Water Resources Management (2026) 40:164
https://doi.org/10.1007/s11269-026-04542-1

Structural Trend and Variability Identification (STVI) Method

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Received: 19 May 2025 / Accepted: 6 February 2026 / Published online: 25 February 2026
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Abstract
This paper proposes an effective internal dynamic trend analysis method based on the mean and standard deviation as variability trends, providing additional information about the tendency of fluctuations around mean values. The novel method, called Structural Trend and Variability Identification (STVI), can identify a range of trends over different time periods in a given time series. To illustrate the proposed methodology, classical linear trends in the mean values and standard deviations (variability) for 10-year and 30-year identifications are given as examples, based on lag-shifting mechanism. A rea-world application of the STVI approach is given for annual Danube River discharge measurements over 160-year period from 1850 to 2010. Cumulative distribution functions (CDF) of trend slopes fitting Weibull and Pearson's theoretical probability distribution function (PDF) are presented. CDFs offer opportunities for trend slope risks based on a range of return periods such as 2-year, 5-year, 10-year, 25-year and 50-year.

Keywords Innovative · Piecewise · Probability · Risk · Structural · Trend · Slope · Variability

1 Introduction

In water resources management, historical records and structural behaviors play the most fundamental role in making predictions for the future (Schramm and Schramm 2018). It is now well known that water structures are subject to successive flood and drought events as a result of the effects of climate change due to the spread of greenhouse gas (GHG) emissions into the troposphere (Sivakumar 2011; Mallakpour and Villarini 2016). Besides the random component, each hydro-meteorology time series may include trend on the mean and standard deviation (variability), and there are several methodologies proposed by different authors (Mann 1945; Kendall 1975; Sen 1968; Haan 1977; Yue and Wang 2004; Almazroui

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and Şen 2020). Until about thirty years ago, it was assumed that the future behavior of a hydro-meteorological time series was a reflection of the past characteristics, especially under the assumption of stationarity or at least second order stationarity. Milly et al. (2008) suggested that hydro-meteorological time series no longer possess the stationarity property, but rather exhibit non-stationarity characteristics. Therefore, the future characteristics of a time series can exhibit different features, particularly in the form of mean and standard deviation (variability) trends. In this vein, many researchers have presented various methodologies to capture these non-stationarity characteristics (Gocic et al., 2013; Zang and Liu 2013; Han et al. 2014; Yang et al. 2017; Li et al. 2017; Toride et al. 2018; Phuong et al. 2022; Dubey et al. 2023). Almost of all these researches relies on monotonic trends identification on the mean values only.

As a departure from classical mean trend analysis methodologies Innovative Trend Analysis (ITA) was presented, which provides visually and numerically increasing or decreasing trends with a simple scatter of ascending order records of two equal half series generated from the original time series (Şen 2012; 2014). This methodology found a wide range of applications in the literature by many researchers (Haktanir and Çıtakoğlu, 2014; Markus et al. 2013; Onyutha 2016; Wu and Qian 2017; Elouissi et al. 2016). On the other hand, many researchers have presented a comparison of classical methodologies with the ITA approach in different regions of the world (Gedefaw et al. 2018; Wu and Qian 2017; Cui et al. 2017; Dorjsuren et al. 2018; Ahmad et al. 2018; Pingale et al. 2014; Chowdhury et al. 2015; Martínez-Austria et al. 2016). In addition, partial monotonic trend analysis can be performed by considering different lengths within the given time series starting from the first observation, for record lengths of at least for 30-year or longer (Öztopal and Şen 2017). Mohorji et al. (2017) considered dividing the time series into 3, 4, 5, 6, 11 and 13 parts and presented comparison results with the whole monotonic trend. Güçlü (2018) proposed different versions of ITA to identify and demonstrate trend stability.

This paper proposes a qualitative and quantitative assessment procedure for a set of mean and variability trends in long-term annual discharge records of the Danube River, enabling the identification of lag-one overlapping and non-overlapping 10-year and 30-year trends. For this purpose, a new version of the ITA, the structural trend and variability identification (STVI) methodology, is proposed, along with detailed applications and comparisons. This new methodology is compared with the classical MK trend test (Mann 1945; Kendall 1975) supported by Sen (1968) trend median slope calculations.

2 Structural Trend and Variability Slope Methodology

As recommended by World Meteorological Organization (WMO 2017), climatic and meteorological data with a base period of at least 30 years can be investigated for the possibilities of the existence of structural mean and standard deviation (variability) trends over shorter periods, such as 10-year base period. For risk assessments, return periods 5-year (20%), 10-year (10%), 20-year (5%), 25-year (4%), 50-year (2%) and 100-year (1%) are considered.

In general, any given time series, $X_1, X_2,..., X_n$, has three components as trend, periodicity and stochastic part. The main topic in this paper is the trend component, which is often

defined as a holistic trend over the entire time series record length. The STVI methodology helps to identify the following three conditions.

a) According to the ITA methodology, determining the holistic trend in a time series depend on two halves, as described by Şen's (2012; 2017) application. Let these two halves be $X_1, X_2,..., X_{n/2}$ and $X_{n/2+1}, X_{n/2+2},..., X_n$,
b) Time series can be divided into non-overlapping 10-year segments such as $X_1, X_2,..., X_{10}$; $X_{11}, X_{12},..., X_{20}$; $X_{21}, X_{22},..., X_{30}$;..; $X_{n-9}, X_{n-8},..., X_n$,
c) Non-overlapping 30-year segments such as, $X_1, X_2,..., X_{30}$; $X_{31}, X_{32},..., X_{60}$; $X_{61}, X_{62},..., X_{90}$;..; $X_{n-29}, X_{n-28},..., X_n$ may also have mean and variability trends for each segment.

According to the ITA formulation, for any period, e.g., m, the mean trend slope, S_{Tm}, can be written as the difference:

$$S_{T_m} = \frac{M\left(X_{m/2+1:m}\right) - M\left(X_{1:m/2}\right)}{m/2} \qquad (m = 2,\ 3,\ \ldots,\ n) \tag{1}$$

Here $M(X_{m/2+1:m})$ and $M(X_{1:m/2})$ are the mean values for the second part from m/2 + 1 to m, and first half from 1 to m/2, respectively. This mathematical expression can be based on the median values as suggested by Sen (1968) for slope calculation. The determination of partial trend slopes can be found by following steps below.

a) Calculation of the holistic or partial time periods such as 10-year and 30-year periods,
b) Determination of two time points as in Fig. 1, for example, for an m-year trend, these time-midpoints are m/4 and 3 m/4 (see Fig. 1).
c) For a monotonic trend, the time series record value points are $M\left(X_{m/2+1:m}\right)$ and $M\left(X_{1:m/2}\right)$. Connecting $[m/4;\ M\left(X_{1:m/2}\right)]$ with $[m/4; M\left(X_{m/2+1:m}\right)]$ with a straight-line gives increasing, decreasing or no trendless lines.

d) The slope, S_{V_m}, of variability trend can be written as Eq. (1) by considering the standard deviation, σ (.) values as follows.

$$S_{V_m} = \frac{\sigma\left(X_{\frac{m}{2}+1:m}\right) - \sigma\left(X_{1:m/2}\right)}{m/2} \qquad (m = 2,\ 3,\ \ldots,\ n) \tag{2}$$

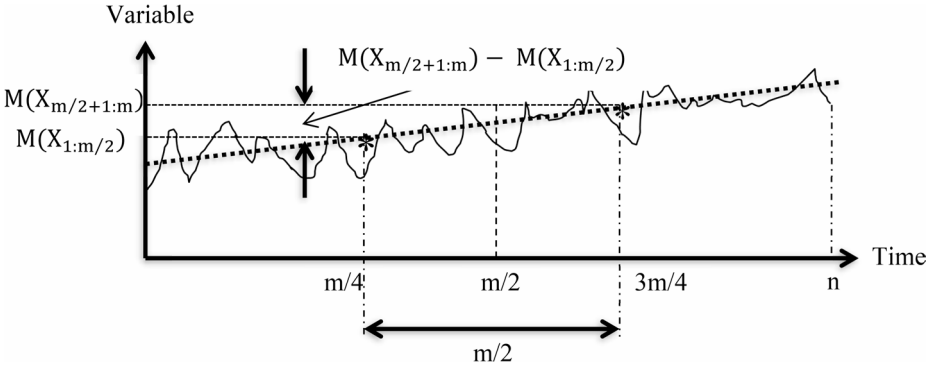


Fig. 1 Trend position determinations

3 Applications

The annual discharge series of the Danube River, Orshava station, Romania with its long record of 160 years from 1840 to 2010, is considered for application. Lag-one overlapping and non-overlapping trends for 10-year and 30-year periods with successive shifts are considered.

3.1 Lag One Overlapping 10-Yearly Trend Slopes and Variability

Figure 2 shows the application of the STVI method for the mean trend slope application according to Eq. (1) and classical Mann-Kendall (MK) trend component based on Sen (1968) slope calculation procedure. The variation of the annual trend values follows each other within an error band of less than $\pm 5\%$. In addition, high or low discharge events occur in extreme slope changes.

On the other hand, based on the standard deviation (variability) of the STVI method, Fig. 3 shows the overlapping annual variability slopes.

As can be seen from this figure, the Danube River records show decreasing variations annually over 10-year periods. In general, the impact of climate change is interpreted in the literature based on holistic monotonic mean trend values, but this example effectively demonstrates the trend in the standard deviation (variability) property as supportive evidence for classical trend concepts.

3.1.1 10-Year Non-Overlapping Trend and Variability Slopes

Furthermore, Fig. 4a shows the successive calculation of 10-year trends over non-overlapping periods. There are 9 increasing and 7 decreasing partial trends. In general, decreasing

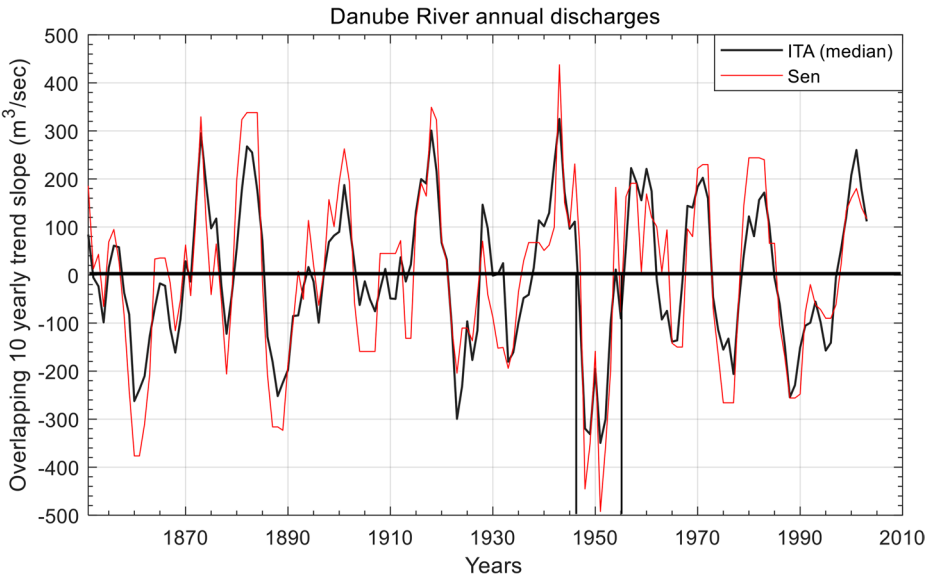


Fig. 2 Overlapping 10-yearly Sen and STVI trend slopes based on median values

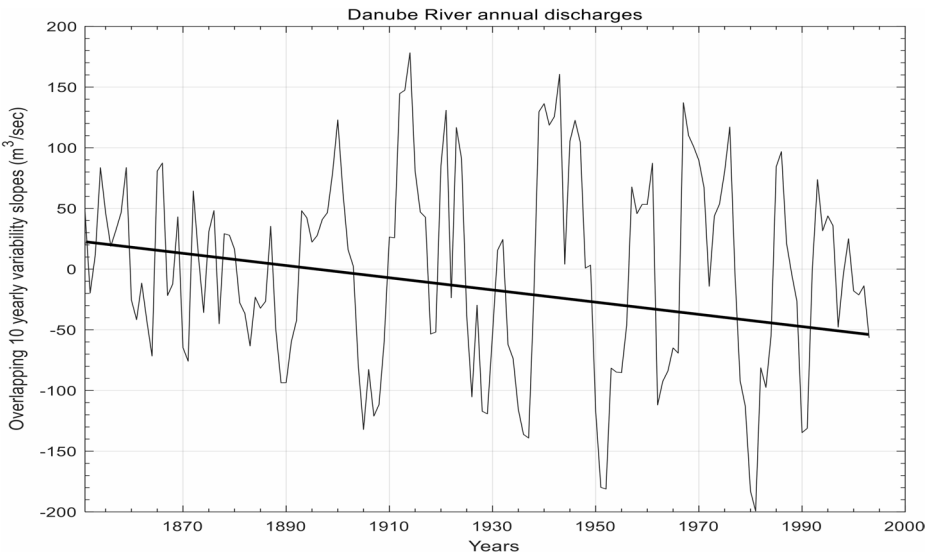


Fig. 3 Overlapping 10-yearly standard deviation (variation) trend changes

trend slopes appear less pronounced than increasing trend slopes. In Fig. 2, the maximum decreasing trend is seen around 1950. Figure 4b shows10-year non-overlapping variability trend, where decreasing trends are seen in the last three decades. These trend slopes are higher that the increasing trend. The comparison of Fig. 4a with 4b provides useful information about sharper increasing and decreasing mean trends than variability trends.

3.2 Lag One Moving 30-Yearly Trend Slopes and Variability

The World Meteorology Organization (WMO 2017) recommends a 30-year period as a standard by for worldwide comparative assessments in studies quantifying climate impact to determine trend components in a given hydro-meteorology time series record. Comparisons of STVI's and Sen's calculations of the mean trend slopes are shown in Fig. 5. These follow each other with a relative error of less than $\pm 10\%$.

The trend slopes of variability over a 30-year period for lag-one overlapping time-series in Fig. 6 show decreasing trend, like the 10-year variability trends as in Fig. 3.

3.2.1 30-Year Non-Overlapping Trend and Variability Slopes

Figure 7a shows non-overlapping successive mean trends over a 30-year period, mostly dominated by decreasing trends. The standard deviation tendency (variability) trend in Fig. 7b, also shows sharply decreasing trends recently.

Comparisons of probability distribution functions (PDFs) have been studied by different researchers and shown to help identify increasing and decreasing trends in their statistical parameters. Table 1 provides numerical values of different non-overlapping time mean and variability trends for comparison across possible climate change. Comparing the 30-year time trend mean slope with variability slope between 1840 and 1870 and 1870–1900 shows

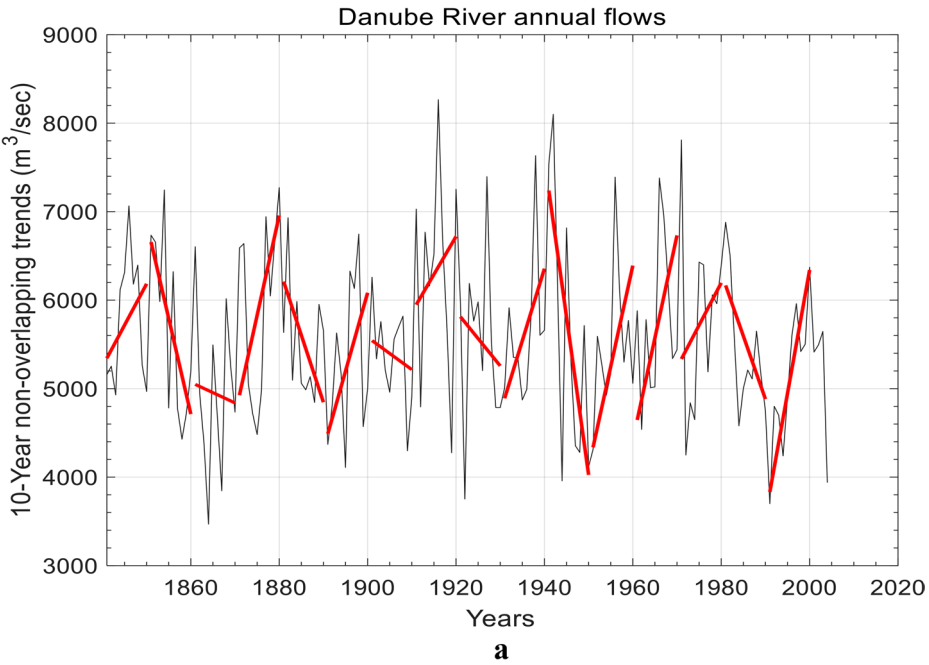


Fig. 4 Non-overlapping 10-yearly (**a**) mean trends, (**b**) variation trends

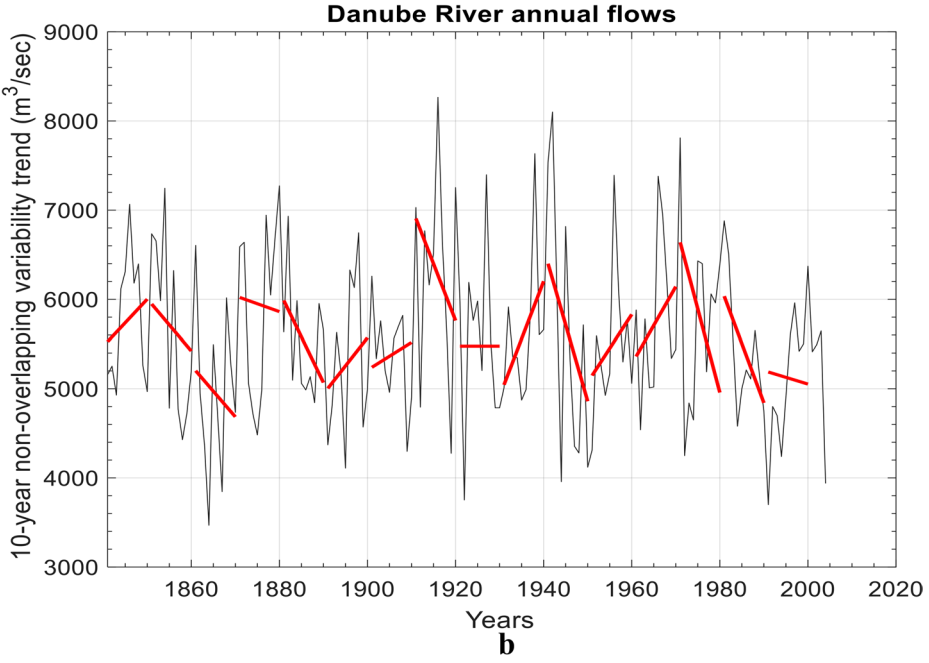


Figure 4 (continued)

decreasing trends of −62.94 and −33.81 in both cases, implying a climate decrease in the mean trend values. On the other hand, for the variability trend slopes, a decrease from a positive value of 2.85 to −12.86 occurs, which means a significant decrease in standard deviation (variability). As a result of these comparisons, it is understood that the climate effect on the variability trend slopes is less than on the mean trends.

Combining the 30-year mean and variability slopes with 10 different alternatives allows the reader to understand the dynamic behaviors throughout the entire time series record length. Between 1980 and 1990 period there is 10-year decreasing mean trend tendency coupled with increasing standard deviation (variability) trend slope (see Fig. 4). Climate change affects the mean (variability) trend slope in an almost equally increasing (decreasing) manner.

Decreasing mean trends based on STVI method and Sen slope procedure, in addition to the classical Mann-Kendall (MK) trend test approach, are shown in Fig. 8. Danube River discharge records show ups and downs in trends throughout the entire record length.

3.3 Slope Probability Distribution Functions

Based on the information obtained in previous sections for STVI and Sen slope methodologies, it has been observed that the slopes exhibit random type variations (see Figs. 2 and 5). Therefore, the probability cumulative distribution functions (CDFs) can be examined for the practicality of slopes based on the STVI method; for Sen slopes, the mean trend

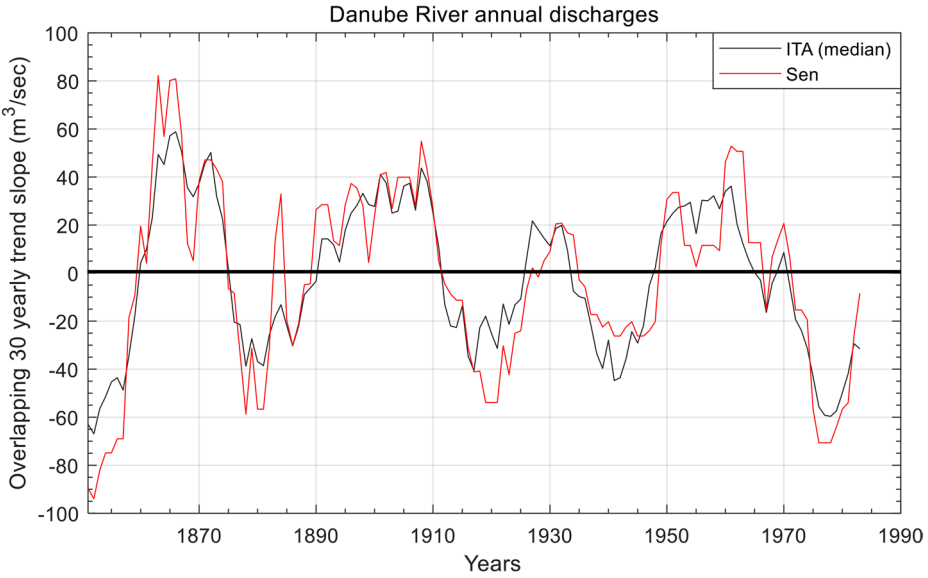


Fig. 5 Overlapping 30-yearly STVI slope based on median

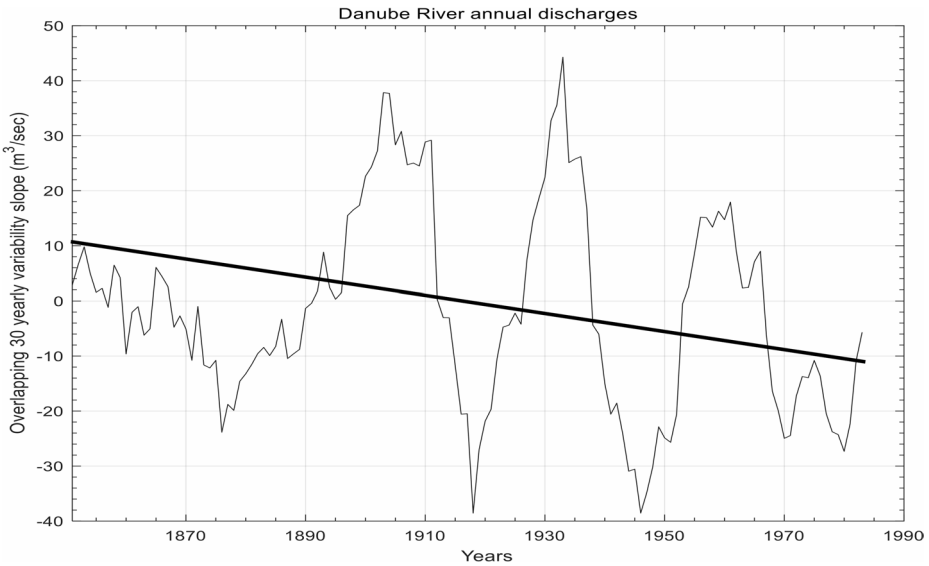


Fig. 6 Overlapping 10-yearly variation changes

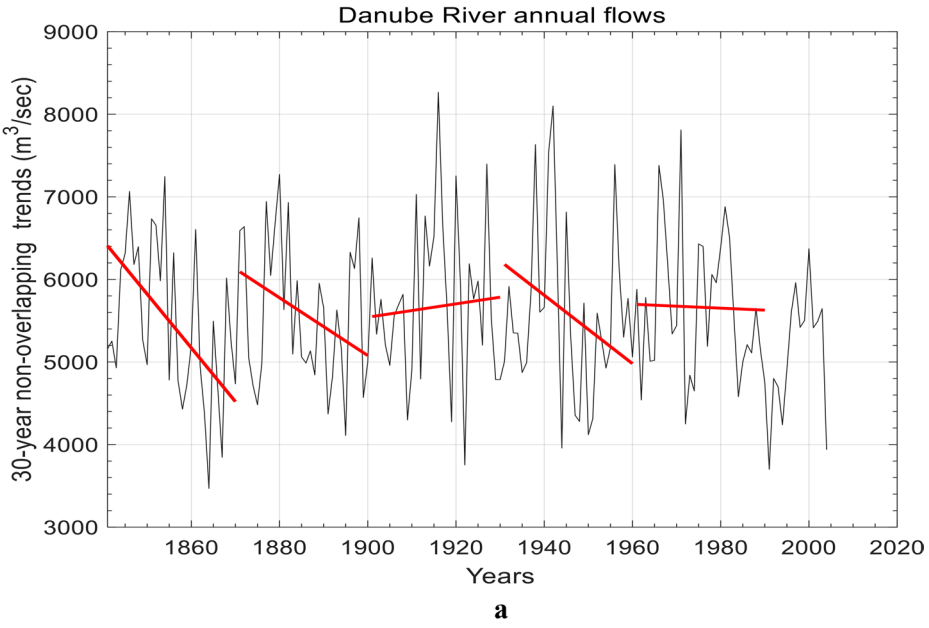
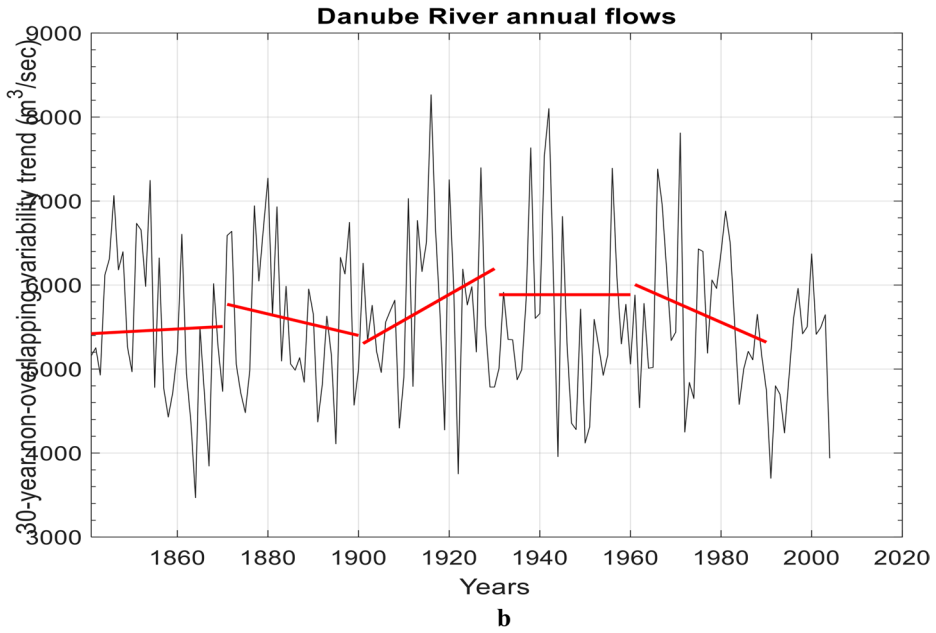


Fig. 7 Non-overlapping 30-year, (**a**) mean trends, (**b**) variability trends



b

Figure 7 (continued)

Table 1 Non-overlapping STVI trend slopes

10-yearly			30-yearly		
Duration	Trend	Variability	Duration	Trend	Variability
1840–1850	+84.2	−52.49	1840–1870	−62.94	+2.85
1850–1860	−194.43	−51.69	1870–1900	−33.81	−12.36
1860–1870	−20.95	−15.88	1900–1930	+13.27	+29.70
1870–1880	+177.6	−9182	1930–1960	+40.05	−20.31
1880–1890	−85.36	+56.61	1960–1990	−2.31	+22.86
1890–1900	+187.3	+27.86			
1900–1910	−49.63	+114.45			
1910–1920	+32.25	−11.57			
1920–1930	+1.88	+115.82			
1930–1940	+129.40	−153.95			
1940–1950	−349.40	+68.31			
1950–1960	+174.60	+78.06			
1960–1970	+202.40	−168.11			
1970–1980	+80.80	−119.37			
1980–1990	−105.60	−13.52			
1990–2000	+105.40	−3.56			
Mean	**23.15**	**−581.93**		**−9.15**	**4.55**
St. Dev	**153.46**	**2294.98**		**40.22**	**21.65**

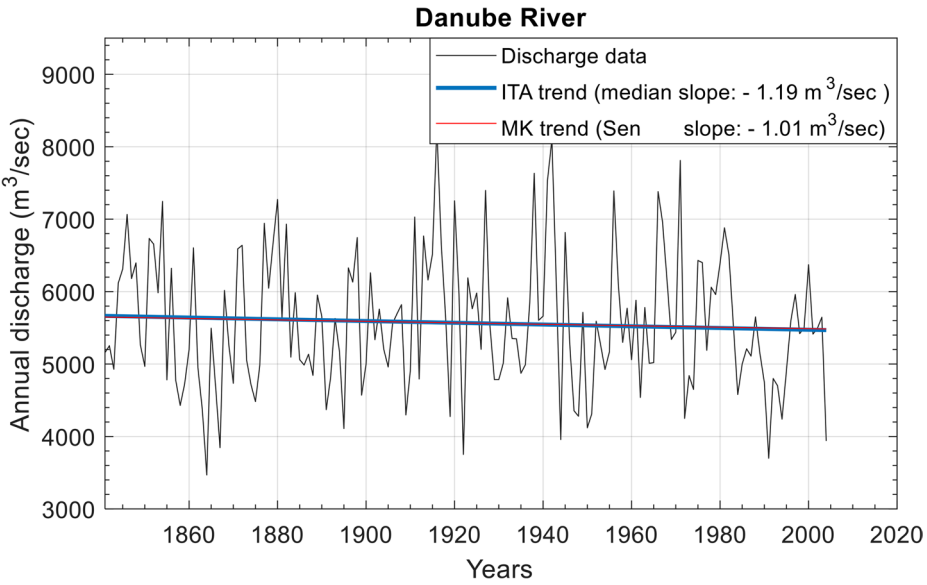


Fig. 8 Danube River annual discharge monolithic trends

confirmation can be examined, where the slope statistical parameters are given in Table 2 for each case, and it is practically acceptable that they fall within $\pm 5\%$ or at most $\pm 10\%$ error margin bands.

All 10-year and 30-year trend slope values have mean and standard deviation values as shown in this table. Minimum values can be used to shift the slope values into a positive range by adding a slightly larger positive value corresponding to each slope series. Figure 9 shows the theoretical CDFs for mean trend slopes obtained from STVI methodology and Sen median trend slopes.

Although the Sen and STVI trend slopes have different CDFs according to the theoretical Weibull and Pearson types, they follow each other with an error margin of less than 10% according to Kolmogorov-Smirnov (KS) test (Shapiro and Francia 1972; Weber et al. 2006), as shown in the upper right of Fig. 9. In addition, the slope values corresponding to risk levels of 0.50, 0.20, 0.10, 0.04, are given as 0.02, as 8.71, 9.94, 9.70, 6.19 and 5.08 for the two datasets, respectively. Since the error percentage error is less than 10%, in practice these relative errors are less than 10% between the two slope sets tare are close to each other.

Table 2 10-year and 30-year trend slope statistical parameters

Trend duration		Mean	St. Dev.	Skew	Minimum
10-year	STVI (median)	−3.47	179.73	−0.16	−492.20
	Sen (1968)	−3.26	112.97	−0.13	−322.40
30-year	STVI (median)	−2.20	38.12	−0.25	−93.93
	Sen (1968)	−1.91	23.46	−0.09	−63.33

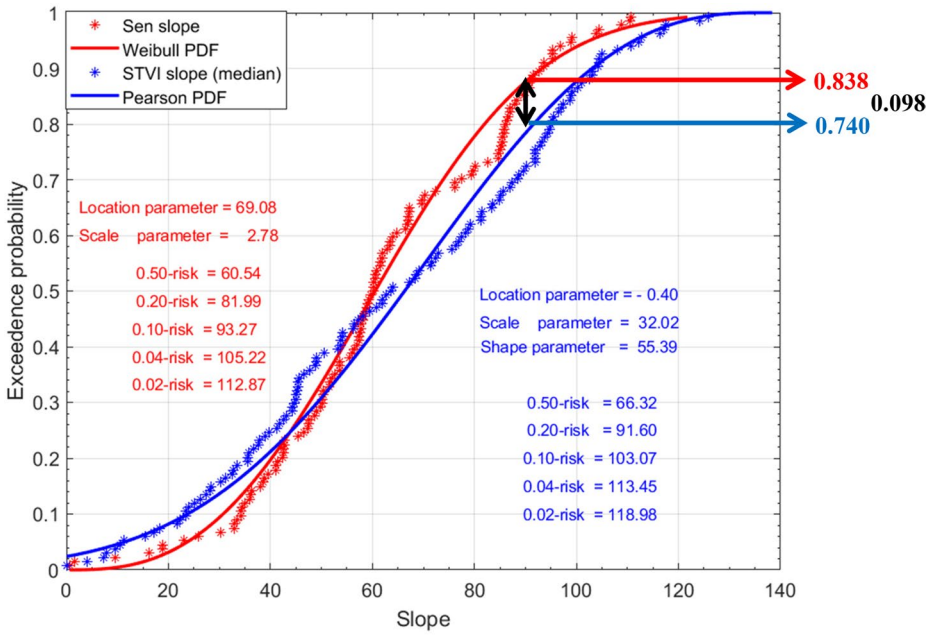


Fig. 9 Theoretical CDF fits for different methodological slope dataset

4 Discussion

The STVI and Sen (1968) trend slope calculation methodologies are described comparatively. It has been observed that they closely follow each other within practically acceptable limits. In the literature, it is well known that Sen (1968) calculates the trend slope as the average of all possible median slopes at different lags. This slope value is used in the classical trend test analysis proposed by Mann (1945) and Kendall (1975). The STVI slope calculation does not depend on any assumption, but the MK test requires assumptions of serial independence, long data length and Gaussian probability distribution function (PDF). None of these assumptions are collectively present in any given hydro-meteorology time series. For this purpose, different methodological procedures such as pre-whitening (Yue and Wang 2002) or over-whitening (Şen 2017) have been proposed. The STVI method, regardless of any assumption, determines the slopes of the monotonic mean and standard deviation (variability) trends lines, even for partial trend searches, as exemplified in this paper using 10-year and 30-year subseries. Figures 2 and 5 show practically acceptable limits for proximity of the STVI and Sen slopes. Comparing the mean and variability trends leads to the conclusion that the impact of global warming and climate change impacts on variability trends is less significant. Figure 9 graphically compares the STVI and Sen slopes and shows that they follow close CDF theoretical functions within practically acceptable error limits of less than 10%.

5 Conclusions

Different trend slope and linear trend straight-line generation methodologies have been proposed for hydro-meteorological time series analysis. Classical methodologies have several restrictive assumptions for trend determination tests. Sen's (1968) proposal for calculating trend median slope is used in the classical Mann-Kendall (MK) trend identification test. The proposed new structural trend and variability identification (STVI) methodology is based on the logical foundation of the innovative trend analysis (ITA) approach to determine partial for trends of various duration lengths in a given time series. Comparison of STVI mean trend and classical Sen slope values a practically acceptable match with error margins of less than 10%. In addition, variability trend slopes can be calculated with the proposed STVI method by considering the partial standard deviation values in a given time series. Danube River annual discharge values were used for the application of the STVI approach and comparison with Sen slopes by considering 10-year and 30-year partial duration subseries. Following an objective comparison using theoretical probability cumulative distribution function (CDF), it was observed that these two approaches yielded similar trends at mean trend level. Trends in variability based on the standard deviation partial sequences for 10-year and 30-year periods appear as decreasing trends, implying a reductions in extreme values of deviations from the mean trends. The STVI methodology provides the possibility to describe the dynamic structure of trends in a given hydrometeorology time series.

Author contributions This is a single author paper. All contribution is done by the single author.

Funding (information that explains whether and by whom the research was supported) Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). This is an entirely innovative methodological scientific paper without any funding.

Data Availability The data will be provided to anyone who requests.

Code availability Whoever requests the code in this article, the author will provide it in Matlab form.

Declarations

Ethics approval/declarations (include appropriate approvals or waivers) This new research paper has been conducted ethically, keeping in mind privacy, consent and appropriate referencing of those related to the subject.

Consent to participate (include appropriate statements) This is a single author paper and all the work is made by the author.

Consent for publication (include appropriate statements) The informed consent document succinctly describes the research theoretical and subsequent application parts.

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