \qquad (2)$$

- According to H_0 null hypothesis, the expectation value of the S_{low} parameter is zero (Eq. 3). Variance of the S_{low} test statistics is given in Eq. 4. NMK standardized test statistics, z_{low}, is calculated according to Eq. 5. If an absolute standardized z_{low} value is bigger than tabulated z values (1.65, 1.96 or 2.58) according to certain confidence levels (90%, 95% or 99%) then there is an increasing or a decreasing trend and H_0, null hypothesis, is rejected.

$$E(S_{low}) = 0 \tag{3}$$

$$Var(S_{low}) = \frac{n_l(n_l-1)(2n_l+5)}{18} \tag{4}$$

$$z_{low} = \begin{cases} \frac{S_{low}-1}{Var(S_{low})} & if\ S_{low} > 0 \\ 0 & if\ S_{low} = 0 \\ \frac{S_{low}+1}{Var(S_{low})} & if\ S_{low} < 0 \end{cases} \tag{5}$$

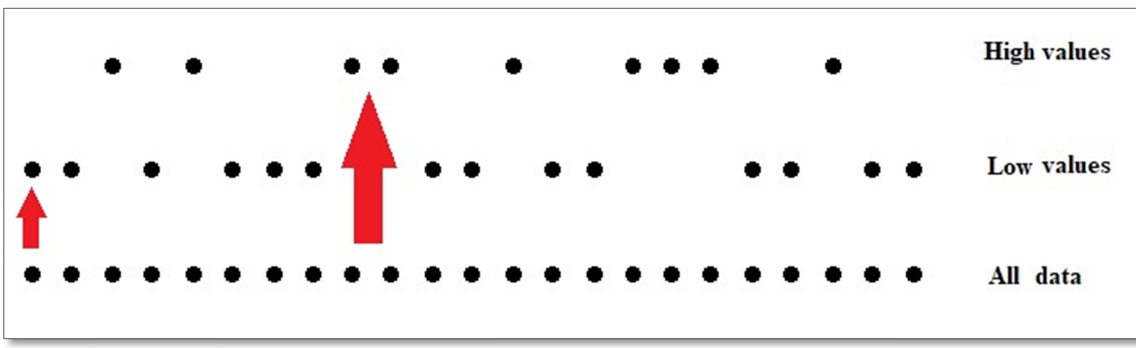

Figure 1 Separation of the main series into low and high sub-series to apply the non-monotonic MK method.

Although MK is a distribution-free test that is not affected by the true distribution of the data, the S parameter approaches the normal (Gaussian) probability distribution function (PDF) as the data length gets larger (Alashan, 2020; Hamed, 2009; Kendall and Gibbons, 1990). In the non-monotonic Mann-Kendall (NMK) method, there are two S parameters such as S_{low} and S_{high}. According to MK method, the null hypothesis, H_0, is accepted when S_{low} and S_{high} are close to zero. Thus, here is no trend and the mean of examined data is almost constant.

If the values of S_{low} and S_{high} are sufficiently different from the zero then there is a trend and the null hypothesis is rejected. For $S_{low} \approx S_{high}$, the mean of the dataset changes but the variances are almost constant. This situation is called as the stationary process and the distribution of data is similar to the previous one.

If the values of S_{low} and S_{high} are statistically different from zero and each other, thus the mean and variance of data change and the dataset is non-stationary. If the values of S_{low} and S_{high} have opposite signs, close to each other and sufficiently different from zero ($S_{low} \approx -S_{high}$), then there is sometimes no monotonic trend on the dataset and MK cannot detect non-monotonic trends. Non-stationary conditions are valid for the dataset, and the distribution of the data changes over time. MK should be modified to detect non-stationary situations and calculate non-monotonic trends on a given time series.

In the stationary conditions, the values of S_{low} and S_{high} must be close to each other ($S_{high} - S_{low} \approx 0$). Non-monotonic trend conditions are valid when the values of $S_{high} - S_{low}$ increase. To overcome this problem, a new test statistic (z_{NMK}) must be launched for MK method. As a main rule, if the S_{low} and S_{high} parameter values have a normal PDF separately then the sum and difference of these parameters must also have a normal PDF (Cramér, 1936). According to this rule, the z_{NMK} parameter has a normal PDF and can be calculated according to Eq. 6. If the calculated z_{NMK} values are bigger than tabulated z values (1.65, 1.96, and 2.58) according to statistical confidence levels (90%, 95%, or 99%), then there is a non-monotonic trend in the dataset. For the first time, this approach (NMK) allows us to detect non-monotonic trends in time series data using the MK method.

$$z_{NMK} = \frac{S_{high} - S_{low}}{\sqrt{Var(S_{high}) + Var(S_{low})}} \tag{6}$$

Study Area and Application

In this study, the Murat River is selected as the study area (Figure 2). It is a branch of the Euphrates River and located in eastern Turkey. The river basin ranges from northeastern to southwestern and has approximately 28,850 km^2 area (Günek, 2011). The elevation of the river basin changes from 819 m to 4,038 m above mean sea level with a 1,834 m average altitude (Alashan et al., 2016).

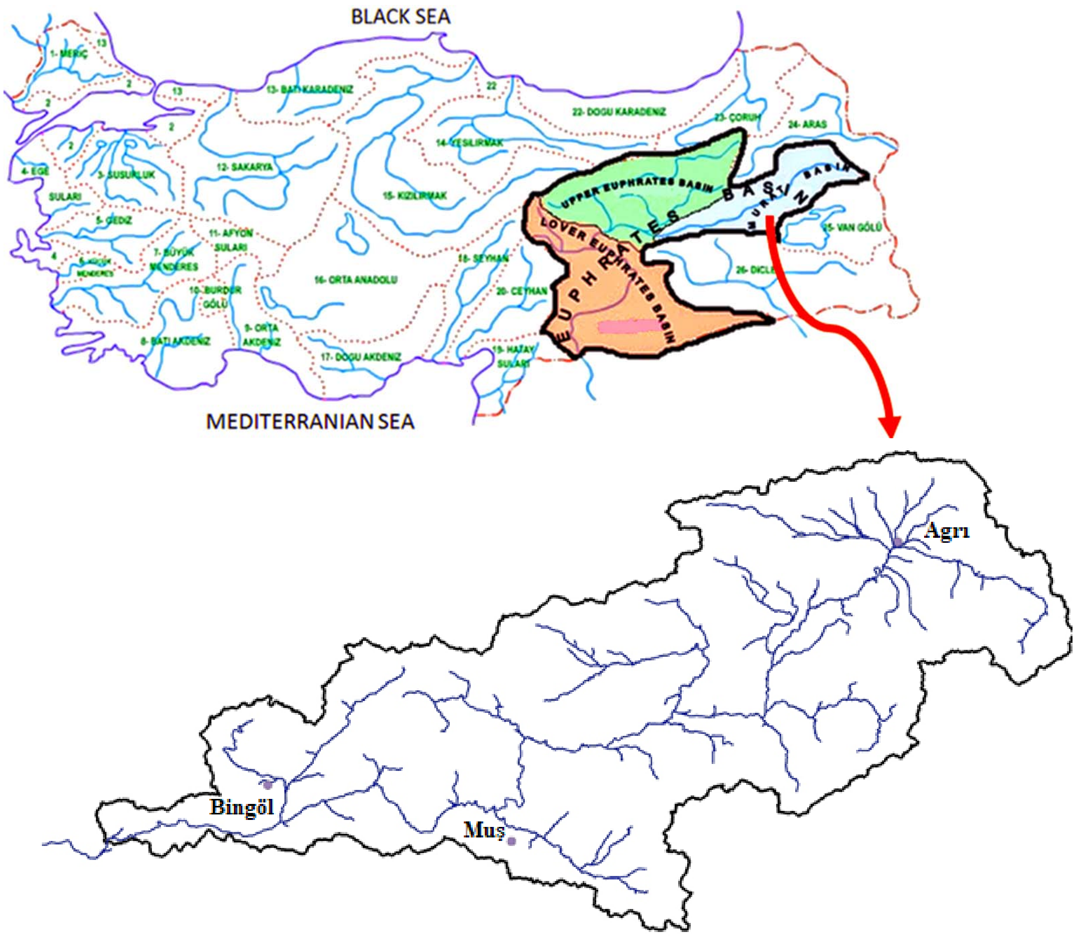

Figure 2 The map of the study area (Murat River Basin).

The dataset used in this study on a 0.5°x0.5° grid produced by the University of East Anglia Climate Research Unit (CRU) is taken from the World Bank Group, Climate Change Knowledge Portal (https://climateknowledgeportal.worldbank.org/download-data). The observed dataset covers the period 1901-2020 and quality controlled (Harris et al., 2020). Statistical features of the selected stations are given in Table 1.

Table 1. Statistical parameters of the selected stations annual total precipitation (mm)

Stations	Latitude	Longitude	Observed Years	Minimum (mm)	Mean (mm)	Maximum (mm)	Standard deviation (mm)	Skewness
Bingöl	38°53'N	40°29'E	1901-2020	505.24	765.38	1146.13	112.08	0.54
Muş	38°44'N	41°30'E	1901-2020	469.10	703.34	1030.56	105.53	0.40
Ağrı	39°43'N	43°02'E	1901-2020	318.93	514.68	743.41	82.12	0.32

MK and NMK methods are conducted to determine trends on precipitation series of the Murat River basin at Bingöl, Muş, and Ağrı stations. According to MK results, there is no monotonic trend at the 90% confidence level at all stations (Table 2). Ağrı has a positive z value (0.60), Bingöl and Muş have negative z values (-0.44 and -0.41). All z values are smaller than ±1.65 and there is no monotonic trend even at the 90% confidence level.

NMK method gives important decreasing trends ($z_{low} > 1.96$) on low sub-series of Bingöl and Muş stations and increasing trend ($z_{high} > 1.65$) on high sub-series of Bingöl station. There is no non-monotonic trend on the high series of Muş station ($z_{high} = 0.00$). Ağrı station has no monotonic or non-monotonic trend on main, low, and high series ($z = 0.60$, $z_{low} = -1.40$, and $z_{high} = -0.04$).

NMK method can also detect whether a time series is stationary (Table 2). Among the three stations, only Bingöl station has lost stationarity at the 95% confidence level ($z_{NMK} = 3.07$). Positive z_{NMK} values represent an increase in the variance of the precipitation series.

Table 2 Mann-Kendall test results for Precipitation Series of Murat River Basin

Mann-Kendall for all series

Stations	Data length (n)	Test statistics, S	$Var(S)$	Standard test statistics, z	Significance level	Tabulated test statistics, z_{tab}	Decision
Bingöl	120	-194	194367	-0.44	90%	±1.65	No trend
Muş	120	-178	194367	-0.41	90%	±1.65	No trend
Ağrı	120	264	194367	0.60	90%	±1.65	No trend

Non-monotonic Mann-Kendall for low series

Stations	Data length (n)	Test statistics, S_{low} $(Eq. 1)$	Var (S_{low}) $(Eq. 4)$	Standard test statistics, z_{low} $(Eq. 5)$	Significance level	Tabulated test statistics, z_{tab}	Decision
Bingöl	61	-390	25823	-2.43	95%	±1.96	Important decreasing trend
Muş	59	-351	23384	-2.30	95%	±1.96	Important decreasing trend
Ağrı	64	-240	29792	-1.40	90%	±1.65	No trend

Non-monotonic Mann-Kendall for high series

Stations	Data length (n)	Test statistics, S_{high} $(Eq. 1)$	Var (S_{high}) $(Eq. 4)$	Standard test statistics, z_{high} $(Eq. 5)$	Significance level	Tabulated test statistics, z_{tab}	Decision
Bingöl	59	291	23384	1.90	90%	±1.65	Increasing trend
Muş	61	1	25823	0.00	90%	±1.65	No trend
Ağrı	56	-4	20020	-0.04	90%	±1.65	No trend

Non-monotonic Mann-Kendall for stationarity test

Stations	Test statistics, S_{low} $(Eq. 1)$	Test statistics, S_{high} $(Eq. 1)$	Var (S_{low}) $(Eq. 4)$	Var (S_{high}) $(Eq. 4)$	Standard test statistics, z_{NMK} *(Eq.6)*	Tabulated test statistics, z_{tab}	Decision
Bingöl	-390	291	25823	23384	3.07	±1.96	Non-Stationary
Muş	-351	1	23384	25823	1.58	±1.65	Stationary
Ağrı	-240	-4	29792	20020	1.05	±1.65	Stationary

Although the Muş station has a noteworthy z_{NMK} value of 1.58, it does not exceed the critical z_{tab} value of 1.65 at the 90% confidence level and therefore has stationarity. The minimum z_{NMK} value of 1.05 is calculated at the Ağrı station. To visualize non-monotonic trends on Murat River Basin (Euphrates) low and high precipitation series and calculate trend slopes, quantiles linear regression method (LR) is used as in Figure 3 to calculate trend slopes at different intervals (Solaimani, 2022).

As in Figure 3, Bingöl station has an important increasing trend (0.37 mm/year) on high precipitation series and decreasing trend (-0.52 mm/year) on low series. These values fit NMK method but MK gives no trend on all series. Muş station has an insignificantly increasing trend (0.01 mm/year) on the high series and an important decreasing trend (-0.43 mm/year) on the low series, which is detectable by NMK method ($z_{low} = -2.30$ and $z_{high} = 0.00$). There is an insignificantly increasing trend (-0.07 mm/year) on the high series although a noteworthy decreasing trend (-0.21 mm/year) exists on the low series of Ağrı station. NMK method results for Ağrı station are again consistent with quantiles linear regression ($z_{low} = -1.40$ and $z_{high} = -0.04$).

Two parameter Gamma PDF is fitted to precipitation series at Bingöl, Muş, and Ağrı stations to compare stationarity between the first period (1901-1960, blue line) and the second period (1961-2020, red line) (Figure 4). Even though the probabilities of low and high values increase in Bingöl station, the probabilities of middle values decrease. The shape of the Bingöl precipitation distribution changes and accordingly the series loses its stationarity ($z_{NMK} = 3.07$).

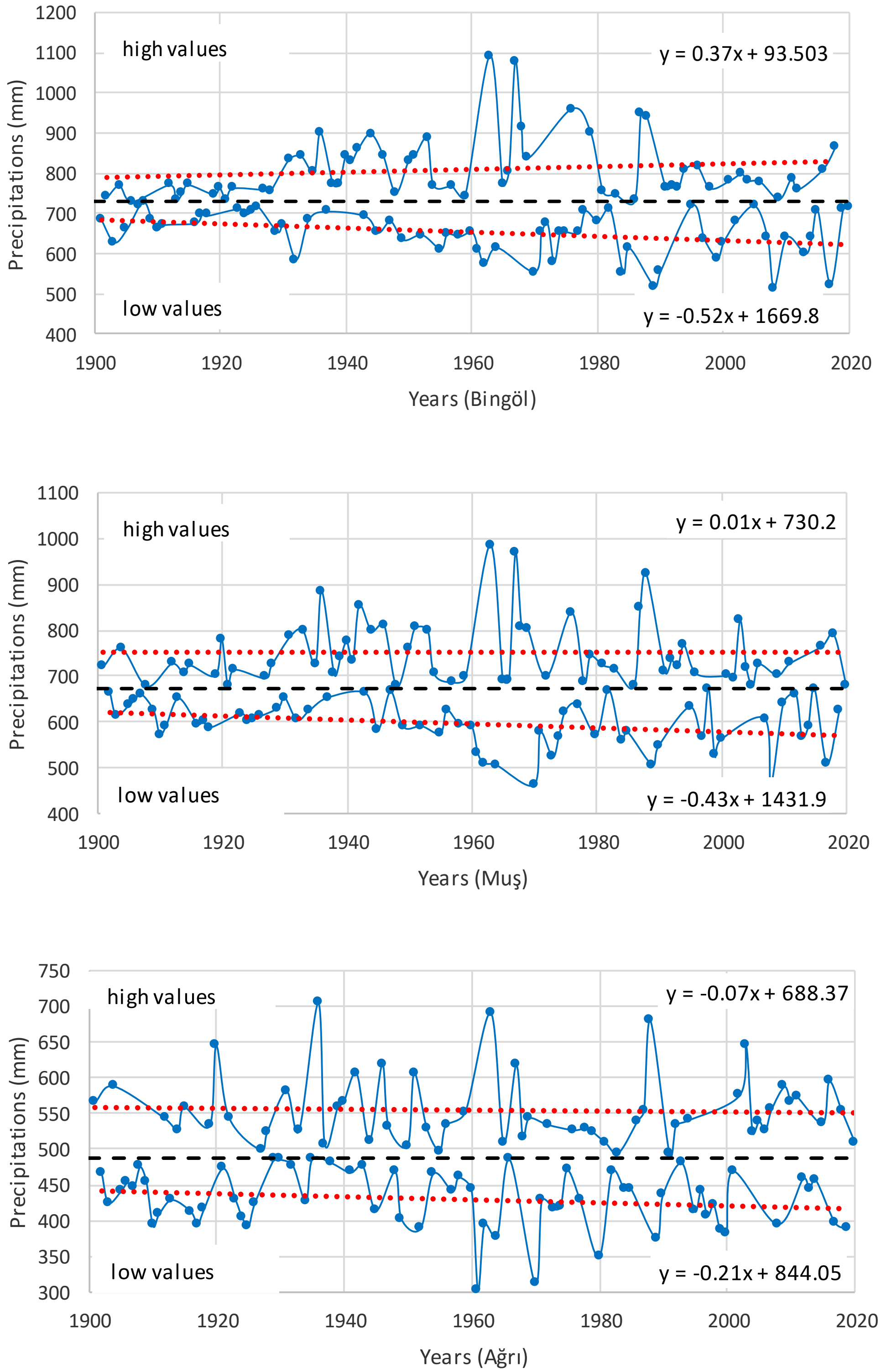

Figure 3 The application of quantiles linear regression method for selected precipitation stations on the Murat River basin.

There is a minor change in the probability of Muş station precipitation high values although there is an important increase in low values probabilities ($z_{low} = -2.30$). The stationarity of the precipitation series at Muş station is considerable with a z_{NMK} value of 1.58. Ağrı station maintains stationarity ($z_{NMK} = 1.05$) but there is a remarkable increase in low precipitation probabilities ($z_{low} = -1.40$).

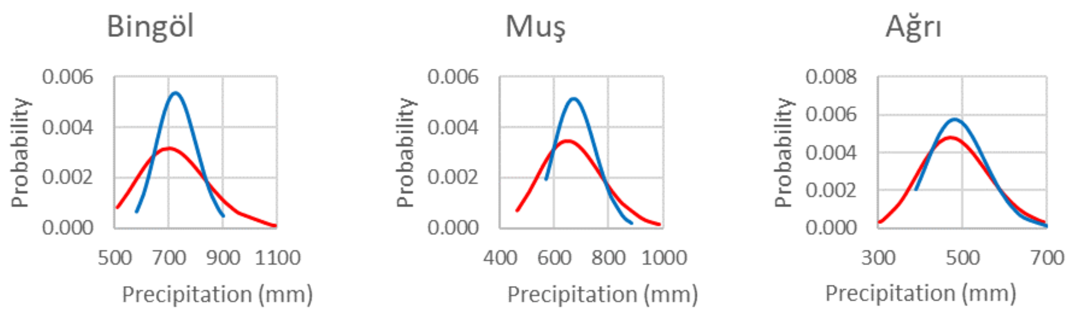

Figure 4 Gamma PDFs of precipitation series at selected stations (Blue lines represent the period 1901-1960, and red lines represent the period 1961-2020).

To double-check the stationarity of precipitation series at Bingöl, Muş, and Ağrı stations and compare those between the 1901-1960 and 1961-2020 periods, the Gamma cumulative distribution functions (CDF) are drawn in Figure 5. The CDF values for the periods 1901-1960 and 1961-2020 are shown on the left side of this figure and the comparison of these cumulative probability values with each other is on the right side. As in Figure 4, although the cumulative probabilities of low values are increasing, the cumulative probabilities of high values are decreasing between the 1921-1960 and 1961-2020 periods. The CDF probability values indicate that a certain probability value or a smaller value will occur. Therefore, while the probability of the resulting values being lower than the low values increases, the probability of the resulting values being lower than the high values decreases, or the risk of the resulting values being higher than the high values increases.

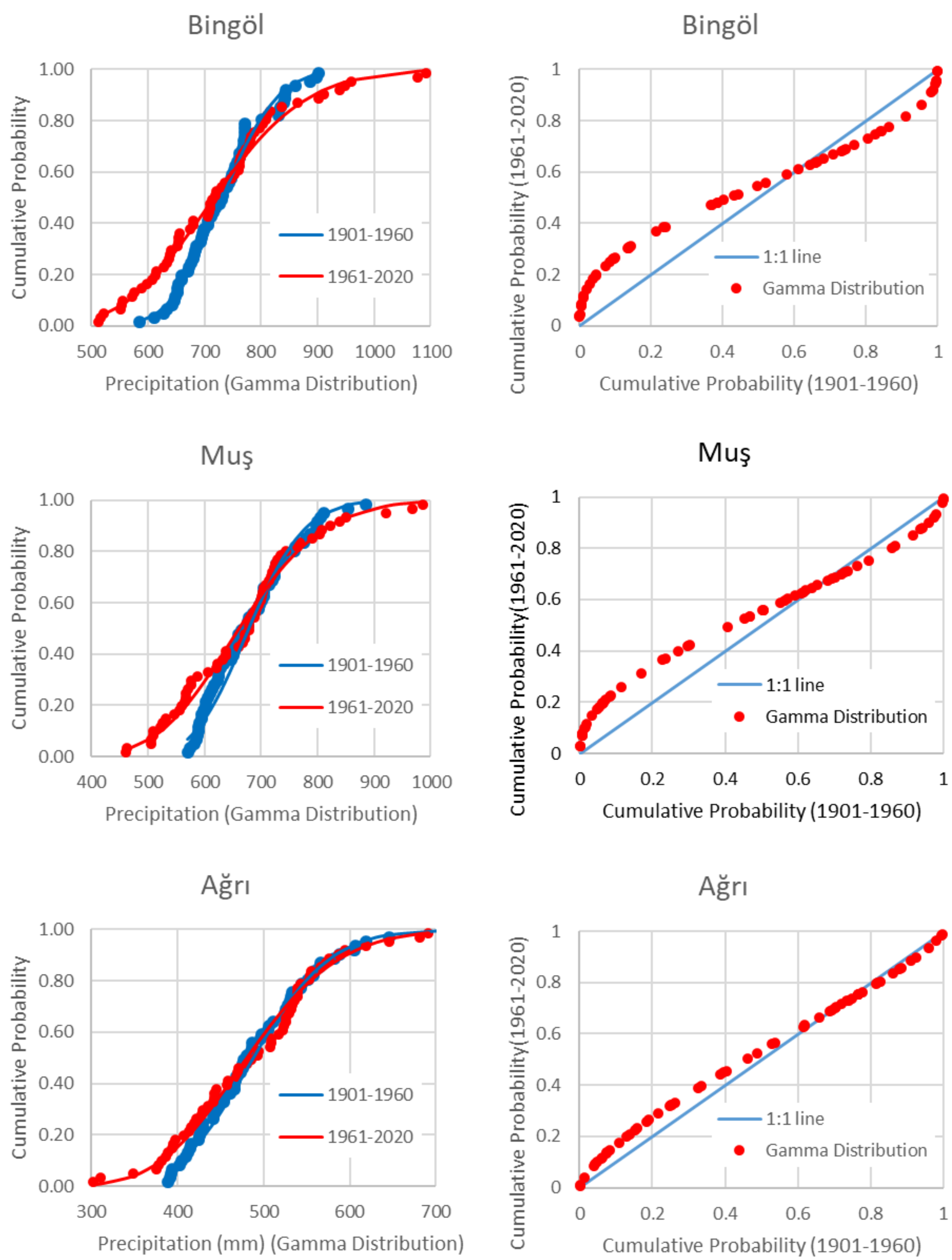

Figure 5 Gamma CDFs of precipitation series and comparison of these values between 1921-1960 and 1961-2020 periods at selected stations.

Accordingly, the recurrence times of droughts and floods are expected to decrease. The differences between the CDF probability values for the 1921-1960 and 1961-2020 periods of Bingöl station ($z_{NMK} = 3.07$) are bigger than those of Muş station with z_{NMK} value of 1.58 (Figure 5). Ağrı station ($z_{NMK} = 1.05$) has no important differences between cumulative probability values between 1921-1960 and 1961-2020 periods as in the figure. The probability of low and high values increases because all z_{NMK} values are positive.

Results and Discussion

Classical MK is frequently used in the literature to detect monotonic trends on hydro-meteorological parameters, despite some restrictive assumptions such as independent time series and normality of test statistics. MK method cannot detect non-monotonic trends that have different effects on low and high values of a given time series. In this study, MK method is improved to detect non-monotonic trends and investigate whether a given time series is stationary. Non-monotonic Mann-Kendall (NMK) is applied in addition to MK and quantiles linear regression to detect trends on precipitation series at Bingöl, Muş, and Ağrı stations of the Murat River basin.

Classical MK cannot detect any trend on all the stations but NMK method gives two important decreasing trends on low values of the precipitation series at Bingöl and Muş stations and one increasing trend on high values of the precipitation series at Bingöl station. Ağrı station has a neither monotonic nor non-monotonic trend on the precipitation series. Quantiles linear regression yields consistent results with NMK method. There are trend slope values of -0.52 mm/year ($z_{low} = -2.43$) and -0.43 mm/year ($z_{low} = -2.30$) for low values of Bingöl and Muş precipitation series. There is also a 0.37 mm/year ($z_{high} = 1.90$) trend slope value for high values of the Bingöl precipitation series. Ağrı station has small trend slopes on the precipitation series such as -0.07 mm/year ($z_{high} = -0.04$) on high values and -0.21 mm/year ($z_{low} = -1.40$) on low values and again it is consistent with NMK method.

To investigate stationarity on the all precipitation series, NMK method gives non-stationarity for only the Bingöl precipitation series ($z_{NMK} = 3.07$), which has an important trend on the low values and an increasing trend on the high values. Although Muş has a considerable z_{NMK} value of 1.58, Muş and Ağrı precipitation series are stationary. It is consistent with NMK values, because Muş has only important decreasing trend on the low values and the Ağrı precipitation series ($z_{NMK} = 1.05$) has no trend. Positive z_{NMK} values represent increasing serial variance and uncertainty on the precipitation series of the Murat River.

Non-monotonic trends cannot be detected by classical methods, but NMK method is helpful to detect non-monotonic trends and enables better prediction of future events and support more efficient design procedure for hydraulic structures. The positive z_{NMK} values found for the Murat River basin indicate that lower values than the low (drought) values and higher values than the high (flood) values of the precipitation series are expected to emerge more frequently in the future.

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