



# Spatial and temporal variabilities in baseflow characteristics across the continental USA

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## Abstract

Trends in baseflows based on observed daily streamflow data are evaluated in this study at several sites in the least anthropogenically affected watersheds in the USA. Trends were determined for annual maximum, annual mean, and annual median baseflow. Baseflow values derived at 574 stations in the USA for the 44 years from 1970 through 2013 are analyzed using two nonparametric trend tests (Spearman's rho (SR) test and Mann-Kendall (MK)). Results from the trend tests are compiled for 18 major regions to understand the spatial variability of changes in baseflows across the USA. Results from SR tests indicate that almost half of the stations show statistically significant trends in annual maximum baseflows. Trends in annual median baseflows show that 32.06% of the gauging stations have downward trends, and a total of 56.45% of sites show significant trends for annual mean baseflows. The Souris-Red-Rainy, Missouri, and California watershed regions have a larger number of sites with higher upward trends compared with those from other regions in the USA. The results from the SR test indicate that 262 sites have statistically significant trends in annual maximum baseflow compared with the 254 sites with similar trends noted from the MK test. Based on limited data, it can be concluded that baseflow and precipitation values accumulated for the same month are correlated in some regions. In general, the number of sites with decreasing trends for annual maximum, mean, and median baseflows is larger than the number of sites with increasing trends. Decreasing trends in baseflows are cause for concern and have serious implications on future planning for low flow management strategies for several streams in the USA.

## 1 Introduction

Climate variability and change are expected to modify the hydroclimatology of a region and hydrologic regime of a watershed. Xu and Singh (2004) emphasized that changes in regional water availability can affect many aspects of human society, from agricultural productivity and energy use to flood control, municipal and industrial water supply, and fisheries and wildlife management. Climate model simulations using enhanced greenhouse forcings generally indicate widespread increases in precipitation and runoff, an outcome frequently

cited as representing an intensified or accelerated hydrologic cycle (Cubasch et al. 2001; Milly et al. 2002). The importance of an intensified hydrologic cycle stems from the possibility that it could lead to an increase in extreme hydrologic events, such as floods, droughts, and other water-related disasters (Milly et al. 2002).

Several past research studies have shown that temporal changes in streamflow characteristics during the twentieth century in different regions of the world. During this period, global warming, which is determined to be the main factor causing climate change, is known to be one of the main contributors to streamflow variations. McCabe and Wolock (2002) indicated that most changes in streamflow statistics in the USA appear as increasing in annual minimum and median daily streamflow in the eastern USA, and all of the increases in annual streamflow statistics appear to have been the result of a step change around 1970 rather than as a gradual trend. Burn (2008) has used partial correlation analysis to evaluate the trends in the runoff in northern Canada. Stahl et al. (2010) found that annual streamflow trends in many regions appear to reflect wetting trends of the winter months. Miao and Ni (2009) found that the natural streamflows during

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two time periods 1470–1880 and 1880–2007 have shown increasing and decreasing trends, respectively, in the Yellow River basin. Similar results were also noted for the USA, where Lins and Slack (2005) reported that streamflow increased in all water resource regions of the conterminous USA between 1940 and 1999.

Baseflow is one of the important components of streamflow that is mainly contributed by the subsurface flow. Knowledge about baseflow is generally used in the assessment of water quality and low flow conditions. According to Sophocleus (2002), baseflow is water that enters a stream from persistent, slowly varying sources and maintains streamflow between inputs of direct flow (also known as events flow, stormflow, or quick flow). Reay et al. (1992) indicated that neglecting groundwater discharge as a nutrient source may lead to misinterpretation of data and error in water quality management strategies. As baseflow is an important hydrological characteristic to understand low-flow occurrences, the baseflow index has a strong relationship with the drainage density index in the Great Ruaha Basin in Tanzania (Mwakalila et al. 2002). Santhi et al. (2008) detected that the volume of baseflow could be affected by precipitation, sand conditions, and relief. Furthermore, the conditions which influence baseflows are related to land-use characteristics and surface slope (Rumsery et al. 2015). Ficklin et al. (2016) found trends in baseflow and stormflow, which were influenced by climate change and variability. Esralew and Lewis (2010) have evaluated trends in the annual and seasonal baseflow index values from 25 sites in Oklahoma in the USA. They found that 23 sites showed upward trends. Meyer (2005) suggested that statistically significant monotonic increasing trends are displayed by the annual median base flows in all three of the streams. Studies evaluating baseflow trends have been carried out in different regions around the world. Zheng et al. (2011) have reported that the baseflow of the Wei River Basin in China has decreased from 1935 to 2005, and this trend is expected to continue in the future. Evaluation of changes and trends in baseflows in both space and time will be beneficial for water resource management. Baseflow separation procedures to obtain baseflow from streamflows have been developed and researched in several studies (Hall 1968; Tallaksen 1995; Eckhardt 2008; Hodgkins and Dudley 2011; Bastola et al. 2018; Jung et al. 2016).

Statistical trend analysis can be used to assess changes in baseflow and that a series of changes in the time series are often used to predict future events. Baseflow trend analysis can be useful for understanding hydroclimatological influences on one of the major components of streamflow. Most studies (Helsel and Hirsch 1992; Tosic et al. 2014; Chen et al. 2016; Rahman et al. 2017; Wang et al. 2015; Meshram et al. 2017) used for evaluation of historical changes in streamflows have used nonparametric statistical trend tests, such as Mann-Kendall and Spearman's rho tests. The main focus of this

study is the evaluation of changes in baseflows in the continental USA. This paper presents an analysis of trends in baseflows derived from long-term US Geological Survey (USGS) daily streamflow records from the USA over the period of 1970–2013. Trend tests and correlation analysis are employed to characterize temporal changes in baseflow. The study is expected to provide a better understanding of changes in low flows and will help in future water use and management affected by possible climate change. Another objective of this study is to understand the spatial and temporal variations in baseflow in the least distributed anthropogenically watersheds of the USA. Evaluation of trends and changes in baseflows is carried out using nonparametric statistical hypothesis tests. The contents of the paper are organized as follows. The methodology adopted in this study, baseflow separation procedures, and statistical hypothesis tests are discussed in the next few sections. Details of the case study and data are provided next. Finally, results and analysis, along with conclusions, are presented.

## 2 Methodology

The methodology used in the current study to evaluate changes in baseflows is shown in Fig. 1 by a series of steps. Streamflow data are used to derive daily baseflow values and are subsequently used for trend analysis. The trends are analyzed using Spearman's rho and Mann-Kendall tests. The variables  $n$  and  $n_{\max}$  indicated in Fig. 1 refer to the streamflow gauging site and the total number of sites, respectively.

### 2.1 Baseflow separation approaches

Baseflow separation methods can be summarized into two main categories: (Adeloye & Montaseri, 2002) graphical methods and (Ahmad et al., 2015) continuous hydrographic separation techniques. Discussion about these methods is provided by Teegavarapu (2012). Constant discharge (Linsley, 1958), constant slope, and concave method are the three typical types of graphical methods that select points on the rising and receding limbs of the hydrograph. Typical methods of continuous hydrographic separation techniques will involve the computation of baseflow from streamflow data by using the entire hydrograph. Also, different baseflow separation techniques have been used in past studies, and they include smoothed minima techniques (Institute of Hydrology 1980; Gustard et al. 1989, Sloto and Crouse 1996), fixed interval method (Pettyjohn and Henning 1979), streamflow partitioning method (Shirmohammadi et al. 1984), antecedent precipitation index (Conger, 1978), and recursive digital filters (Smakhtin 2001, Nathan and McMahan 1990, Hughes et al. 2004).

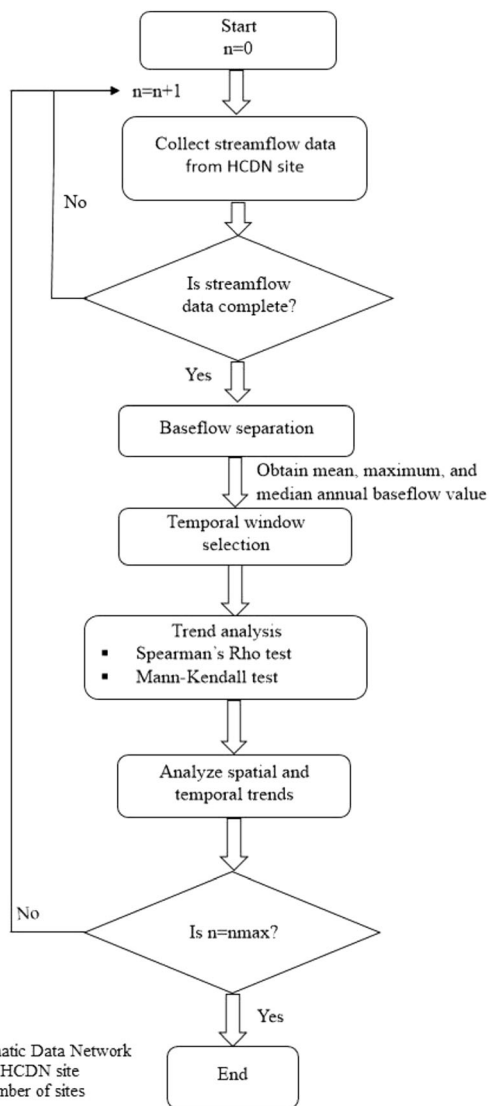


Fig. 1 Methodology to assess trends in baseflows explained in a series of steps

Sloto and Crouse (1996) developed a software to separate the baseflow and surface runoff components of daily streamflow. This software referred to as the HYdrograph SEPeration (HYSEP) includes three methods: (Adeloye & Montaseri, 2002) fixed-interval, (Ahmad et al., 2015) sliding-interval, and (Bastola et al., 2018) local- minimum. Several recent studies (Meyer, 2005; Dai et al. 2010; Brandes et al. 2005; Stadnyk et al., 2014; Stewart et al., 2007) have used HYSEP to derive and evaluate baseflows. The duration of surface runoff that is required in the three methods of HYSEP is computed using Eq. (1).

$$N = A^{0.2} \tag{1}$$

The variable  $N$  is the number of days after which the surface runoff ceases, and  $A$  is the drainage area in square miles (Linsley, 1982). The fixed-interval method finds the lowest

discharge in each interval ( $2 N^*$ , where  $N^*$  is the integer). The sliding-interval method assigns the lowest discharge in one-half the interval minus 1 day ( $0.5(2 N^* - 1)$  days). The local-minimum method selects the minimum flow before and after  $0.5(2 N^* - 1)$  day, and then each minimum point is connected by a straight line. The baseflow value of each day is obtained by linear interpolations. In this study, HYSEP with the local-minimum method is used for obtaining the estimates of baseflows.

### 2.2 Kernel density estimates

Kernel density estimates (KDEs) are used to analyze the distribution of annual maximum, mean, and median baseflows. The baseflows derived from streamflows are evaluated using the kernel smoothing function estimate, which is similar to a smoothed histogram. The KDE for a set of baseflow values is obtained using Eq. (2) (Parzen 1962),

$$f_h(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x-x_i}{h}\right) \tag{2}$$

where  $h$  controls the size of the neighborhood around  $x_0$ , and it is the smoothing parameter. The variable  $K$  is referred to as the kernel, and it controls the weight given to the observation  $x_i$  at each point  $x_0$  (Teegavarapu et al. 2013).

### 2.3 Runs test

Runs test is generally used to evaluate a series of data which satisfies randomness from a particular distribution. This test that analyzes the difference occurring in similar events is described by McGhee (1985). The runs test can determine whether an outcome of a trial is truly random, which is important to evaluate the hydrological data set using a trend test. A random model can be written as Eq. (3):

$$Y_t = \mu + \epsilon_t \quad \forall t \tag{3}$$

where  $\mu$  is a constant, the average of the  $Y_t$ , and  $\epsilon_t$  is the residual (or error) term, which is assumed to have a zero mean and a constant variance and to be probabilistically independent. To find out,  $T$  is the number of observations,  $T_A$  is the number above the mean and  $T_B$  is the number below the mean. Let  $R$  be the observed number of runs. Then using combinatorial methods Eqs. (4), (5), and (6), the probability  $P(R)$  can be established, and the mean and variance of  $R$  can be derived (Adeloye and Montaseri 2002):

$$E(R) = \frac{T + 2T_A T_B}{T} \tag{4}$$

$$V(R) = \frac{2T_A T_B (2T_A T_B - T)}{T^2 (T-1)} \tag{5}$$

$$Z = \frac{R - E(R)}{\text{Stdev}(R)} \sim N(0, 1) \quad (6)$$

## 2.4 Spearman's rho test

The Spearman's rho (SR) test, also known as the Spearman rank-order correlation coefficient test, is a nonparametric statistical test that determines the relationship between two variables on an ordinal scale of measurement (Corder and Foreman 2014). This test can be used for confirmation of the existence of trends in time series data. The SR test has been used in the past several studies (Ahmad et al. 2015; Shadmani et al. 2012; Tuomisto et al. 2012; Kamnitiui et al. 2019) for evaluation of hydroclimatic variables. The rank correlation analysis is used to test the null hypothesis that there is no correlation in the sample between the ranked data (Zar 1972). Equation (7) (Corder and Foreman 2014) can be used to find the correlation coefficient ( $\rho$ ) between the two rank-ordered independent variables, in this case, baseflow data and time.

$$\rho = 1 - \frac{6 \sum_{i=1}^n D_i^2}{n^3 - n} \quad (7)$$

where  $D_i$  is the difference between a ranked pair,  $n$  is the number of rank pairs, and  $\rho$  is the Spearman rank-order correlation coefficient.

The magnitude of rho ( $\rho$ ) indicates the strength of the relationship between two independent variables (Cohen 1988). After computing the Spearman rank-order correlation, a hypothesis test was used to determine, with 95% significance, whether a correlation exists or not. The null ( $H_0$ ) and the alternative ( $H_a$ ) hypotheses used are as follows: (Adeloye & Montaseri, 2002)  $H_0$ :  $\rho = 0$ , correlation or trend does not exist (95% confidence). (Ahmad et al., 2015)  $H_a$ :  $\rho < 0$ , correlation or trend exists ( $p$ -value  $< 0.05$ ). (Bastola et al., 2018)  $H_a$ :  $\rho > 0$ , correlation or trend exists ( $p$ -value  $< 0.05$ ).

## 2.5 Mann-Kendall test

The Mann-Kendall (MK) test is a rank-based nonparametric test that detects linear and non-linear trends, where the null and alternative hypotheses are equal to the non-existence and existence of a trend in a time series, respectively. The MK test has been used in several past studies for the evaluation of trends in streamflows and other hydrologic variables. A comprehensive list of studies using the MK test for hydroclimatic variables was provided by Teegavarapu (2018). Bawden et al. (2014) used the MK test for the evaluation of hydrological trends and variability analysis in the Athabasca River region in Canada. Kisi et al. (2018) used the MK test to evaluate streamflow data in the Black Sea Region of Turkey. The

following Eqs. (8) and (9) are used to calculate the MK test statistic ( $S$ ) (Sagarika et al., 2014).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (8)$$

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (9)$$

where  $S$  is the Mann-Kendall test statistic,  $n$  is the length of the time series, and  $x_j$  and  $x_k$  are sequential data values in time series  $j$  and  $k$ . When the length of the time series  $n \geq 8$ , studies have shown that the Mann-Kendall statistic is nearly normally distributed with a mean  $E(S) = 0$  (Mann 1945), and the variance  $\text{Var}(S)$  was calculated using Eq. (10).

$$\text{Var}(S) = \frac{1}{18} [n(n-1)(2n+5)] \quad (10)$$

If tied values are found in the data, then Eq. (11) can be used to determine the variance  $\text{Var}(S)$  value:

$$\text{Var}(S) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \quad \forall p \quad (11)$$

where  $q$  is the number of tied groups and  $t_p$  is the number of ties. The standardized MK test statistic  $Z_{MK}$  was calculated using Eq. (12):

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (12)$$

A positive value for  $S$  indicates a positive trend. Whereas, a negative value for  $S$  indicates a negative trend. The trend is said to be significant when  $Z_{MK}$  is greater than the standard normal variate  $Z_{\alpha/2}$ , where  $\alpha$  was the percent significant level. Additionally, tau ( $\tau$ ) is calculated using Eq. (13) to identify whether the slope of the data is rising or reducing.

$$\tau = \frac{S}{n(n-1)/2} \quad (13)$$

## 3 Data and study domain

Daily streamflow data from a network of 574 gauging stations located in the least anthropogenically influenced watersheds in the continental USA with complete data for the period of 1970–2013 are used for analysis in this study. This network of stations identified by the US



Geological Survey (USGS) as Hydro-Climatic Data Network (HCDN) is ideal for studying variations in US surface water conditions (Slack and Michaels, 1992). The stations that are part of the HCDN are identified by the USGS (Slack and Michaels, 1992) using several criteria, and they are (Adeloye & Montaseri, 2002) unimpaired basin conditions; (Ahmad et al., 2015) no flow diversion or augmentation and no regulation of flows by any impoundment structure; (Bastola et al., 2018) no reduction of baseflow by ground-water pumping; and (Bawden et al., 2014) no changes to land use and substantial human activity that will affect the streamflow characteristics. The long-term streamflow datasets from this network are suitable for analyzing hydrological variations and trends and establish possible links to climate variability and change. Currently, 793 stations are part of the HCDN for which long-term data is available. A revised data set that consists of daily streamflow for 574 stations located in unimpaired watersheds for the period of 1970–2013 is used in this study. The locations of these sites are shown in Fig. 2. The reduction of 165 stations from 739 was a result of the data not being updated on the USGS website for the period of interest and also due to missing data. A total of 136 stations had data that began later than 1970, and observations at 29 sites ended before 2013. The analysis in this study is carried out on a calendar year basis (i.e., January 1 to December 31). Baseflows are known to be heavily influenced by human activities; therefore, selecting sites located in the least anthropogenically influenced watersheds can help evaluate the influences of climate change without other known influences. The USA is divided and subdivided into successively smaller

hydrologic units, which are classified into four levels: regions, sub-regions, accounting units, and cataloging units (Seaber et al. 1987). Each unit is assigned a unique hydrologic unit code (HUC), which provides an identification number. The analysis in this study focuses on 18 major geographic regions identified by HUC2 and HUC8 (i.e., HUCs identified by two-digit and eight-digit numbers).

## 4 Results and analysis

The baseflow variations throughout the continental USA are evaluated using two nonparametric tests discussed in the previous sections. The tests were used to evaluate annual maximum, mean, and median baseflow values derived from 574 stations to detect the existence or non-existence of trends, as well as to understand the historical data behavior by analyzing the entire baseflow data at each station.

### 4.1 Evaluation of runs test results

The results of the runs test to evaluate of annual maximum, mean, and median baseflow are shown in Fig. 3 a, b, and c. Results show that annual maximum baseflow values at 144 stations have failed the runs test, which suggests that these values are not random. A total of 430 stations noted that the annual maximum baseflows are random based on the test evaluated at a 5% significance level for the period of 1970–2013. Furthermore, the annual mean baseflows at 297 sites showed nonrandom characteristics; it has decreased the 30% of sites to compare with the annual maximum. In the east coast area,

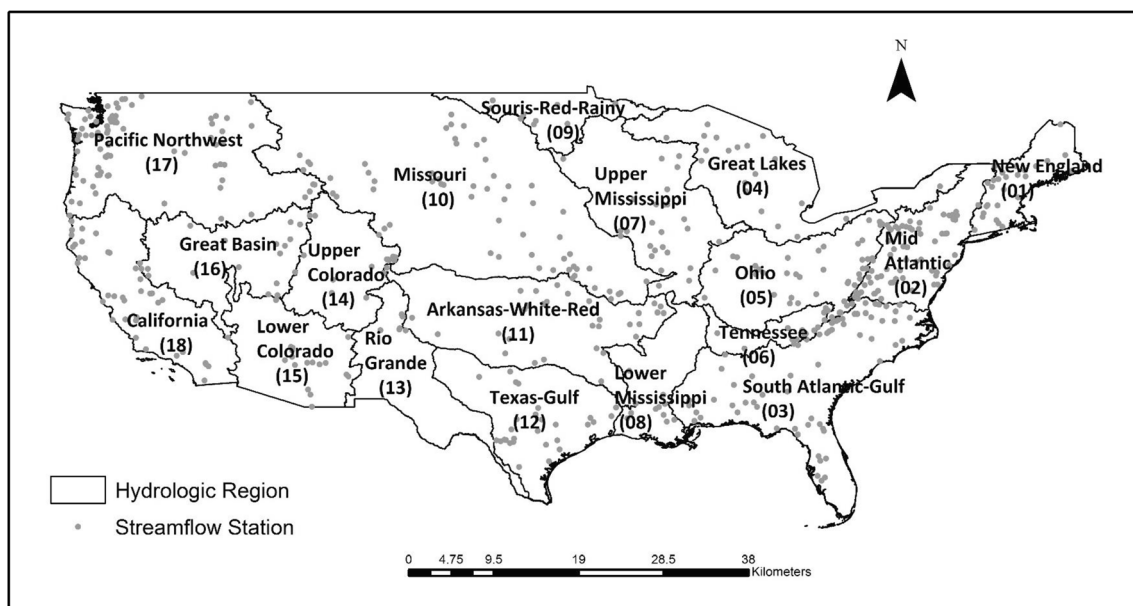
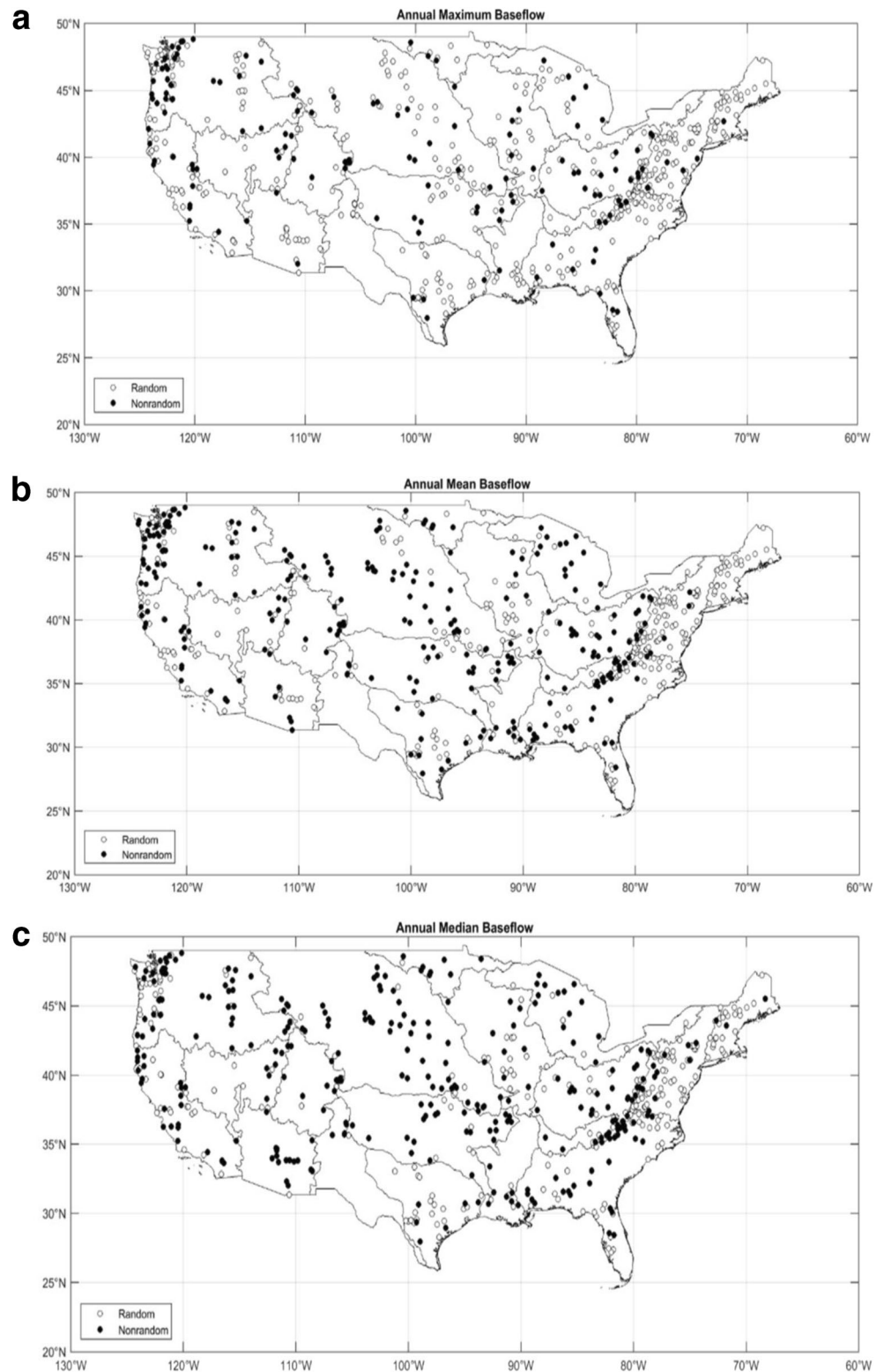


Fig. 2 Spatial distribution of 574 streamflow gauging sites in 18 hydrologic regions across the continental USA

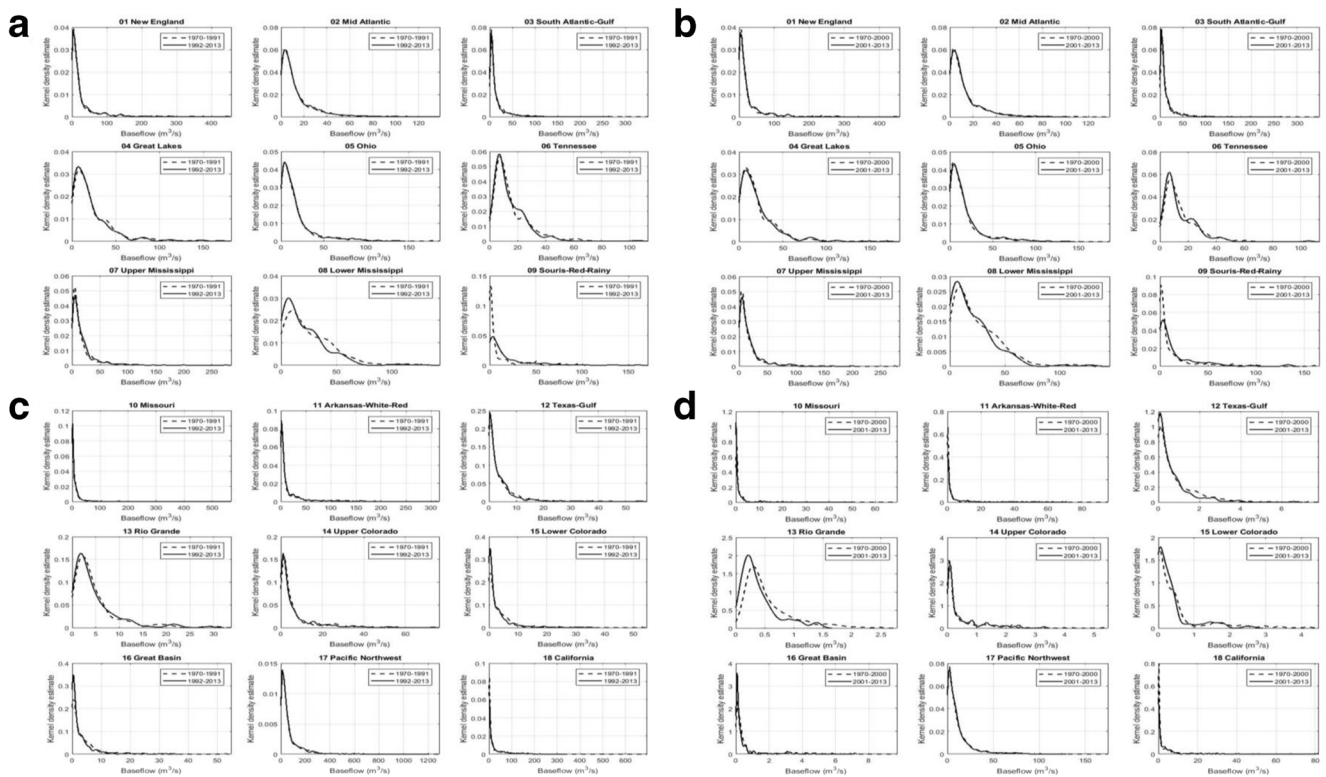
**Fig. 3** Results from the runs test evaluations of the randomness of (a) annual maximum, (b) annual mean, and c annual median baseflow for the period of 1970–2013



more than 86% of total stations showed that the annual median baseflows are random. The comparison of annual maximum, mean, and median baseflow and the annual median baseflows show the least number of sites that have a random series of values.

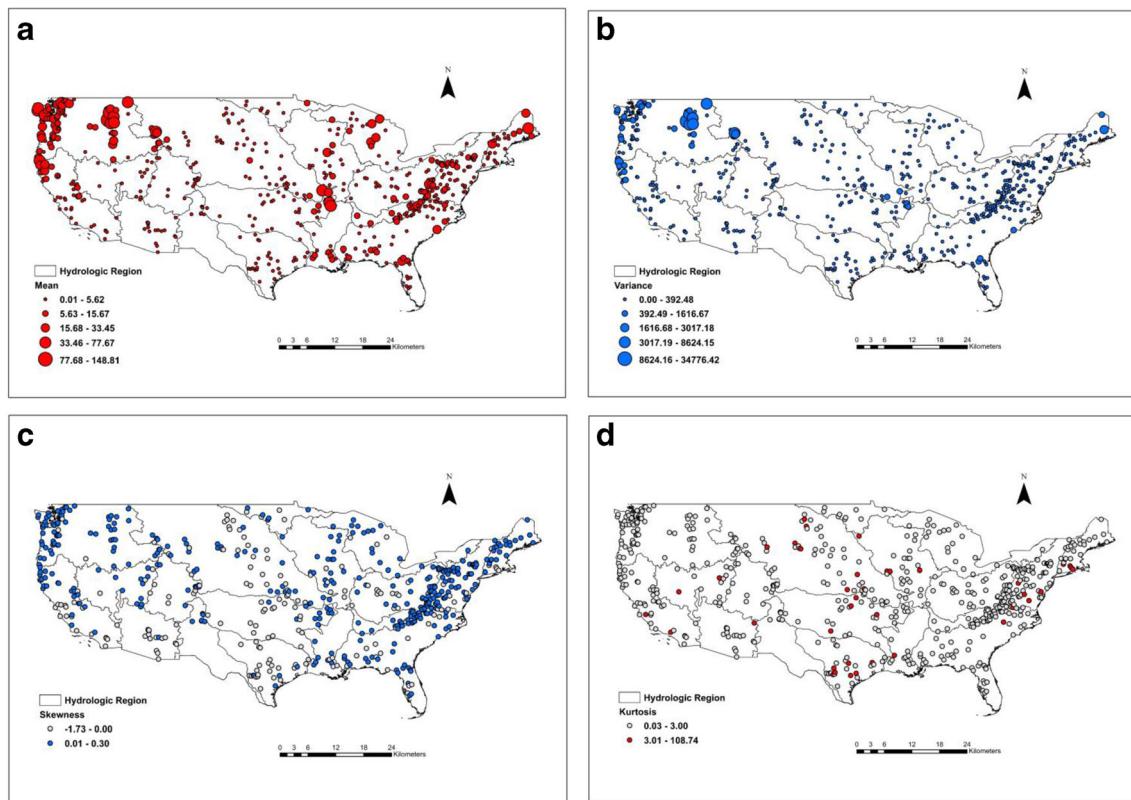
#### 4.2 Kernel density estimates

Kernel density estimates (KDEs) provide a visual representation of the changes in the distribution of the variable of interest. In this study, they are used to show the changes in



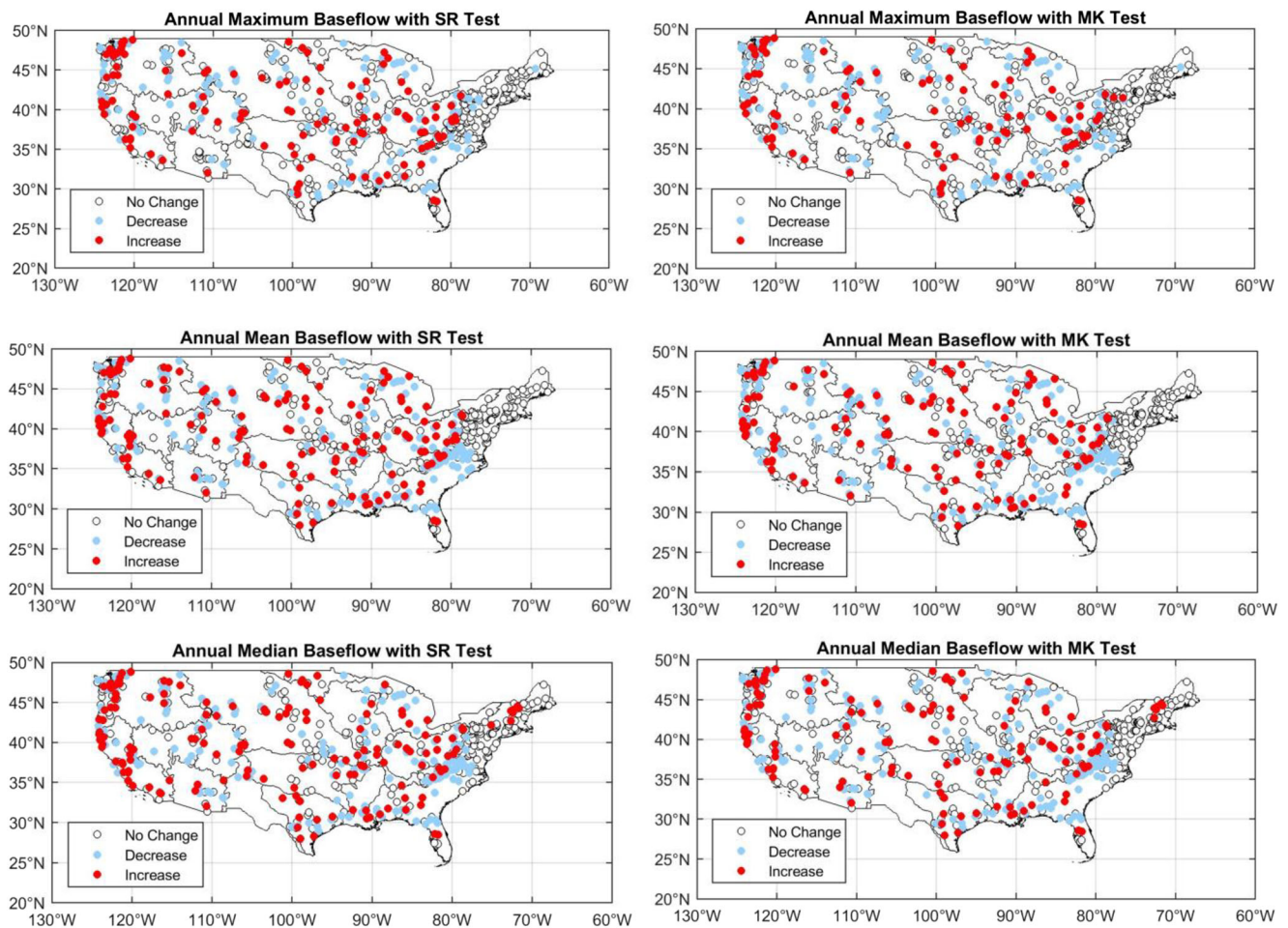
**Fig. 4** Kernel density estimates based on (a), (b) annual maximum baseflow in two temporal windows (1970–1991 and 1992–2013) in 01 to 09 watershed regions and 10 to 18 watershed regions and (c), (d)

annual median baseflow in two temporal windows (1970–2000 and 2001–2013) in 01 to 09 watershed regions and 10 to 18 watershed regions



**Fig. 5** Spatial variation of mean, variance, skewness, and kurtosis of daily baseflow value in the continental USA (1970–2013)





**Fig. 6** Variation of annual maximum, mean, and median baseflow trends based on Spearman’s rho and Mann-Kendall test in the continental USA (1970–2013)

distributions of the baseflows in two temporal windows. Kernel density estimates (KDEs) are used to analyze the distributions of annual maximum and median baseflow occurrences during two different sets of temporal windows (1970–1991 and 1992–2013, 1970–2000 and 2001–2013) in 18 major regions. The KDEs of annual maximum and median baseflow are shown in Fig. 4 a, b, c, and d, respectively. It appears that there is very little variation between the distributions of the baseflows in the two temporal windows. The annual maximum and median baseflow data from South Atlantic-Gulf (03), Lower Mississippi (08), Souris-Red-

Rainy (09), Missouri (Corder & Foreman, 2014), Lower Colorado (Ficklin et al., 2016), and Great Basin (Gustard et al., 1989) regions have different distributions in 1970–1991 and 1992–2013. The distribution of annual maximum and median baseflow values in South Atlantic-Gulf (03), Lower Mississippi (08), Missouri (Corder & Foreman, 2014), Lower Colorado (Ficklin et al., 2016), and Great Basin (Gustard et al., 1989) regions has shifted to the left, and the distribution in the Souris-Red-Rainy (09) has moved to the right. In the other two temporal windows (1970–2000 and 2001–2013), the number of regions that have differences

**Table 1** Annual maximum daily baseflow trend analysis summary results based on two tests

Temporal window	Spearman’s rho (SR) test			Mann-Kendall (MK) test		
	1970–2013	1980–2013	1990–2013	1970–2013	1980–2013	1990–2013
No significance (%)	54.35	51.92	50.70	55.75	52.96	52.44
Significance (%)	45.65	48.08	49.30	44.25	47.04	47.56
Increasing (%)	44.27	47.46	45.94	38.58	45.19	44.32
Decreasing (%)	55.73	52.54	55.06	61.42	54.81	55.68



**Table 2** Annual mean daily baseflow trend analysis summary results based on two tests

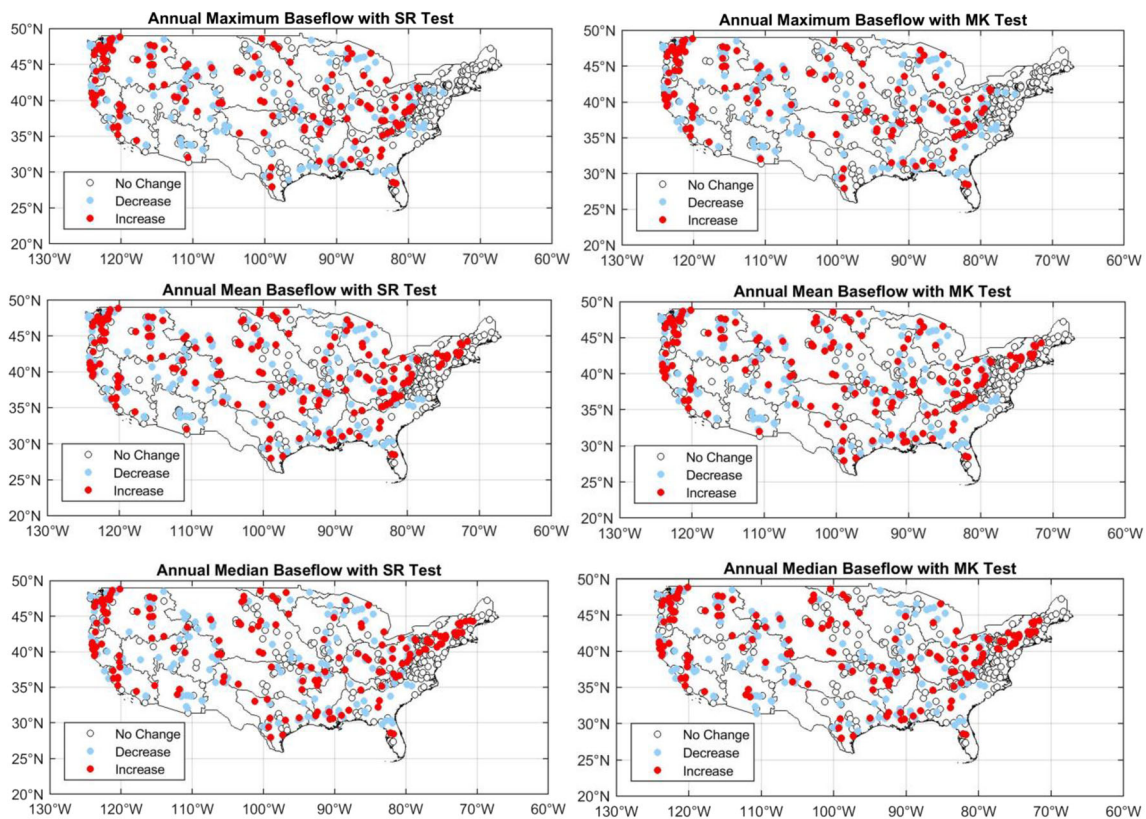
Temporal window	Spearman’s rho (SR) test			Mann-Kendall (MK) test		
	1970–2013	1980–2013	1990–2013	1970–2013	1980–2013	1990–2013
No significance (%)	43.55	42.51	41.29	44.43	43.03	43.90
Significance (%)	56.45	57.49	58.71	55.57	56.97	56.10
Increasing (%)	43.83	52.12	45.70	38.87	50.15	44.41
Decreasing (%)	56.17	47.88	54.30	61.13	48.85	55.59

in distributions increased from six to nine. Texas-Gulf (Dai et al., 2010), Rio Grande (Eckhardt, 2008), Upper Colorado (Esralew & Lewis, 2010), and California (Hamed & Rao, 1998) represented that the distribution of annual maximum and median baseflows has shifted to the left, and the remaining watershed regions show the distribution has moved to the right.

**4.3 Summary statistics**

Variations of summary statistics of baseflows for the 1970–2013 period are presented in Fig. 5a–d. From the mean daily baseflow values shown in Fig. 5a, it can be noted that there is an increase in the mean values in Pacific Northwest (Hall, 1968), upper of California (Hamed & Rao, 1998), east of Arkansas-White-Red (Cubasch et al., 2001), Great Lakes

(04), and upper of New England (01) compared with those in other regions. It can also be noted that the mean values are lower in Texas-Gulf (Dai et al., 2010), Rio Grande (Eckhardt, 2008), Lower Colorado (Ficklin et al., 2016), and Great Basin (Gustard et al., 1989). Occurrences of low streamflow and semi-arid climate may contribute to low baseflows. Figure 5 b shows the changes in variance values at different sites. Higher variance values are noted at those sites which have higher mean values in the 1970–2013 period. Sites with the lowest variance values are located in Ohio (05), Mid-Atlantic (02), and South Atlantic-Gulf (03) regions. The results of the daily baseflow skewness values are shown in Fig. 5c, the most positive baseflow skewness values located on the east and west coasts, and the negative values located in central and southwest USA. Figure 5 d shows the variation of daily baseflow kurtosis values in the period of 1790–2013. A total



**Fig. 7** Variation of annual maximum, mean, and median baseflow trends based on Spearman’s rho and Mann-Kendall test in the continental USA (1980–2013)

**Table 3** Annual median daily baseflow trend analysis summary results based on two tests

Temporal window	Spearman’s rho (SR) test			Mann-Kendall (MK) test		
	1970–2013	1980–2013	1990–2013	1970–2013	1980–2013	1990–2013
No significance (%)	40.94	42.68	41.99	41.46	44.95	44.25
Significance (%)	59.06	57.32	58.01	58.54	55.05	55.75
Increasing (%)	45.72	50.46	48.35	39.58	50.95	45.31
Decreasing (%)	54.28	49.54	51.65	60.42	49.05	54.69

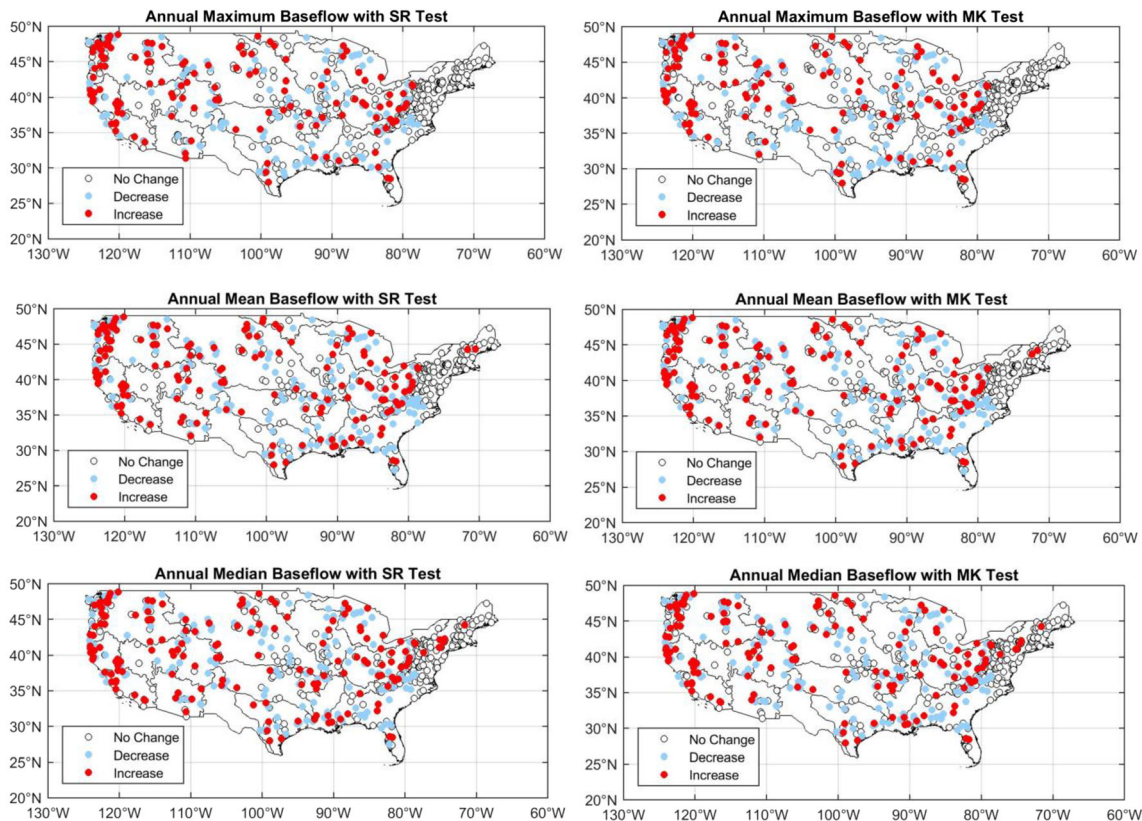
of 90% of sites show the kurtosis values of more than three and the highest rate of kurtosis values, which are below three and distributed in Texas-Gulf (Dai et al., 2010).

**4.4 Trends analysis**

The SR and MK tests are used to evaluate trends in annual maximum, mean, and median baseflow data at all the selected sites. The tests are carried out at a 5% significance level. A summary of trend analysis results for annual maximum, mean, and median baseflow for the period of 1970–2013 is provided in Fig. 6. The results show that a total of 262 stations (45.65%) have an upward or downward trend and are statistically significant. A total of 146 stations (55.73%) show a decreasing trend, and the remaining 116 stations (44.27%) show no change in the annual maximum baseflow time series.

The Mid-Atlantic and Texas-Gulf regions show high percentages of downward trends. Most of the sites in the New England watershed show no statistically significant trends. However, a large number of sites with an upward trend in annual maximum baseflow trends are in Souris-Red-Rainy and Pacific Northwest watersheds. The results from the MK test for the annual maximum are similar to those from the SR test.

The MK test results shown in Fig. 6 for the annual maximum indicate that a total of 156 stations have a downward trend, and 98 stations show an upward trend. The remaining 320 stations show no change for the time series. A comparison between MK and SR tests suggests that there is a higher percentage of positive trends on the west coast than from those indicated by the MK test. Furthermore, the SR results have 8 more stations that have statistically significant trends, and 18



**Fig. 8** Variation of annual maximum, mean, and median baseflow trends based on Spearman’s rho and Mann-Kendall test in the continental USA (1990–2013)

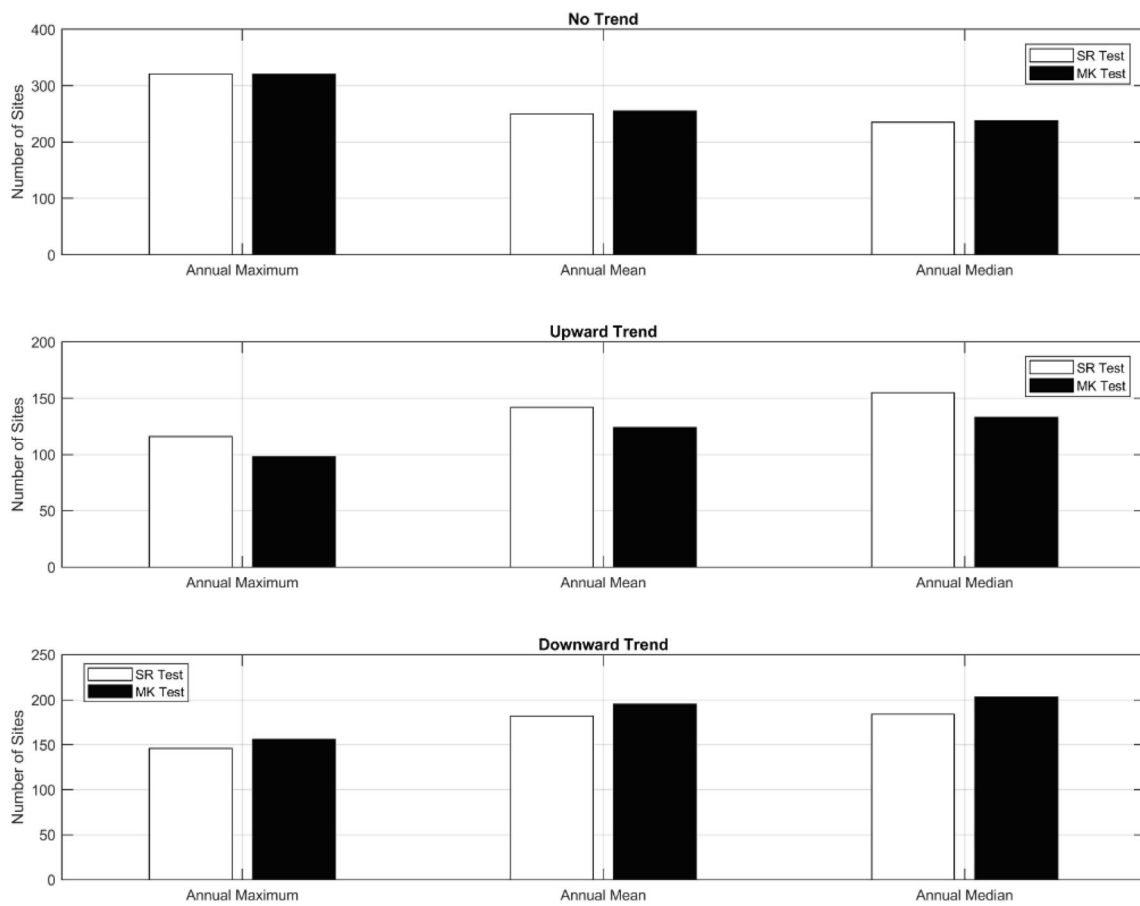


Fig. 9 Results from two trend tests for annual maximum, mean, and median baseflow in the period of 1970–2013

Table 4 Results of the Mann-Kendall (MK) tests with annual maximum baseflow in the period of 1970–2013

Hydrologic region (HUC#)	Region name	Number of stations with the trend			
		Downward	No significance	Upward	Total
01	New England	1	26	0	27
02	Mid-Atlantic	2	62	2	66
03	South Atlantic-Gulf	21	38	5	64
04	Great Lakes	8	8	4	20
05	Ohio	15	12	14	41
06	Tennessee	5	7	4	16
07	Upper Mississippi	4	15	6	25
08	Lower Mississippi	4	5	2	11
09	Souris-Red-Rainy	2	4	2	8
10	Missouri	18	32	11	61
11	Arkansas-White-Red	8	13	10	31
12	Texas-Gulf	10	14	4	28
13	Rio Grande	0	7	0	7
14	Upper Colorado	7	7	2	16
15	Lower Colorado	5	11	2	18
16	Great Basin	7	7	4	18
17	Pacific Northwest	30	34	15	79
18	California	9	18	11	38
Total		156	320	98	574

**Table 5** Results from Mann-Kendall (MK) and modified Mann-Kendall tests with annual maximum baseflow in the period of 1970–2013 for sites with statistically significant autocorrelation

MK test	Modified MK test	Number of sites
Downward trend	Upward trend	10
Upward trend	Downward trend	20
Upward trend	No trend	5
Downward trend	No trend	2
No trend	Upward trend	1
No trend	Downward trend	5

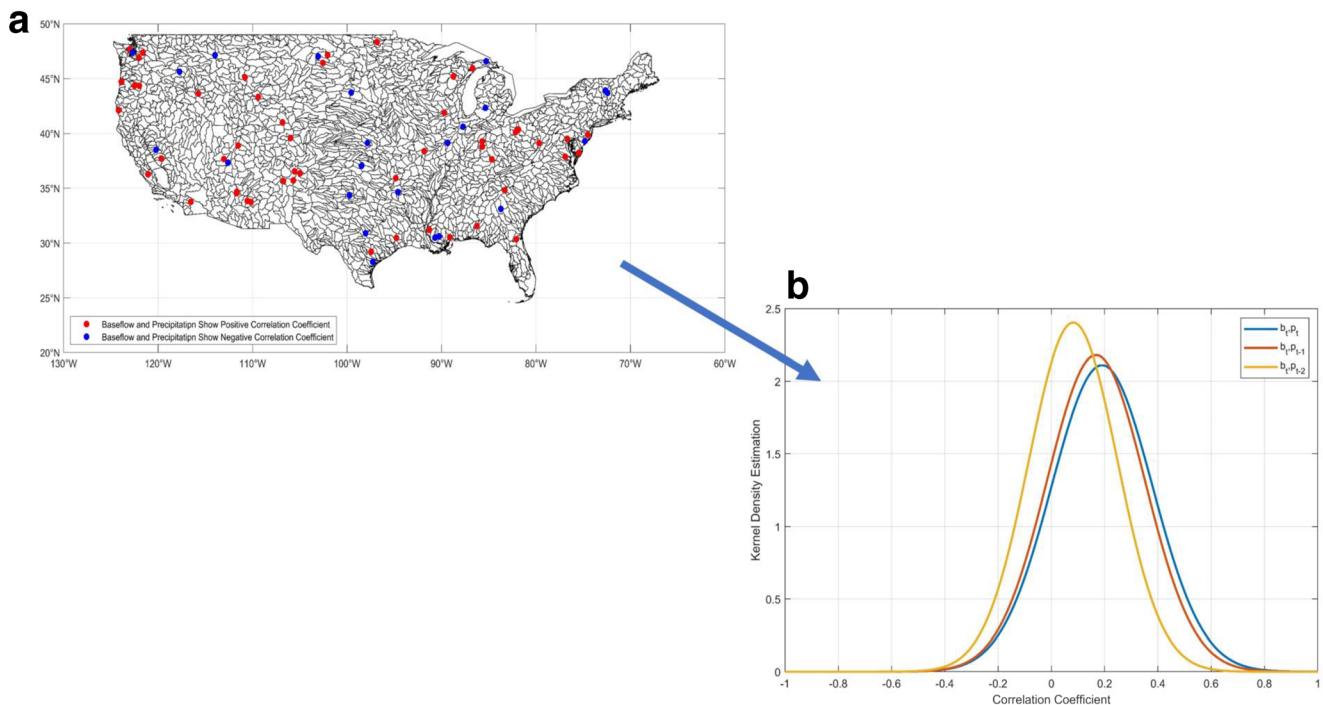
more stations have increasing trends. A summary of the results from SR and MK tests is provided in Table 1.

The analysis of changes in the annual mean baseflow provides more stations with statistically significant trends in both two nonparametric tests. Trends are noted at 62 and 65 sites based on SR and MK tests, respectively. Evaluation of annual mean baseflow trends suggests that 24.74% of stations have increasing trends, and 31.71% of stations have decreasing trends. It can be noted that sites from the west coast have a higher percentage of upward trends. However, the sites with a high percentage of downward trends are noted in the east coast. Out of 11 sites, 7 sites showed increasing trends in the MK test in the Souris-Red-Rainy watershed. In the South Atlantic-Gulf watershed, the higher percentages of sites with decreasing trends are noted, but most of the stations have no statistically significant trends in New England and Mid-Atlantic watersheds.

Table 2 presents the results obtained from the SR and the MK trend tests.

Trend analysis results for annual maximum, mean, and median baseflow for the period of 1980–2013 with two non-parametric tests are shown in Fig. 7. It is clear from this figure that the Great Lakes and Great Basin have a large number of sites with negative trends. However, there are no statistically significant trends in the southeast of Missouri. In the New England region, no statistically significant trends in annual maximum and mean baseflows were observed, but almost one-third of stations have upward trends for annual median baseflows. Changes in this dataset have the highest percentage (57.49%) of statistically significant trends. Differences between SR and MK test results are shown in Table 3. It is interesting to note that a greater number of stations show increasing trends in annual mean and median baseflow in this period (i.e., 1980–2013). In the case of annual mean trends, the SR test indicated that 172 and 158 stations have upward and downward trends, respectively. SR tests reveal that five more stations (166) show increasing trends for annual median baseflows compared with the MK test (161).

Results from SR and MK tests for annual maximum, mean, and median baseflows for the period of 1990–2013 are shown in Fig. 8. The sites with no trends are largest for annual maximum baseflows compared with mean and median baseflows. Also, sites with the most statistically significant trends are noted for annual mean baseflows. The maximum difference in sites (i.e., 36 stations) between upward and downward is noted for the period of 1990–2013. The results of trend



**Fig. 10** (a) Variation of the relationship between baseflow and precipitation trends based on Spearman's rho test in the continental USA in HUC8 (1970–2013). (b) Variation of correlations between baseflow ( $b_t$ ) and precipitation ( $p_t$ ) totals in a month  $t$ , for the period of 1970–2013



analyses for annual maximum baseflow show similar numbers with no changes and statically significant trends. Especially, there are more decreasing trends (161 stations) than increasing (172 stations). In the other two variables, the number of stations with downward trends is larger than sites with upward trends. Furthermore, the results suggest that there is a large number of sites (i.e., 337 sites) with statistically significant trends in annual mean baseflow.

The differences in the trend analysis results based on SR and MK tests are shown in Fig. 9. The total of number sites that display no statistical significance is almost similar in annual maximum, mean, and median baseflows. SR test has more stations with an upward trend, and the MK test has more stations with a downward trend. Results from the MK test for annual maximum baseflow for sites located in different HUC 2 regions for the period of 1970–2013 are provided in Table 4. In southern USA, the South Atlantic-Gulf (03), Great Lakes (04), and Ohio (05) regions have a large number of stations with a downward trend. The Missouri (Corder & Foreman, 2014), Arkansas-White-Red (Cubasch et al., 2001), and Texas-Gulf (Dai et al., 2010) regions show a large number of sites with a decreasing trend in central USA. In western USA, the Pacific Northwest (Hall, 1968) and California (Hamed & Rao, 1998) regions have a large number of stations with decreasing trends. The results of annual mean and median baseflow in different hydrological regions are similar to annual maximum baseflow. The regions which have a large number of sites with a downward trend will need changes in low flow management strategies in the future. Modified Mann-Kendall test (Hameed & Rao, 1998) that accounts for autocorrelation in time series is also used for 304 out of 574 sites, which showed statistically significant autocorrelation. Differences in the results from modified MK and MK tests were noted only at 48 sites. These differences are reported in Table 5.

The study has some limitations due to the lack of chronologically continuous (i.e., gap-free) data at several sites. Missing data is unavoidable as streamflow gauge installations change in time, errors, and equipment malfunctions occur. Also, the streamflow gauges used in this study are not uniformly distributed; therefore, this cannot give a full representation of variations in baseflow across the continental USA.

#### 4.5 Correlation between baseflow and precipitation

Relationships between monthly baseflow and monthly precipitation were also evaluated using the cross-correlation coefficients in this study. The strength of the monotonic association between precipitation and baseflow is assessed using Spearman's correlation coefficient test at the 5% significance level. Cross-correlations between baseflow ( $b_t$ ) in any given month  $t$ , and the monthly precipitation values in the same month and previous months (i.e.,  $P_t, P_{t-1}, P_{t-2}$ ) are estimated.

A total of 228 HUC8 regions are identified in which streamflow and precipitation gauging stations are located using to assess these relationships. The probability distributions of these cross-correlations are shown in Fig. 10a using kernel density estimates. The results shown are based on a statistically significant positive correlation between baseflow and precipitation in 50 out of 228 regions. Baseflow and precipitation observations at 23 stations, mostly located in the eastern part of the USA, showed a negative correlation. Based on these correlations (i.e., or associations), it can be inferred that the variations in monthly baseflows are either dependent on precipitation values in some basins. The cross-correlations between baseflow and lagged monthly precipitation totals are shown in Fig. 10b. The distribution characteristics of the correlations suggest that associations are stronger between precipitation and baseflows as evidenced by the correlation coefficient for the same month compared with those based on lagged monthly precipitation totals. This indicates a possible delayed response of the baseflows due to precipitation events in some basins.

## 5 Conclusions

This study presents a comprehensive analysis of trends in daily baseflow values derived from daily streamflow records from 574 stations in the continental USA for three study periods (1970–2013, 1980–2013, and 1990–2013). The Spearman's rho and Mann-Kendall trend detection tests are used to assess trends in annual maximum, mean, and median baseflows at each site. The random nature of three different baseflow series (i.e., annual maximum, mean, and median) and summary statistics are also evaluated. Results from this analysis indicate that:

- 1 Annual maximum baseflow values seem to be random at 75% of the sites, and almost half of the sites showed non-random character in annual mean baseflow.
- 2 The distributions of annual maximum baseflow data from 9 hydrological regions have skewed to the right from 1970–2000 to 2001–2013, indicating that the annual maximum baseflow values occurrences higher range frequently in the period of 2001–2013.
- 3 Almost half of the stations showed a statistically significant trend in the continental USA during 1970–2013. A high percentage of sites with downward and non-existent trends in the annual maximum baseflow values are noted in New England.
- 4 Decreases in the annual mean baseflow were observed in the South Atlantic-Gulf watershed and western coast and some downward trends in comparison with other regions, as did the South Atlantic-Gulf watershed.

- 5 The differences in the trend analysis results based on SR and MK tests in the period of 1970–2013 indicated that those two tests show a similar number of stations that have no statistical significance. However, the SR test shows a larger number of stations with upward trends than the results of the MK test in annual maximum, mean, and median baseflow.
- 6 Monthly baseflows have the highest correlation with same month precipitation value than with the precipitation from the preceding 1 and 2 months. The results suggest that almost half of the stations have statistically significant trends, and sites with downward trends are larger than those with increasing trends. These downward trends in baseflows in multiple regions of the USA will have serious implications on low flows and water quality management strategies for streams to support aquatic habitat.

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**Authors' contribution** Hao Chen: conceptualization, methodology, software, formal analysis, writing of the original draft. Ramesh S.V. Teegavarapu: supervision, writing review and editing.

## Compliance with ethical standards

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

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