1 **Innovative trend analysis of annual and seasonal rainfall in the**
2 **Yangtze River Delta, eastern China**

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Abstract: Trend detection in hydro-climatological time series is a prime task under the context of climate changes. Rainfall is a key component of the water cycle and its variability can profoundly influence agriculture, ecosystems and water resource management. In this paper, an innovative trend analysis (ITA) method with a significant test is used for rainfall trend detection at 14 stations in the Yangtze River Delta (YRD) during 1961 to 2016. The trends are separately evaluated for low (<10th percentile), medium (10th-90th percentile) and high (>90th percentile) rainfall at the annual and seasonal scales. The slope and significance of the rainfall trends derived from the ITA method are compared with those from the classical trend analysis methods Theil-Sen approach and Mann-Kendall test, respectively. The ITA shows significant increasing trends at the 99% confidence level in annual rainfall at all stations. While the same significant increasing trends are identified for summer and winter, decreasing trends dominate in spring and autumn. Contrasting trends are found for extreme rainfall with strong increasing trends in high rainfall in summer and winter and decreasing trends in low rainfall in spring and autumn. The results of the ITA confirmed by the classical trend analysis methods call for more attention to the risk management of flood in extreme seasons and drought in transitional seasons across the YRD region.

Keywords: Rainfall trends, Extremes, Graphical trend analysis, Trend significance and magnitude

1 Introduction

Climate change can have considerable impacts on the variability in hydro-meteorological variables such as rainfall, temperature, and evaporation (Zhang et al., 2005, Scalzitti et al., 2016, Xu et al., 2017, Mohan et al., 2018). Of them, rainfall is a primary component of the water cycle, and its variability is closely associated with drought and flood, which can threaten water supply, agricultural irrigation and socio-economic development (Milly et al., 2002, Wang et al., 2017). As reported by the Intergovernmental Panel on Climate Change (IPCC), rainfall induced hazards have become more intense and more frequent over the past decades as a result of anthropogenic influences (IPCC, 2014). Accurate estimation of long-term trends in rainfall has, therefore, become an increasingly active topic of research for effective regional managements of water resources and related hazards (Zhang et al., 2007, Milly et al., 2008, Zolina et al., 2010, Fatichi et al., 2012, Sun et al., 2018).

Over the past few decades, numerous methods have been developed for analyzing trends in rainfall time series such as linear regression analysis, Mann-Kendall (MK) test, Spearman's rho (SR) test, Theil-Sen approach (TSA) and seasonal Kendall methods (Becker et al., 2006, Tabari et al., 2011, Gemmer et al., 2011, Sonali and Kumar, 2013, Sang et al., 2014, Song et al., 2015, Asadi et al., 2015, Esterby, 2015, Wang et al., 2016, Sun et al., 2016). Among these methods, the MK test is the most popular approach which has been applied in many regions worldwide. Zang and Liu (2013) employed the MK test to investigate the variation of rainfall as well as runoff and evapotranspiration in the Heihe River Basin. Westra et al. (2013) used the MK test to evaluate monotonic trends in annual maximum daily rainfall globally during 1900 to 2009. Chowdhury et al. (2015) analyzed more than 100 years of rainfall data in South Australia using the linear regression, Mann-Kendall and Spearman's rho test. However, application of these classical methods is restricted by some assumptions such as serial independence of time series (von Storch, 1995, Yue et al., 2002). Moreover, these cited methods are pure statistical methods and do not allow to identify trends in low, medium and high values at one calculation process. Thus, a flexible graphical technique is needed to explore data trends in order to avoid errors in detecting significant hidden trends (Dabanlı et al., 2016).

Recently, an innovative trend analysis (ITA) method, proposed by Şen (2012), has been applied for the trend detection in rainfall, streamflow, pan evaporation and water quality parameters in different regions of the world (Sonali and Kumar, 2013, Kisi and Ay, 2014, Kisi, 2015, Dabanlı et al., 2016, Tabari et al., 2017, Zhou et al., 2018, Ahmad et al., 2018, Caloiero et al., 2018). The comparisons made in these studies between the ITA and classical methods showed some advantages of the ITA

with respect to other methods. Ay and Kisi (2015) use MK and the ITA methods to investigate the trends of monthly total rainfall in Black Sea and Central Anatolia regions. Dabanlı et al. (2016) provided some differences between MK test and the ITA application to hydro-meteorological series in Ergene basin of Turkey. A studied by Kisi (2015) revealed that the graphical plots of the ITA method can identify more hidden trends in pan evaporation than the MK and SR tests. Wu and Qian (2017) also suggested that the ITA method has more powerful test effects in detecting trend compared with linear regression and MK test. Şen (2017a) further improved the ITA method and developed a calculation formulation to derive monotonic trend and significance test, making it easier to obtain trend behavior for different categories (low, medium and high) of time series (Dabanlı et al., 2016, Güçlü, 2018).

The Yangtze River Delta (YRD) is one of the major economic centers of China with a high population density and a rapid urbanization in recent years. Due to unevenly spatial-temporal distribution of rainfall, frequent and destructive floods in this region threaten society and economic development. For instance, the 1998 flood in the YRD killed over 3000 people and caused \$20 billion damages (Yin et al., 2009). As reported by Wang et al. (2016), a long-term wet tendency was identified across the YRD from 1960 to 2012. With further urbanization and a projected increase for future summer rainfall in this region, the flood risks are expected to increase by approximately 4-15 times by 2050 (Wang et al., 2013). Although much attention has been paid to the studies of rainfall changes in the YRD (Zeng et al., 2005, Sang et al., 2013, Han et al., 2015a, Pei et al., 2018), very limited studies have focused on temporal variations in different rainfall categories, especially the low and high rainfall which are important signals for occurrence of flood and drought.

Therefore, the objectives of this study are to (1) investigate the trends of long-term rainfall data in the YRD by the means of the ITA method, (2) quantitatively evaluate trends in different rainfall categories (low, medium and high), and (3) assess the reliability of the ITA by comparing its results with classical methods. Compared with previous studies, the major novelty of the paper is to identify trend slope in different rainfall categories on the basis of the approach developed by Şen (2017a).

2 Study area and data

2.1 Study area

The Yangtze River Delta (YRD), covering an area of about 95,400 km², is the largest estuarine delta in China. It statues in eastern China and extends between latitude 29°12'-33°19' N and longitude 118°19'-122°19' E (Fig. 1). Mountain and hills mainly are located in the southwest of the YRD with mean elevation higher than 500

m, while alluvial plain are mainly located in the north and east of the YRD with mean elevation lower than 50 m. The annual average temperature is in the range from 14 to 18 °C and the annual rainfall is from 1,000 to 1,400 mm. With the East Asian monsoon climate, the temporal distribution of rainfall is rather uneven, with 70% of the rainfall concentrating in spring and summer (specifically, from May to September). In addition, the YRD is the most economically developed and rapidly urbanizing city cluster including 14 municipalities (e.g., Shanghai, Nanjing and Hangzhou), which represents 11.62% of the population and 20.25% of the gross domestic product (GDP) of China (National Bureau of Statistics of China, 2015). Recently, the YRD has frequently influenced by severe flood and drought disasters, which seriously threatened the living environment (Pei et al., 2018, Yuan et al., 2019).

Fig. 1 Digital elevation model of the YRD along with the locations of 15 meteorological stations.

2.2 Selection, quality control and homogeneity test of the rainfall data

There are hundreds of rain gauges in the YRD which are designed and managed by different departments. To ensure data quality, only those from China Climate Reference Network (CCRN) are employed in this study. The CCRN, managed by China Meteorological Administration, is composed of the most advanced stations which are equipped with high quality instruments and follow a strict observational

protocol, especially designed to detect climate change signals (Wu et al., 2017). There are 20 CCRN stations with observed records over the YRD. Some of them have data beginning in the 1950s; however, the majority do not have data until 1961. To make the best use of available data with the best spatial coverage, monthly data from 15 stations covering January 1961 to December 2016 were selected (Fig. 1). The data of these stations without missing values were acquired from the National Meteorological Information Center of the China Meteorological Administration (<http://data.cma.cn>). In this study, four seasons are defined as follows: spring (March-April-May), summer (June-July-August), autumn (September-October-November), and winter (December-January-February).

Table 1 The geographical information of meteorological stations along with mean rainfall during 1961-2016 in the YRD.

Code	Station name	Longitude (°E)	Latitude (°N)	Elevation (m)	Mean rainfall (mm)
58238	Nanjing	118.80	32.00	35.20	1059.72
58255	Gaoyou	119.45	32.80	5.40	1030.44
58259	Nantong	120.88	31.98	4.80	1072.56
58345	Liyang	119.48	31.43	5.90	1134.24
58354	Wuxi	120.72	30.85	6.22	1095.82
58358	Dongshan	120.43	31.07	16.70	1136.76
58362	Baoshan	121.45	31.40	5.50	1149.96
58436	Ningguo	118.98	30.62	87.30	1429.93
58457	Hangzhou	120.17	30.23	41.70	1397.04
58464	Pinghu	121.08	30.62	5.40	1210.08
58467	Cixi	121.27	30.20	4.50	1302.90
58543	Chunan	120.34	30.78	203.82	1197.02
58556	Shengzhou	120.82	29.60	104.30	1045.56
58562	Yinxian	121.57	29.87	5.00	1409.40

Besides, quality control and homogenization for the data in climate studies are also crucial before analysis (Gonzalez-Rouco et al., 2001). For this study, the RClimDex software was utilized to conduct quality control checks for rainfall data. Any identified potential outliers such as negative values or values greater than the maximum possible were manually checked. Furthermore, data homogeneity was also assessed using the RHtestsV4 software, which uses a two-phase regression model to check for potential change points in a time series (Wang, 2003). The penalized maximal F (PMF) test showed the values of the test statistic for one station (i.e., Huzhou) was significant at 0.05 level. Therefore, monthly rainfall from the remaining 14 high-quality stations were used in the trend analysis (Table 1).

3 Methodology

In this study, an innovation trend analysis (ITA) method is employed for trend detection in annual and seasonal rainfall. Meanwhile, two classical trend analysis methods, namely, Theil-Sen approach (TSA) and Mann-Kendall (MK) test, are used to compare and evaluate the magnitude and significance of trends obtained from ITA method, respectively.

3.1 Innovative trend analysis (ITA)

The ITA method, proposed by Şen (2012) divides any given hydro-meteorological time series into two equal halves, and then sort both sub-series in ascending order. The first half series (x_i) is located on the horizontal axis and the second half series (y_i) on the vertical axis of the Cartesian coordinate system as shown in Fig. 2. The 1:1 line on the coordinate system is considered as no-trend line which separates increasing and decreasing trends. If the scatter points fall above (below) 1:1 line, the time series exhibit a monotonic increasing (decreasing) trend (Fig. 2(a)). Otherwise, if the scatter points show non-monotonic trend (i.e., composition of different trends in the time series), the time series is classified into several clusters. As shown in Fig. 2(b), the classification of given hydro-meteorological data into “low”, “medium” and “high” groups can be achieved by dividing the variation domain of the data into three intervals. It allows trend detection of rainfall for different clusters with important implication: high rainfall for flooding and low rainfall for drought (Öztopal and Şen, 2017). In this study, rainfall intensities are divided three categories based on the percentiles (Gershunov, 1998, Brunetti et al., 2004), i.e., low (<10th), medium (10th-90th), and high (>90th) rainfall.

Fig. 2 The illustration of the ITA method: (a) monotonic and (b) non-monotonic trends.

The straight-line trend slope (s) plotted by the ITA can be calculated according to the following expression (Şen, 2017a).

$$s = \frac{2(\bar{y}_2 - \bar{y}_1)}{n} \quad (1)$$

where $\bar{y}_1$ and $\bar{y}_2$ are the arithmetic averages of the first and second half of the dependent variable, and n is the number of data. Actually, the arithmetic averages of the two halves appear as “centroid point” falling on the data line. As shown in Fig. 3, annual rainfall at Nanjing is taken as an application of this proposed method. The substitution of the numerical values as $n = 56$ and the arithmetic averages from Fig. 3 (b) as $\bar{y}_1 = 1163.6$ and $\bar{y}_2 = 1285.7$ into Eq. (1), yields $s = 2 \times (1285.7 - 1163.6)/56 = 4.36$. According to Şen (2017a), relative error between innovative trend plot and deterministic trend can be acceptable within 5% (Fig. 4). Moreover, the trend slope (s) of each cluster (low, medium and high) is easily calculated by detecting their centroid points, especially for these non-monotonic scatter points (Alashan, 2018).

Fig. 3 (a) Deterministic and (b) innovative trend plots of annual rainfall at Nanjing station (1961-2016).

To test the significance of the trend slope value, s , the null hypothesis, H_o , implies that there is not significant trend if the calculated slope value, s , is below a critical value, s_{cr} (Şen, 2017a). Otherwise, an alternative hypothesis, H_a , is valid when $s > s_{cr}$. As for the trend slope parameter, Eq. (1) shows that the stochastic property of s is a function of the first and second half time series arithmetic average values. Because $\bar{y}_1$ and $\bar{y}_2$ are also stochastic variables, the first-order moment (expectation) of the slope can be computed by taking the expectation of both sides:

$$E(s) = \frac{2}{n} [E(\bar{y}_2) - E(\bar{y}_1)] \quad (2)$$

In case of no trend, the centroid point falls on the 1:1 line and $E(\bar{y}_2) = E(\bar{y}_1)$, and therefore, $E(s) = 0$. The difference between the expectations of both sides gives

the variance of slope:

$$\sigma_s^2 = \sigma_s^2 = E(s^2) - E^2(s) = \frac{4}{n^2} [E(\bar{y}_2^2) - 2E(\bar{y}_2\bar{y}_1)] + E(\bar{y}_1^2) \quad (3)$$

As $E(\bar{y}_2^2) = E(\bar{y}_1^2)$, the above relationship is written in the following form:

$$\sigma_s^2 = \frac{8}{n^2} [E(\bar{y}_2^2) - E(\bar{y}_2\bar{y}_1)] \quad (4)$$

The final relationship is obtained as follows by substitution of the numerator of correlation coefficient into Eq. 4 and considering $\sigma_{\bar{y}_2} = \sigma_{\bar{y}_1} = \sigma/\sqrt{n}$:

$$\sigma_s^2 = \frac{8}{n^2} \frac{\sigma^2}{n} (1 - \rho_{\bar{y}_1\bar{y}_2}) \quad (5)$$

where $\rho_{\bar{y}_1\bar{y}_2}$ is the correlation coefficient between the two mean values in stochastic processes:

$$\rho_{\bar{y}_1\bar{y}_2} = \frac{E(\bar{y}_1\bar{y}_2) - E(\bar{y}_1)E(\bar{y}_2)}{\sigma_{\bar{y}_1}\sigma_{\bar{y}_2}} \quad (6)$$

Finally, the confidence limits (CL) of a standard normal PDF with zero mean and standard deviation are s_{cri} , then the confidence limits (CL) of the trend slope is given as

$$CL_{(1-\alpha)} = 0 \pm s_{cri} \times \sigma_s \quad (7)$$

where α is the significance level and σ_s is standard deviation of the slope:

$$\sigma_s = \frac{2\sqrt{2}}{n\sqrt{n}} \sigma \sqrt{1 - \rho_{\bar{y}_1\bar{y}_2}} \quad (8)$$

The slope, s , of time series is statistically significant if it falls outside the confidence limits. Because all the odd-order moments of the slope variable are equal to zero, the PDF of slope follows a Gaussian PDF with zero mean and the standard deviation given in Eq. (8). More information can be found in Şen (2017a)

3.2 Classical trend analysis methods

To evaluate the results of the ITA method, they are compared with the results of conventional trend tests. The Mann-Kendall (MK) test, proposed by Mann (1945) and Kendall (1975), as a popular rank based nonparametric method is used to investigate the sign and significance of rainfall trends. The Theil-Sen approach (TSA; Sen, 1968) as another nonparametric method resistant to outliers in time series is also applied to estimate the magnitude of the trends (e.g., Zhang et al., 2011, Tabari et al., 2015). It should be noted here that the results of the trend tests are affected by serial correlations within the time series, which may lead to a disproportionate rejection of the null hypothesis of no trend whereas it is actually true (von Storch, 1995). For this

study, trends in rainfall series ($x_1, x_2, x_3, \dots, x_n$) are detected using the following steps (Yue et al., 2002): (1) calculate the lag-1 serial correlation r_1 ; (2) if the calculated r_1 is significant at the 0.05 level, the original series is assumed to be serially independent and is directly used for the trend analysis; otherwise (3) the trend analysis methods are applied on the pre-whitened series ($x_2 - r_1 \times x_1, x_3 - r_1 \times x_2, \dots, x_n - r_1 \times x_{n-1}$). For this study, the 0.01 and 0.05 levels are used as the thresholds to evaluate the significance of trends, corresponding to $Z_{1-\alpha/2} = \pm 2.58$ and $Z_{1-\alpha/2} = \pm 1.96$, respectively.

4 Results

4.1 Annual trends

The lag-1 serial correlation coefficients of annual and seasonal rainfall time series are calculated and shown in Fig. 2. Among the 14 study stations, lag-1 serial correlation of annual rainfall is significant at the 0.05 level at three stations (Wuxi, Pinghu and Yinxian). In seasonal rainfall series, significant serial correlations vary with seasons and are more pronounced in winter series. Considering the existence of the significant serial correlation in rainfall series, pre-whitening of the series is necessary to limit the effect of serial correlations before trend analyses (Yue et al., 2002).

Fig. 4 Mann-Kendall Z for original and pre-whitened annual and seasonal rainfall series together with lag-1 serial correlation (r_1): (a) annual, (b) spring, (c) summer, (d) autumn and (e) winter.

The monotonic trends in annual rainfall from 1961 to 2016 detected by two classical methods (TSA and MK) are summarized in Table 2. The magnitudes of the trends at all selected stations are positive and vary between 0.89 and 6.97 mm/year. Specifically, the stations in southern YRD (i.e., Baoshan, Pinghu, Cixi, Chunan and Hangzhou) show strong slopes (higher than 6.0 mm/year), while the stations in northern areas (i.e., Nanjing, Liyang and Gaoyou) mainly show weak slopes (less than 3.0 mm/year). As for MK statistics, positive values are also shown for all selected stations with 8 stations of them (53.3%) exhibiting significant trends at the 95% confidence level. Trends at 4 stations are significant at the higher confidence level of

99%, confirming the results of the TSA.

Table 2 Results of Theil-Sen approach (TSA) Mann-Kendall (MK) test for annual and seasonal rainfall.

Station name	Annual		Spring		Summer		Autumn		Winter	
	TSA	MK	TSA	MK	TSA	MK	TSA	MK	TSA	MK
Nanjing	2.00	1.25	-1.49	-1.46	3.32	2.21*	-0.85	-1.04	1.78	3.91**
Gaoyou	0.89	0.61	4.79	2.47*	-1.69	-1.67	-0.67	-1.39	1.94	1.68
Nantong	4.53	2.28*	-1.39	-1.69	4.76	3.19**	0.15	0.19	1.51	3.53**
Liyang	1.78	1.11	-0.63	-0.57	1.85	1.45	-1.54	-1.94	2.19	3.21**
Wuxi	4.25	2.32*	-0.39	-0.20	2.79	2.25*	-0.24	-0.39	2.16	3.17**
Dongshan	3.32	1.65	-0.63	-0.59	2.96	2.25*	-1.29	-1.56	2.19	2.87**
Baoshan	6.26	3.05**	-0.86	-0.90	4.48	2.82**	0.03	0.05	1.97	2.51*
Ningguo	2.28	1.19	-1.73	-1.43	2.27	1.69	-1.28	-1.59	2.51	2.76**
Hangzhou	6.48	2.93**	-0.29	-0.05	5.35	3.06**	-1.16	-0.90	3.09	2.87**
Pinghu	6.97	3.02**	-0.25	-0.16	6.15	3.68**	-0.80	-0.71	2.20	2.66**
Cixi	6.43	2.85**	-0.45	-0.86	4.62	3.33**	0.93	0.80	2.33	2.50*
Chunan	6.72	2.51*	0.19	0.41	2.92	1.65	0.29	0.36	2.82	3.41**
Shengzhou	3.36	1.39	-1.25	-1.31	2.18	1.58	-0.13	-0.09	2.07	3.07**
Yinxian	5.19	2.37*	0.06	0.02	4.57	2.79**	-0.24	-0.12	2.28	3.30**

* and ** represent 0.05 and 0.01 significance levels, respectively. The slope by TSA is in *mm/year*.

The trends in annual rainfall using the ITA method are provided in Table 3. The results show that slope s of annual rainfall is dominated by positive values, and all of them are significant at the 99% confidence level. It indicates that some significant increasing trends neglected by the MK test can be detected using the ITA, approving the ability of this method to identify the hidden trends in time series. The increasing tendency of annual rainfall also can be clearly seen from Fig. 5 considering that scatter points (blue point) of most stations fall above the 1:1 line in the Cartesian coordinate system.

With regards to different rainfall clusters (Fig. 5), green, pink and red points illustrate mean central points of low, medium, and high rainfall, respectively. The innovative trend slopes, s , of each rainfall cluster are also calculated based on Eq. (1). It should be noted that the trends in each rainfall cluster are quite distinct at the same station. For instance, at Nanjing station, slight increases of 1.78 and 1.68 mm/year are detected for the low and medium rainfall, while a strong upward trend of 9.09 mm/year is found for high rainfall. And at Gaoyou station, there is no trend in medium rainfall as all the scatter points fall almost on the 1:1 line, while positive trends are clear for the low and high rainfall. Comparison of three rainfall clusters,

high rainfall has the strongest increasing trend at 8 stations (i.e., Nanjing, Nantong, Wuxi, Hangzhou, Pinghu, Cixi, Yinxian and Chuanan), slopes of which are more than 6.0 mm/year.

Table 3 Results for innovative trend test (slope s) of annual rainfall in the YRD.

Station	Slope s	Standard deviation σ	Correlation ρ_{y1y2}	Slope standard deviation σ_s	Sig. level 0.05	Sig. level 0.01
Nanjing	4.36**	292.28	0.94	0.47	± 0.92	± 1.21
Gaoyou	2.17**	277.72	0.95	0.40	± 0.79	± 1.04
Nantong	5.57**	264.16	0.97	0.29	± 0.57	± 0.75
Liyang	3.01**	271.90	0.95	0.41	± 0.8	± 1.05
Wuxi	6.22**	256.69	0.95	0.37	± 0.72	± 0.95
Dongshan	3.42**	230.56	0.97	0.27	± 0.53	± 0.69
Baoshan	5.92**	250.98	0.98	0.24	± 0.47	± 0.61
Ningguo	2.63**	297.37	0.96	0.42	± 0.83	± 1.09
Hangzhou	6.38**	288.27	0.97	0.32	± 0.64	± 0.84
Pinghu	7.01**	254.69	0.96	0.36	± 0.71	± 0.94
Cixi	6.61**	266.91	0.98	0.24	± 0.48	± 0.63
Chunan	7.88**	308.52	0.96	0.39	± 0.77	± 1.01
Shengzhou	2.97**	258.01	0.97	0.32	± 0.62	± 0.81
Yinxian	5.68**	276.19	0.95	0.44	± 0.85	± 1.12

* and ** represent 0.05 and 0.01 significance level, respectively.

Fig. 5 Results of the ITA for annual rainfall at 14 stations in the YRD (Green, pink and red points illustrate mean central points of low, medium and high rainfall, respectively).

4.2 Seasonal trends

The rainfall trends in each season detected by TSA and MK test are summarized in Table 2. Spring rainfall is dominated by negative trends, but almost all of them are insignificant. Only one station (Gaoyou) exhibits significant increasing trend. Summer rainfall shows significant trends at 9 stations mainly scattered in the central and southern parts of the YRD. Summer rainfall trends are similar to the results of annual rainfall because of the concentrated rainfall in summer in the region. Autumn rainfall of most stations (73.3%) exhibits downward trends, but significant at one station (Liyang). Winter rainfall of all stations shows significant upward trends except Gaoyou station. These results imply that the increasing annual trends at most stations is due largely to summer and winter rainfall. It is noteworthy that the annual trends at

Gaoyou and Liyang stations are insignificant although they both exhibit significant trends in different seasons, which can be interpreted by the opposing trends in winter and other seasons.

Table 4 Results for innovative trend test (slope s) of seasonal rainfall in the YRD.

Station	Spring	Summer	Autumn	Winter
Nanjing	-0.84*	4.25**	-1.29**	2.24**
Gaoyou	4.20**	-3.17**	-0.76*	1.90**
Nantong	-1.37**	5.25**	-0.26	1.95**
Liyang	-0.32	2.07**	-1.43**	2.69**
Wuxi	-0.31	4.49**	-0.62*	2.66**
Dongshan	-0.66*	2.96**	-1.60**	2.72**
Baoshan	-1.13**	5.06**	-0.74*	2.72**
Ningguo	-1.33**	2.47**	-1.38**	2.86**
Hangzhou	-0.49	5.23**	-1.88**	3.52**
Pinghu	-0.39	6.72**	-2.11**	2.78**
Cixi	-0.72*	4.83**	-0.40	2.90**
Chunan	0.63	4.73**	-0.62*	3.14**
Shengzhou	-1.23**	2.10**	-0.33	2.43**
Yinxian	-0.74*	3.60**	-0.05	2.87**

* and ** represent 0.05 and 0.01 significance levels, respectively.

The rainfall trends over four seasons by the ITA method are also given in Table 4. Positive values of slope s are found for all stations in summer (except Gaoyou) and winter, and all of them are significant at the 0.01 level. The slope s in spring and autumn is mainly dominated by negative values. There are 9 and 10 stations exhibit significant trends at the 0.05 level in spring and autumn, respectively. The corresponding graphical illustration of these results is presented for the three rainfall clusters in Figs. 6-9. For summer and winter seasons, the scatter points (blue point) of most stations fall above the 1:1 line, confirming the statistical results obtained based on the slope s (Table 4).

Further inspection of the ITA plots presents different tendencies of rainfall in different clusters. For spring, decreasing tendencies are detected for low and medium rainfall at most stations, while high rainfall exhibits a slight increasing trend (Fig. 6). The opposite trend of high and low rainfall is also evident in summer (Fig. 7) when slight increases are detected for low rainfall and a strong upward trend for high rainfall at most stations in the central and southern parts of the YRD (e.g., Nantong, Hangzhou, Wuxi, Pinghu and Chunan). The temporal variations of rainfall clusters are more consistent for autumn and winter. Decreasing trends dominate all rainfall

clusters in autumn, especially for high rainfall (Fig. 8). In contrast, strong increasing trends are identified for all rainfall clusters in winter (Fig. 9).

Fig. 6 Results of the ITA for spring rainfall at 14 stations in the YRD (Green, pink and red points illustrate mean central points of low, medium, and high rainfall, respectively).

Fig. 7 Results of the ITA for summer rainfall at 14 stations in the YRD (Green, pink and red points illustrate mean central points of low, medium, and high rainfall, respectively).

Fig. 8 Results of the ITA for autumn rainfall at 14 stations in the YRD (Green, pink and red points illustrate mean central points of low, medium, and high rainfall, respectively).

Fig. 9 Results of the ITA for winter rainfall at 14 stations in the YRD (Green, pink and red points illustrate mean central points of low, medium, and high rainfall, respectively).

5 Discussions

Due to the influence of the East Asian monsoon, the spatiotemporal distribution of rainfall in the YRD is uneven, with annual total rainfall ranging from 1024 mm in Gaoyou to 1429 mm in Ningguo, and more than 60% of rainfall amount concentrating in summer. Thus, an in-depth knowledge about the variability in different rainfall clusters over the YRD is necessary for better water resources management and hazard risk mitigation. However, most of the previous studies in the YRD analyzed the variability in annual rainfall time series, which did not reflect rainfall characteristics at the seasonal scale. Moreover, no study has been conducted in the YRD considering different rainfall clusters. Regarding the identified knowledge gaps and the

importance of analyzing the spatiotemporal rainfall variation in the YRD, this study examined the temporal variability in low, medium and high rainfall at the annual and seasonal time series.

The results of this study show strong trends of extreme rainfall associated with drought and flood. Drought and flood events have frequently been occurred in the YRD over the years (Wang et al., 2016, Pei et al., 2018). As reported by Han et al. (2015b), rainy days with short duration showed upward occurrence and fractional contribution to annual rainfall in the YRD. Our study revealed significant increasing trends for summer and winter rainfall for all stations. Especially, summer high values exhibited strong upward trends in the central and southern part of the YRD, including Shanghai, Suzhou and Ningbo cities, which is one of the most rapidly urbanized region of China. Thus, some measures should be taken for these areas threatened by high flood risks in the future. Moreover, decreasing rainfall trends may result in an increase of drought which is more sensitive to low rainfall changes. As for the YRD, a considerable amount of water is usually used for agriculture irrigation in spring and autumn. Our results, however, showed decreasing trends in spring and autumn rainfall. If these trends continue in the future, they may have consequences for agriculture section in the YRD. The deficient rainfall in recent years has already resulted in water resources reduction for agriculture irrigation over the YRD (Geng et al., 2016; Huang et al., 2017). Thus, in terms of management, more attention should be paid to spring and autumn drought in this region.

To validate the reliability of the annual and seasonal rainfall trends obtained from the ITA in the YRD, two traditional methods of TSA and MK were used. The ITA results of annual and seasonal rainfall are summarized and compared with MK test in Table 5. For the 70 annual and seasonal time series studied, significant trends are detected in 31 time series by MK test. However, 61 time series exhibit significant trends using the ITA method. All significant trends detected by MK test are also identified via the ITA method. It is clearly seen from Table 5 that MK and ITA give similar trend results for annual, summer and winter rainfall series. However, many significant trends (especially in spring and autumn) that cannot be detected by MK test can be identified effectively using the ITA method. It should be said that the ITA method benefits for analyzing many hidden variation trends of rainfall series across the YRD. Besides, compared with previous studies, confidence intervals of the ITA method are given in this study to determine whether rainfall trends are statistically significant (Dabanlı et al., 2016, Şen, 2017b). Moreover, this study also contributes to the ITA method in terms of a quantitative evaluation of low, medium and high rainfall clusters. It thus presents a very different aspect from the one shown by TSA and MK test. TSA and MK test are quantitative methods giving pure numerical results and do

not provide any categorization in trend detection. Indeed, an efficient and optimum management of water resources requires not only the identification of monotonic trends for a given time series, but also trends in the low, medium and high values (Şen, 2012, Caloiero et al., 2018). By this way, water authorities and risk managers interested in identifying trends for any rainfall category can benefit from the comprehensive assessment provided by ITA.

Table 5 Comparison of the results of MK test and the ITA method in the YRD.

Station	Annual		Spring		Summer		Autumn		Winter	
	MK	ITA	MK	ITA	MK	ITA	MK	ITA	MK	ITA
Nanjing	No	Yes (++)	No	Yes (-)	Yes (+)	Yes (++)	No	Yes (-)	Yes (++)	Yes (++)
Gaoyou	No	Yes (++)	Yes (+)	Yes (++)	No	Yes (--)	No	Yes (-)	No	Yes (++)
Nantong	Yes (+)	Yes (++)	No	Yes (++)	Yes (++)	Yes (++)	No	No	Yes (++)	Yes (++)
Liyang	No	Yes (++)	No	No	No	Yes (++)	No	Yes (--)	Yes (++)	Yes (++)
Wuxi	Yes (+)	Yes (++)	No	No	Yes (+)	Yes (++)	No	Yes (-)	Yes (++)	Yes (++)
Dongshan	No	Yes (++)	No	Yes (-)	Yes (+)	Yes (++)	No	Yes (--)	Yes (++)	Yes (++)
Baoshan	Yes (++)	Yes (++)	No	Yes (++)	Yes (++)	Yes (++)	No	Yes (-)	Yes (+)	Yes (++)
Ningguo	No	Yes (++)	No	Yes (++)	No	Yes (++)	No	Yes (--)	Yes (++)	Yes (++)
Hangzhou	Yes (++)	Yes (++)	No	No	Yes (++)	Yes (++)	No	Yes (--)	Yes (++)	Yes (++)
Pinghu	Yes (++)	Yes (++)	No	No	Yes (++)	Yes (++)	No	Yes (--)	Yes (++)	Yes (++)
Cixi	Yes (++)	Yes (++)	No	Yes (-)	Yes (++)	Yes (++)	No	No	Yes (+)	Yes (++)
Chunan	Yes (+)	Yes (++)	No	No	No	Yes (++)	No	Yes (-)	Yes (++)	Yes (++)
Shengzhou	No	Yes (++)	No	Yes (--)	No	Yes (++)	No	No	Yes (++)	Yes (++)
Yinxian	Yes (+)	Yes (++)	No	Yes (-)	Yes (++)	Yes (++)	No	No	Yes (++)	Yes (++)

+ and - indicate significant increasing or decreasing trends at 0.05 significance level;

++ and -- indicate significant increasing or decreasing trends at 0.01 significance level.

No indicates no significant trend.

6 Conclusions

In this study, the variation of annual and seasonal rainfall across the YRD during 1961 to 2016 was investigated by means of the ITA method which can visually provide results and trends in different rainfall clusters (low, medium and high). Furthermore, two conventional methods of TSA and MK test were used to verify the results of the ITA. These conclusions and remarks derived from this study are summarized as follows.

(1) According to the ITA method, annual rainfall in the YRD showed increasing trends, and all of them were significant at the 0.01 level. At the seasonal scale,

significant increasing trends were detected for summer and winter rainfall for all stations, while spring and autumn rainfall exhibited decreasing trends for most stations. Different trends and in some cases even opposite trends were identified for low, medium and high rainfall clusters at the same station. High rainfall in summer and winter showed strong upward trends at most stations, while low rainfall in spring and autumn mainly exhibited decreasing trends. It indicated that the YRD might encounter risk of flood in summer and of agriculture drought in spring (autumn).

(2) Compared with the traditional trend analysis, the ITA method has several advantages. This method has more powerful test for trend detection, which benefits for analyzing hidden variation trends of rainfall series that cannot be detected using traditional tests. It provides a visual-graphical illustration of trends which helps to identify the trend of extreme events, such as high rainfall for flood and low rainfall for drought. Furthermore, the ITA method exhibits a wide range of applications without considering any assumptions, such as serial correlation and sample number.

This study presented a comprehensive investigation of the temporal variation of annual and seasonal rainfall across the YRD from 1961 to 2016. The results are helpful for water resources and agricultural managers involved in predicting and managing risk associated with flood and drought disasters in the study area. This study also makes contribution to the ITA method by quantitatively evaluating trends of different categories of time series. The possible drivers of the obtained variability in different rainfall clusters in the YRD are large-scale atmospheric circulations and urbanization development (Wang et al., 2019a, b) which needs further research.

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Conflict of Interest – None

Reference

- [1] Ahmas I., Zhang F., Tayyab M., Anjum M., Zamam M., Liu J., Farid U. and Saddique Q. (2018) Spatiotemporal analysis of precipitation variability in annual, seasonal and extreme values over upper Indus River basin. *Atmospheric Research* 213: 346-360.
- [2] Alashan S. (2018). An improved version of innovative trend analyses. *Arabian Journal of Geosciences* 11(3), 50-56.
- [3] Asadi, M.A., Sivakumar, B. and Sharma, A. (2015) Droughts in a warming climate: a global assessment of standardized precipitation index (SPI) and reconnaissance drought index (RDI).

- Journal of Hydrology 526, 183-195.
- [4] Ay, M. and Kisi, O. (2015) Investigation of trend analysis of monthly total precipitation by an innovative method. *Theoretical & Applied Climatology* 120(3-4), 617-629.
- [5] Becker, S., Gemmer, M. and Jiang, T. (2006) Spatiotemporal analysis of precipitation trends in the Yangtze River catchment. *Stochastic Environmental Research & Risk Assessment* 20(6), 435-444.
- [6] Brunetti, M., Maugeri, M., Monti, F. and Nanni, T. (2004) Changes in daily precipitation frequency and distribution in Italy over the last 120 years. *Journal Geophysical Research: Atmospheres* 109, (D05102) 1-16.
- [7] Caloiero, T., Coscarelli, R. and Ferrari, E. (2018) Application of the innovative trend analysis method for the trend analysis of rainfall anomalies in southern Italy. *Water Resources Management* 32(15), 4971-4983.
- [8] Chowdhury, R.K., Beecham, S., Boland, J. and Piantadosi, J. (2015) Understanding south Australian rainfall trends and step changes. *International Journal of Climatology* 35(3), 348-360.
- [9] Dabanlı, İ., Şen, Z., Yeleğen, M., Şişman, E., Selek, B. and Güçlü, Y. (2016) Trend Assessment by the Innovative-Şen Method. *Water Resources Management* 30(14), 1-11.
- [10] Esterby, S. (2015) Review of methods for the detection and estimation of trends with emphasis on water quality applications. *Hydrological Processes* 10(2), 127-149.
- [11] Fatichi, S., Ivanov, V. and Caporali, E. (2012) Assessment of a stochastic downscaling methodology in generating an ensemble of hourly future climate time series. *Climate Dynamics* 40(7-8), 1841-1861.
- [12] Gemmer, M., Fischer, T., Jiang, T., Su, B. and Liu, L. (2011) Trends in precipitation extremes in the Zhujiang River basin, south China. *Journal of Climate* 24(3), 750-761.
- [13] Geng, G., Wu, J., Wang, Q., Lei, T., He, B., Li, X., Mo, X., Luo, H., Zhou, H. and Liu, D. (2016) Agricultural drought hazard analysis during 1980-2008: a global perspective. *International Journal of Climatology* 36(1), 389-399.
- [14] Gershunov, A. (1998) ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous United States: implications for longrange predictability. *Journal of Climate* 11, 3192-3203.
- [15] Gonzalez-Rouco, J., Jiménez J., Quesada, V., & Valero, F. (2001). Quality control and homogeneity of precipitation data in the southwest of Europe. *Journal of Climate*, 14, 964-978.
- [16] Güçlü, Y. (2018) Multiple Şen-innovative trend analyses and partial Mann-Kendall test. *Journal of Hydrology* 566, 685-704.
- [17] Han, L., Xu, Y., Pan, G., Deng, X., Hu, C., Xu, H. and Shi, H. (2015a) Changing properties of precipitation extremes in the urban areas, Yangtze River Delta, China, during 1957-2013. *Natural Hazards* 79(1), 437-454.
- [18] Han, L., Xu, Y., Yang, L. and Deng, X. (2015b) Changing structure of precipitation evolution during 1957-2013 in Yangtze River Delta, China. *Stochastic Environmental Research & Risk Assessment* 29(8), 1-12.
- [19] Huang, J., Armt, I., Zhang, F. and Hu, Z. (2017) Spatiotemporal analysis the precipitation extremes affecting rice yield in Jiangsu province, southeast China. *International Journal of Biometeorology* 61(6), 1-10.
- [20] IPCC (2014) Impacts, adaptation, and vulnerability. Part B: regional aspects-contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge, UK and New York, NY.

- [21] Kendall, M. (1975) Rank correlation methods. Charles Griffin, London
- [22] Kisi, O. (2015) An innovative method for trend analysis of monthly pan evaporations. *Journal of Hydrology* 527, 1123-1129.
- [23] Kisi, O. and Ay, M. (2014) Comparison of Mann-Kendall and innovative trend method for water quality parameters of the Kizilirmak River, Turkey. *Journal of Hydrology* 513(5), 362-375.
- [24] Kundzewicz Z. and Robson A. (2000) World climate program-water. Detecting trend and other changes in hydrological data. WMO/TD-No. 1013. WMO, Geneva.
- [25] Mann H.B. (1945) Nonparametric tests against trend. *Econometrica* 13: 245-259
- [26] Milly, P., Betancourt, J., Falkenmark, M., Hirsch, R., Kundzewicz, Z., Lettenmaier, D. and Stouffer, R. (2008) Stationarity Is dead: whither water management? *Science* 319(5863), 573-574.
- [27] Milly, P., Wetherald, R., Dunne, K. and Delworth, T. (2002) Increasing risk of great floods in a changing climate. *Nature* 415(6871), 514-517.
- [28] Mohan, P., Srinivas, C., Yesubabu, V., Baskaran, R. and Venkatraman, B. (2018) Simulation of a heavy rainfall event over Chennai in Southeast India using WRF: Sensitivity to microphysics parameterization. *Atmospheric Research* 210, 83-99.
- [29] National bureau of statistics of China (2015) China Statistical Yearbook 2015. China Statistics Press, Beijing.
- [30] Öztopal, A. and Şen, Z. (2017) Innovative trend methodology applications to precipitation records in Turkey. *Water Resources Management* 31(3), 1-11.
- [31] Pei, F., Wu, C., Liu, X., Hu, Z., Xia, Y., Liu, L.A., Wang, K., Zhou, Y. and Xu, L. (2018) Detection and attribution of extreme precipitation changes from 1961 to 2012 in the Yangtze River Delta in China. *Catena* 169, 183-194.
- [32] Sang, Y.F., Wang, Z. and Liu, C. (2014) Comparison of the MK test and EMD method for trend identification in hydrological time series. *Journal of Hydrology* 510(3), 293-298.
- [33] Sang, Y., Wang, Z., Li, Z., Liu, C. and Liu, X. (2013) Investigation into the daily precipitation variability in the Yangtze River Delta, China. *Hydrological Processes* 27(2), 175-185.
- [34] Scalzitti, J., Strong, C. and Kochanski, A. (2016) Climate change impact on the roles of temperature and precipitation in western U.S. snowpack variability. *Geophysical Research Letters* 43(10) 5361-5369.
- [35] Sen, P. K. (1968) Estimates of the Regression Coefficients Based on Kendall's Tau. *Journal of the American Statistical Association* 63, 1379-1389.
- [36] Şen, Z. (2012) Innovative Trend Analysis Methodology. *Journal of Hydrologic Engineering* 17(9), 1042-1046.
- [37] Şen, Z. (2017a) Innovative trend significance test and applications. *Theoretical & Applied Climatology* 127(3-4), 1-9.
- [38] Şen, Z. (2017b) Hydrological trend analysis with innovative and over-whitening procedures. *Hydrological Sciences Journal* 62(2), 294-305.
- [39] Sonali, P. and Kumar, D. (2013) Review of trend detection methods and their application to detect temperature changes in India. *Journal of Hydrology* 476(1), 212-227.
- [40] Song, X., Song, S., Sun, W., Mu, X., Wang, S., Li, J. and Li, Y. (2015) Recent changes in extreme precipitation and drought over the Songhua River Basin, China, during 1960-2013. *Atmospheric Research* 157, 137-152.
- [41] Storch, H. (1995) Misuses of statistical analysis in climate research, Springer Berlin Heidelberg.
- [42] Sun, F., Roderick, M. and Farquhar, G. (2018) Rainfall statistics, stationarity, and climate change.

- Proceedings of the National Academy of Sciences of the USA 115(10), 2305-2310.
- [43] Sun, W., Mu, X., Song, X., Wu, D., Cheng, A. and Qiu, B. (2016) Changes in extreme temperature and precipitation events in the Loess Plateau (China) during 1960-2013 under global warming. *Atmospheric Research* 168, 33-48.
- [44] Tabari, H., Marofi, S. and Ahmadi, M. (2011) Long-term variations of water quality parameters in the Maroon River, Iran. *Environmental Monitoring & Assessment* 177(1-4), 273.
- [45] Tabari, H., Taye, M.T., Onyutha, C. and Willems, P. (2017) Decadal analysis of river flow extremes using quantile-based approaches. *Water Resource Management* 31 (11), 3371–3387.
- [46] Tabari, H., Taye, M.T. and Willems, P. (2015) Statistical assessment of precipitation trends in the upper Blue Nile River basin. *Stochastic Environmental Research and Risk Assessment* 29(7), 1751-1761.
- [47] Wang, R., Chen, J., Chen, X. and Wang, Y. (2017) Variability of precipitation extremes and dryness/wetness over the southeast coastal region of China, 1960-2014. *International Journal of Climatology* 37(5895).
- [48] Wang X. (2003) Comments on “Detection of undocumented change points: a revision of the two-phase regression model”. *Journal of Climate*, 16: 3383–3385.
- [49] Wang, Y., Xu, Y., Lei, C., Li, G., Han, L., Song, S., Yang, L. and Deng, X. (2016) Spatio-temporal characteristics of precipitation and dryness/wetness in Yangtze River Delta, eastern China, during 1960-2012. *Atmospheric Research* 172-173, 196-205.
- [50] Wang, Y., Song, H., Chao Y. and Chang, H. (2013) The flood risk and flood alleviation benefit of land use management in Taihu Basin. *Journal of Hydraulic Engineer* 44(3):327-335, 44, 2013. (In Chinese)
- [51] Wang, Y., Tabari, H., Xu, Y. and Willems, P. (2019a) Atmospheric and human induced impacts on temporal variability of water level extremes in the Taihu Basin, China. *Journal of Flood Risk Management* doi: 10.1111/jfr3.12539.
- [52] Wang, Y., Tabari, H., Xu, Y., Xu, Y. and Wang, Q. (2019b). Unraveling the role of human activities and climate variability in water level changes in the Taihu Plain using artificial neural network. *Water* 11(4), 720, doi:10.3390/w11040720
- [53] Westra, S., Alexander, L. and Zwiers, F. (2013) Global increasing trends in annual maximum daily precipitation. *Journal of Climate* 26(11), 3904-3918.
- [54] Wu, H. and Qian, H. (2017) Innovative trend analysis of annual and seasonal rainfall and extreme values in Shaanxi, China, since the 1950s. *International Journal of Climatology* 37, 2582-2592.
- [55] Xu Y., Xu, Y., Wang, Y., Wu L., Li, G. and Song, S. (2016) Spatial and temporal trends of reference crop evapotranspiration and its influential variables in Yangtze River Delta, eastern China. *Theoretical & Applied Climatology* 130(3-4), 1-14.
- [56] Yin, Z., Cai, Y., Zhao, X. and Chen, X. (2009) An analysis of the spatial pattern of summer persistent moderate-to-heavy rainfall regime in Guizhou Province of southwest China and the control factors. *Theoretical & Applied Climatology* 97(3-4), 205-218.
- [57] Yuan, J., Xu, Y., Wu, L., Wang J., Wang Y., Xu Y. and Dai X. (2019) Variability of precipitation extremes over the Yangtze River Delta, eastern China, during 1960–2016. *Theoretical and Applied Climatology* 1-15.
- [58] Yue, S., Pilon, P., Phinney, B. and Cavadias, G. (2002) The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes* 16(9), 1807-1829.
- [59] Zang C. and Liu, J. (2013) Trend analysis for the flows of green and blue water in the Heihe River

- basin, northwestern China. *Journal of Hydrology* 502(8), 27-36.
- [60] Zeng H., Gao X. and Zhang W. (2005) Evolution characteristics of the precipitation in the Yangtze River delta based on the probability density. *Chinese Phys* 14(6): 1265-1271.
- [61] Zhang Q., Singh V. P., Sun P., Chen X., Zhang Z. and Li J. (2011) Precipitation and streamflow changes in China: changing patterns, causes and implications. *Journal of Hydrology* 410:204-216
- [62] Zhang, X., Zwiers, F., Hegerl, G., Lambert, F., Gillett, N., Solomon, S., Stott, P. and Nozawa, T. (2007) Detection of human influence on twentieth-century precipitation trends. *Nature* 448(7152), 461-465.
- [63] Zhang, X., Aguilar, E., Sensoy, S., Melkonyan, H. and Semawi, M. (2005) Trends in middle east climate extreme indices from 1950 to 2003. *Journal of Geophysical Research: Atmospheres* 110(D22), 3159-3172.
- [64] Zhou, Z., Wang, L., Lin, A., Zhang, M. and Niu, Z. (2018) Innovative trend analysis of solar radiation in China during 1962-2015. *Renewable Energy* 119, 675-689.
- [65] Zolina, O., Simmer, C., Gulev, S. and Kollet, S. (2010) Changing structure of European precipitation: Longer wet periods leading to more abundant rainfalls. *Geophysical Research Letters* 37(6), 460-472.