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# Trend Analysis of Streamflow Drought Events in Nebraska

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**Abstract** A streamflow drought event, defined by applying the threshold level approach on streamflow time series, is composed of three parameters: duration, severity and magnitude. This study reveals statistical characteristics on streamflow drought event parameters and detects spatial and temporal trends in the streamflow drought in terms of frequency, duration and severity in Nebraska. The studies are conducted on three time periods: 1970–2001 (60 stations), 1950–2001 (43 stations), and 1932–2001 (9 stations). The statistical tests performed on the drought event parameters include correlation between event parameters tests, Hurst coefficients and lag-one coefficients, and trend-free pre-whitening Mann–Kendall (TFPW-MK) tests. The analysis shows that there is no uniform trend on the streamflow drought in the whole state. However, some trends are evident for specific regions. Specifically, it is most likely that droughts in the Republican watershed have become more intense; whereas the drought has become slightly alleviated in the Missouri and nearby watersheds.

**Key words** drought · statistics · surface water · time series analysis · trend · Nebraska

## 1 Introduction

Water resource management is critical, especially to rapidly expanding urban and rural communities that suffer from droughts (de Villiers 1999). Mismanagement may lead to

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overuse or misuse, which in turn may lead to water disputes among competing parties. For example, about 40% of the world population lives in 250 major river basins that are shared by multiple countries (Homer-Dixon 1995). Competing uses of these rivers have led to conflicts and disputes between upstream and downstream countries, e.g. between Egypt and Sudan over the use of the Nile River, Geum River Basin on the Korean Peninsula (Ryu et al. 2003), and the case of Cauvery in India (Ohlsson 2004). Downstream countries or states are directly affected by the water use of the upstream counterparts and are vulnerable to water overuse and misuse upstream. Further, in the High Plains Region of the United States, droughts often accelerate the impacts of water conflicts. During the peak of the 1934 drought, for example, downstream Nebraskans had little water for irrigation because water users in Wyoming held back as much water as they could, leading to fiercely contested arguments between the two states (Flowerday 1993). Recent multi-state lawsuits (Colorado, Kansas, Nebraska, and Wyoming) over water allocations on the Republican and Platte Rivers have emphasized the need for hydrologic information systems and decision support.

The National Assessment Synthesis Team (NAST 2000) for the U.S. Global Change Research Program has recommended for the High Plains region, the development of integrated approaches to examining the impacts and vulnerabilities to multiple stresses at regional and national scales. As part of these recommendations, the NAST identified the need for improved understanding of the spatial and temporal character of hydrological processes, including precipitation, soil moisture, and runoff and the potential for future changes in severe weather, extreme events, and the seasonal to annual variability. Particularly, improved understanding of the amount of water available, the frequency of water deficiencies and excesses, the duration of various low-flow conditions, and the impacts of irrigation at different locations along a river are key to supporting the resolution of water conflicts (Leopold 1994).

Numerous studies of the spatial and temporal patterns of drought in the United States were conducted. The primary focus of these studies was on meteorological drought represented by the Palmer Drought Severity Index (PDSI), either at a climatic division level or a state level, covering either the whole or a part of the country. The study periods ranged from about 80 years to a decade (e.g. Skaggs 1975; Klugman 1978; Karl 1983; McGregor 1985; and Oladipo 1986).

There were also some studies that focused on hydrological/stream drought. For instance, Soule (1992) examined patterns of drought frequency and duration based on the Palmer Hydrological Drought Index (PHDI) for the period of 1895–1988 at a climatic division level. The isoline maps of total number of both drought and major drought events, mean length of the events, coefficient of variation of the event length, and ratio of the drought frequency to drought duration were used to display the patterns of the drought frequency and duration over the study period. Lins and Slack (1999) evaluated streamflow trends for 395 stream gauge stations in the conterminous United States over the period 1944–1993. The trends were calculated over selected quantiles of discharge using the non-parametric Mann–Kendall test. In addition, intra- to multidecadal variation in annual streamflow during 1939–1998 was detected through the calculation of the Mann–Whitney U statistics over running-time windows of 6–30 years on 167 Hydro-Climatic Data Network streamflow stations across the country (Mauget 2003).

However, there is a lack of systematic examination of streamflow drought characteristics and trend in specific regions in the United States. Thus, the objectives of this study are to reveal statistical characteristics on streamflow drought event parameters and to detect spatial and temporal trends in the streamflow drought in terms of frequency, duration and severity in Nebraska over various time periods, ranging from 30 to 70 years.

## 2 Water Resources in Nebraska

In Nebraska, there are 67 streams with a total length of more than 10,000 km. The Platte River, flowing from west to east Nebraska and about 720 km in length, is the longest among the streams and joins the Missouri River on the eastern border of Nebraska. Water resource shortage occurred in most parts of Nebraska, particularly in western and central Nebraska where annual precipitation is smaller than that in eastern Nebraska.

The High Plains aquifer, one of the largest in the United States, is beneath about 85% of Nebraska's land surface, and is absent only in the very eastern part of Nebraska. Its thickness varies from about 10 to more than 100 m and stores a significant amount of groundwater. Most streams and the High Plains aquifer are hydrologically connected. This aquifer provides baseflow to numerous streams. For example, the streamflow of several rivers in the Loup watershed of central Nebraska consists of more than 85% of groundwater discharging from the adjacent aquifers (X Chen and XH Chen 2004). The highly permeable streambed in several rivers makes stream water and groundwater virtually a single source (Chen 2004).

In Nebraska, there are about 100,000 registered wells, each of which can pump groundwater at the rates from 2,700 to 8,000 $m^3$/d. The number of irrigation wells in some parts of Nebraska is greater than 10 per square miles (Burbach, 2006, personal communication). Groundwater irrigation serves about 85% of the state's irrigated land. According to Hutson et al. (2004), Nebraska, after California and Texas, is the third largest state for groundwater irrigation in the United States. The estimated groundwater withdrawals in Nebraska alone were 7,860 million gallons per day in 2000. This volume is more than double the streamflow of the Platte River as it discharges into the Missouri River in eastern Nebraska. Intensive groundwater development for irrigation or other land use has potential impact on the nearby streams.

In the Platte watershed, one major issue is the potential depletion of the Platte River. The reach of the river in south-central Nebraska provides critical habitats for a number of endangered and threatened species (whooping crane, piping plover, least tern, pallid sturgeon). In 1997, Nebraska, Colorado, and Wyoming and the US Department of the Interior signed a memorandum to protect the streamflow of the Platte River in south-central Nebraska. In the North Platte watershed, conflicts occurred between Nebraska and Wyoming regarding to the reduced streamflow in the North Platte River. In the Republican watershed, litigation occurred between Nebraska and Kansas regarding the streamflow in the Republican River. Apparently, analysis of streamflow drought conditions in Nebraska is essential for better evaluation of the available water resources in these river systems.

## 3 Data and Methodology

### 3.1 Definition of Streamflow Drought Event

Defining a streamflow drought event mathematically based on streamflow data is the first step for this study. Dracup et al. (1980b) recommended a formulation of a streamflow drought event by the theory of runs. Thus, in this study, a drought event for a particular stream is determined by (1) computing the *long-term mean flow* of stream's historical streamflow record and then (2) combining all adjacent years for which the record is *below* the long-term mean into a *drought event*. As a result, a defined drought event (indicating a streamflow drought in this study) is characterized by three parameters: duration, magnitude and severity. Duration is the period during which streamflow is below the long-term mean continually. Magnitude is the average water deficiency. Severity is the cumulative water deficiency. The relationship between the three parameters is given by:

$$\text{Magnitude}=\frac{\text{Severity}}{\text{Duration}} \tag{1}$$

Duration and severity are directly related to streamflow record, and therefore, they are primary parameters. Magnitude, determined by the duration and severity, can be considered as a secondary parameter.

If the original daily streamflow data are used to define a drought, two problems will be introduced: dependency among the defined droughts and presence of minor droughts. It will also result in a large sample size and large serial correlation (Dracup et al. 1980b). The common way to overcome these problems is to include a pooling procedure, i.e., performing an *N*-day moving average on the original streamflow record (Tallaksen et al. 1997; Hisdal and Tallaksen 2000). Based on their assessment of different moving window sizes, an 11-day moving average procedure is applied to the original daily streamflow data before determining the drought parameters. Consequently, the original daily flow data are smoothed, essentially pooling adjacent minor peaks (i.e., minor high-flows) and valleys (i.e., minor droughts) into a larger high-flow or drought. In addition to the pooling procedure, the severity of the drought events included in this study is with at least a 3-year return period because there were still minor drought events within the defined drought events even after the pooling procedure. In this study, the focus is on the drought events that have negative impacts on water resources. To calculate the return period, refer to Hann (1977).

A stream usually has one or more high- and low-flow seasons caused by a number of reasons (Tallaksen et al. 1997; Hisdal and Tallaksen 2000). Generally, a stream may have a low-flow season because of lack of precipitation. However, the causes of a low-flow season might also include: (1) precipitation is stored as snow and/or ice during the winter months in snow and ice-affected regions, and (2) irrigation diverts streamflow. Further, dam and reservoir regulations may also induce significant streamflow changes (Yang et al. 2004). A stream may have a high-flow season because of flooding. The reasons also include: (1) snowmelt in the spring leading to more water channeled into the stream and (2) reduction of irrigation and water use after harvest. Further, precipitation may not necessarily lead to flood flow due to rainwater catchments and different types of land use (Gaume et al. 2004). It is thus important to distinguish the statistical measurements and spatial and temporal trends in the different low- and high-flow seasons.

In this study, the high- and low-flow seasons for each streamflow station are determined by the distribution of the long-term average monthly streamflow. For example, Fig. 1 illustrates the average monthly streamflow for the station Missouri River at Omaha, Nebraska during 1932–2001. The low flow season includes December, January and February. The long-term mean flow for the low-flow season, therefore, is computed based on the corresponding three months to define the drought events for this season. The mean flow for the high-flow season is computed using the remaining months. This approach intends to keep the drought analyses consistent for each gauge station.

### 3.2 Data Source

The daily streamflow data used in this study are from streamflow gauge stations in Nebraska, operated by the U.S. Geological Survey (USGS). USGS makes periodic flow measurements on rivers and streams using standardized methods and maintains the data from these stations in a national database. As we know, numerous dams and reservoirs have been built along the

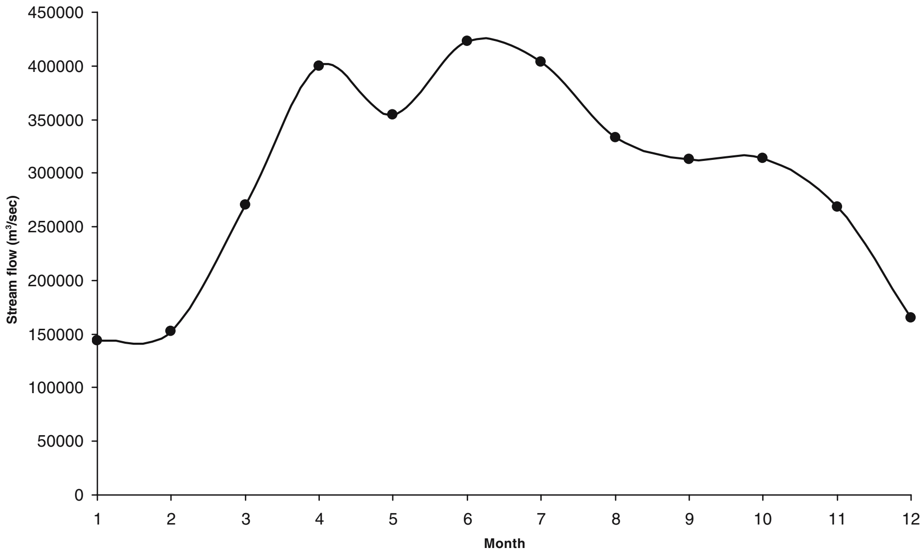



**Fig. 1** Demonstration of low- and high-flow seasons for a stream gauge during 1931–2001 on the Missouri River at Omaha, NE. The low-flow season includes December, January and February. The high-flow season includes the remaining months

rivers in Nebraska for irrigation, recreations, power generation, flood control, and municipal and industrial use. Therefore, the streamflow data used in this study should be affected by these factors.

The record length of streamflow records varies from one station to another. This study groups the stations into three time periods: 1970–2001 (60 stations), 1950–2001 (43 stations), and 1932–2001 (9 stations), resulting in three streamflow datasets for the further study. Obviously, some stations appear in more than one of the three time periods. The spatial coverage and the frequency of the selected stations appearing in the three periods are shown in Fig. 2. Stations included in all three periods are shown with the biggest dark circle. Stations included in two periods are shown using a smaller circle, and so on. As illustrated in Fig. 2, the spatial coverage of the three datasets is quite different. The streamflow stations appearing in all three time periods have a poorer spatial coverage than those appearing in fewer time periods. The spatial and temporal trends of droughts in Nebraska streams will be revealed through studying on the statistical characteristics and trends in the stream drought over the different historical time periods. Note that since there are three different time periods in this study, the long-term mean flow that is used to define a drought event will be computed in the three time periods, respectively, for each individual station.

### 3.3 Statistical Characteristics on Drought Event Parameters

In order to gain a more thorough understanding of the complex nature of streamflow drought events, three fundamental statistical characteristics of the drought event parameters, i.e., duration, magnitude, and severity, are investigated. These statistical characteristics include correlation between any two of the three parameters (Dracup et al. 1980a), Hurst coefficient and lag-one coefficient (Hurst 1951; Dracup et al. 1980a; Sakalauskiene 2003).

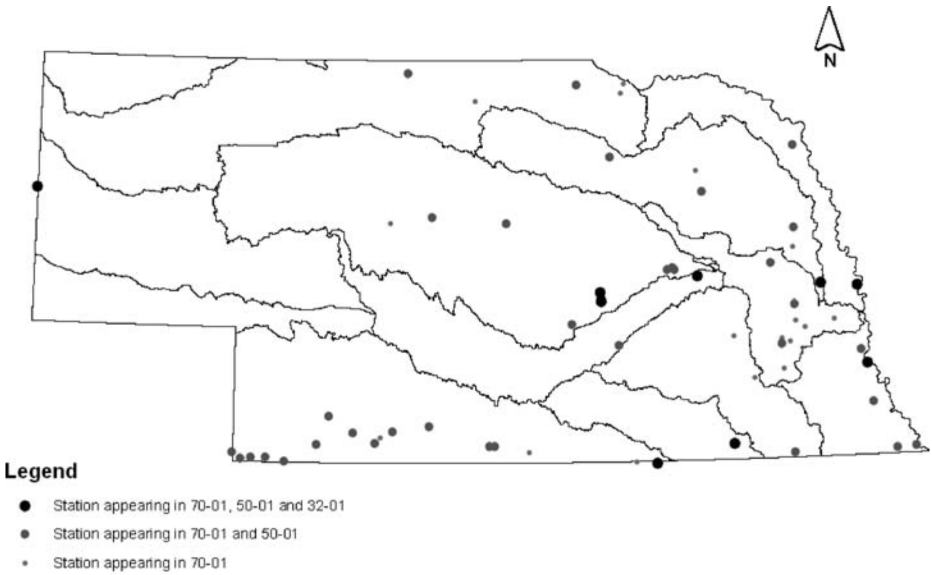



**Fig. 2** Distribution of streamflow stations and the frequencies used in the study. Stations included in all three periods are shown with the biggest dark circle. Stations included in two periods are shown using a smaller circle, and so on

### *3.3.1 Correlation between Two Parameters*

This test identifies the internal relationship between the three possible pairings, i.e., duration and severity, duration and magnitude, and severity and magnitude. The strongest and weakest relationships between the event parameters are crucial in the frequency analysis to assess the future events. The result of this test will give a quantification of the internal structure of drought event series.

The degree of the significant association between any two drought parameters is determined by using the *t* statistic to test the correlation coefficients. The null hypothesis is that the two parameters being tested are independent each other over the period (correlation coefficient=0). If *p*-value is equal to or less than 0.05, the null hypothesis is rejected, indicating that the two parameters are significantly dependent each other over the period; if *p*-value is greater than 0.05, the null hypothesis cannot be rejected, indicating that the two are independent of each other.

### *3.3.2 Hurst Coefficient and Lag-one Correlation Coefficient*

Hurst coefficient $H$ is a measure of long-term persistence and quantifies stochastic fluctuations on hydrological time series discovered by Hurst (1951). $H$ always lies between 0 and 1. The Hurst coefficient $H=0.5$ means a white noise series, indicating the values of a time series are uncorrelated with each other. $0<=H<0.5$ indicates an anti-persistent event, meaning increases in the values are more likely to be followed by subsequent decreases and vice versa. $0.5<H<=1$ indicates a persistent time series, meaning that increases in the values are more likely to be followed by subsequent increases, and similarly decreases are more likely to be followed by subsequent decreases. The method to compute the Hurst coefficients of the drought event parameters (duration, magnitude, and severity) follows

**Table 1** Hurst coefficients for stations from 1970–2001, 1950–2001 and 1932–2001

| Station | 1970–2001 | | | 1950–2001 | | | 1932–2001 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Duration | Severity | Magnitude | Duration | Severity | Magnitude | Duration | Severity | Magnitude |
| 6453600 | 0.70 | 0.67 | 0.72 | – | – | – | – | – | – |
| 6461500 | 0.69 | 0.69 | 0.67 | 0.73 | 0.75 | 0.77 | – | – | – |
| 6463500 | 0.63 | 0.73 | 0.85 | – | – | – | – | – | – |
| 6465000 | 0.62 | 0.66 | 0.75 | 0.62 | 0.68 | 0.75 | – | – | – |
| 6465500 | 0.69 | 0.71 | 0.76 | – | – | – | – | – | – |
| 6601000 | 0.67 | 0.71 | 0.80 | 0.47 | 0.57 | 0.70 | – | – | – |
| 6610000 | 0.67 | 0.78 | 0.60 | 0.73 | 0.85 | 0.84 | 0.86 | 0.85 | 0.84 |
| 6674500 | 0.73 | 0.78 | 0.79 | 0.69 | 0.80 | 0.82 | 0.64 | 0.76 | 0.86 |
| 6770500 | 0.69 | 0.67 | 0.59 | 0.70 | 0.79 | 0.80 | – | – | – |
| 6774000 | 0.80 | 0.76 | 0.62 | 0.68 | 0.73 | 0.76 | 0.72 | 0.76 | 0.78 |
| 6775500 | 0.55 | 0.64 | 0.84 | 0.60 | 0.65 | 0.76 | – | – | – |
| 6775900 | 0.87 | 0.86 | 0.69 | – | – | – | – | – | – |
| 6784000 | 0.59 | 0.61 | 0.60 | 0.63 | 0.62 | 0.59 | – | – | – |
| 6785000 | 0.76 | 0.74 | 0.26 | 0.74 | 0.88 | 0.75 | 0.67 | 0.79 | 0.83 |
| 6786000 | 0.77 | 0.78 | 0.65 | 0.76 | 0.74 | 0.57 | – | – | – |
| 6790500 | 0.72 | 0.68 | 0.60 | 0.71 | 0.68 | 0.58 | 0.73 | 0.67 | 0.63 |
| 6792500 | 0.69 | 0.65 | 0.56 | 0.69 | 0.68 | 0.66 | – | – | – |
| 6793000 | 0.79 | 0.79 | 0.78 | 0.56 | 0.64 | 0.78 | – | – | – |
| 6794000 | 0.74 | 0.68 | 0.50 | 0.63 | 0.61 | 0.57 | – | – | – |
| 6796000 | 0.77 | 0.77 | 0.67 | 0.63 | 0.61 | 0.74 | – | – | – |
| 6797500 | 0.61 | 0.64 | 0.73 | 0.50 | 0.66 | 0.69 | – | – | – |
| 6799000 | 0.41 | 0.56 | 0.64 | 0.61 | 0.59 | 0.67 | – | – | – |
| 6799100 | 0.56 | 0.61 | 0.74 | – | – | – | – | – | – |
| 6799500 | 0.66 | 0.69 | 0.71 | 0.59 | 0.62 | 0.59 | – | – | – |
| 6800000 | 0.61 | 0.73 | 0.91 | – | – | – | – | – | – |
| 6800500 | 0.55 | 0.66 | 0.76 | 0.62 | 0.54 | 0.68 | 0.55 | 0.64 | 0.79 |
| 6803000 | 0.45 | 0.55 | 0.71 | – | – | – | – | – | – |
| 6803500 | 0.59 | 0.63 | 0.68 | 0.56 | 0.63 | 0.79 | – | – | – |
| 6803510 | 0.70 | 0.74 | 0.76 | – | – | – | – | – | – |
| 6803520 | 0.75 | 0.72 | 0.77 | – | – | – | – | – | – |
| 6803530 | 0.75 | 0.76 | 0.75 | – | – | – | – | – | – |
| 6803555 | 0.59 | 0.63 | 0.65 | – | – | – | – | – | – |
| 6804000 | 0.56 | 0.60 | 0.77 | 0.68 | 0.70 | 0.71 | – | – | – |
| 6805500 | 0.73 | 0.74 | 0.67 | – | – | – | – | – | – |
| 6806500 | 0.58 | 0.59 | 0.73 | 0.47 | 0.68 | 0.82 | – | – | – |
| 6807000 | 0.80 | 0.80 | 0.55 | 0.62 | 0.78 | 0.80 | 0.82 | 0.81 | 0.83 |
| 6811500 | 0.53 | 0.57 | 0.67 | 0.63 | 0.59 | 0.68 | – | – | – |
| 6813500 | 0.81 | 0.81 | 0.63 | 0.60 | 0.77 | 0.78 | – | – | – |
| 6815000 | 0.52 | 0.55 | 0.72 | 0.62 | 0.62 | 0.66 | – | – | – |
| 6821500 | 0.61 | 0.63 | 0.73 | 0.70 | 0.66 | 0.72 | – | – | – |
| 6823000 | 0.87 | 0.88 | 0.69 | −0.10 | −0.12 | −0.10 | – | – | – |
| 6823500 | 0.65 | 0.62 | 0.58 | 0.74 | 0.66 | 0.72 | – | – | – |
| 6824000 | 0.79 | 0.80 | 0.80 | 0.78 | 0.79 | 0.80 | – | – | – |
| 6827500 | 0.67 | 0.70 | 0.65 | 0.68 | 0.67 | 0.68 | – | – | – |
| 6828500 | 0.52 | 0.58 | 0.60 | 0.71 | 0.68 | 0.65 | – | – | – |
| 6834000 | 0.67 | 0.70 | 0.62 | 0.70 | 0.77 | 0.57 | – | – | – |
| 6835500 | 0.64 | 0.65 | 0.67 | 0.83 | 0.78 | 0.74 | – | – | – |
| 6836500 | 0.71 | 0.67 | 0.56 | 0.73 | 0.80 | 0.93 | – | – | – |
| 6837000 | 0.76 | 0.64 | 0.58 | – | – | – | – | – | – |
| 6838000 | 0.69 | 0.62 | 0.67 | 0.72 | 0.76 | 0.64 | – | – | – |
| 6843500 | 0.61 | 0.60 | 0.58 | 0.79 | 0.73 | 0.71 | – | – | – |
| 6844500 | 0.68 | 0.61 | 0.57 | 0.73 | 0.61 | 0.76 | – | – | – |
| 6847500 | 0.61 | 0.66 | 0.49 | 0.67 | 0.72 | 0.63 | – | – | – |
| 6849500 | 0.74 | 0.79 | 0.64 | – | – | – | – | – | – |
| 6852500 | 0.64 | 0.66 | 0.62 | – | – | – | – | – | – |
| 6853500 | 0.62 | 0.67 | 0.79 | 0.62 | 0.67 | 0.74 | 0.70 | 0.69 | 0.71 |
| 6880800 | 0.62 | 0.58 | 0.84 | – | – | – | – | – | – |
| 6881000 | 0.64 | 0.75 | 0.58 | – | – | – | – | – | – |
| 6882000 | 0.68 | 0.65 | 0.76 | 0.61 | 0.64 | 0.75 | – | – | – |
| 6884000 | 0.52 | 0.52 | 0.60 | 0.56 | 0.65 | 0.66 | 0.62 | 0.63 | 0.58 |

Sakalauskiene (2003). In this study, we define that a time series is “Long-term persistent” if $H>0.59$, is “Anti-persistent” if $H<0.40$, and is a “White noise” if $0.40<H<0.59$.

While the Hurst coefficient measures the long-term persistence, the lag-one correlation coefficient measures the short-term persistence. The degree of the short-term persistence is determined by using the $t$ statistic to test the lag-one correlation coefficient. The null hypothesis is that the parameter being tested is short-term random over the period (lag-1 serial correlation coefficient=0). If $p$-value is equal to or less than 0.05, the null hypothesis is rejected, indicating that the parameter being tested is significantly correlated in terms of lag-1 correlation over the period, or short-term correlated; if $p$-value is greater than 0.05, the null hypothesis cannot be rejected, indicating that the parameter is short-term random over the period.

## 3.4 Trend Analysis on Drought Event Statistical Indicators

### *3.4.1 Drought Event Statistical Indicators*

Five additional streamflow drought statistical indicators are extracted. They are: (1) annual maximum drought duration (AMD), (2) annual cumulative duration of all drought events (ACD), (3) annual maximum deficit volume standardized by seasonal mean flow (AMV), (4) annual cumulative deficit volume standardized by seasonal mean flow (ACV) and (5) number of drought events per year (ND) (Zelenhasic and Salvai 1987; Hisdal et al. 2001). The AMD and ACD are duration-based indicators, while the AMV and ACV are deficit-based indicators. The ND reflects the frequency of drought events. To detect whether there is a significant trend in the drought duration, drought deficit or drought frequency in a certain time period, the widely used and recently modified trend test, Trend-free Pre-whitening Mann–Kendall (TFPW-MK) test (Yue et al. 2002; Yue and Pilon 2003), is performed.

### *3.4.2 Trend-free Pre-whitening Mann–Kendall Test (TFPW-MK)*

The Mann–Kendall is a nonparametric trend test, i.e., it does not require that the data follow a certain statistical distribution. Mann–Kendall test is chosen for the study as it is able to identify any trend in a time series without specifying whether the trend is linear or non-linear (Salas 1993; Lins and Slack 1999; Hisdal et al. 2001). Also, the Mann–Kendall test is rank order based, insensitive to missing values, and easy to calculate.

**Table 2** Mean and stand deviation of the five drought statistical indicators during the three time period

| Period | Statistics | AMD (day) | ACD (day) | AMV | ACV | ND |
|---|---|---|---|---|---|---|
| 1932–2001 | Mean | 93.86 | 168.74 | 13.00 | 17.87 | 4.20 |
| | Standard Deviation | 33.04 | 54.95 | 9.37 | 11.70 | 0.82 |
| 1950–2001 | Mean | 97.65 | 175.99 | 35.69 | 52.31 | 3.96 |
| | Standard Deviation | 32.35 | 53.59 | 17.78 | 25.59 | 0.83 |
| 1970–2001 | Mean | 96.39 | 197.96 | 18.97 | 30.19 | 5.08 |
| | Standard Deviation | 40.00 | 74.97 | 10.60 | 16.11 | 1.13 |

AMD denotes annual maximum drought duration; ACD denotes annual cumulative duration of all drought events; AMV denotes annual maximum deficit volume standardized by seasonal mean flow; ACV denotes annual cumulative deficit volume standardized by seasonal mean flow; and ND denotes number of drought events per year

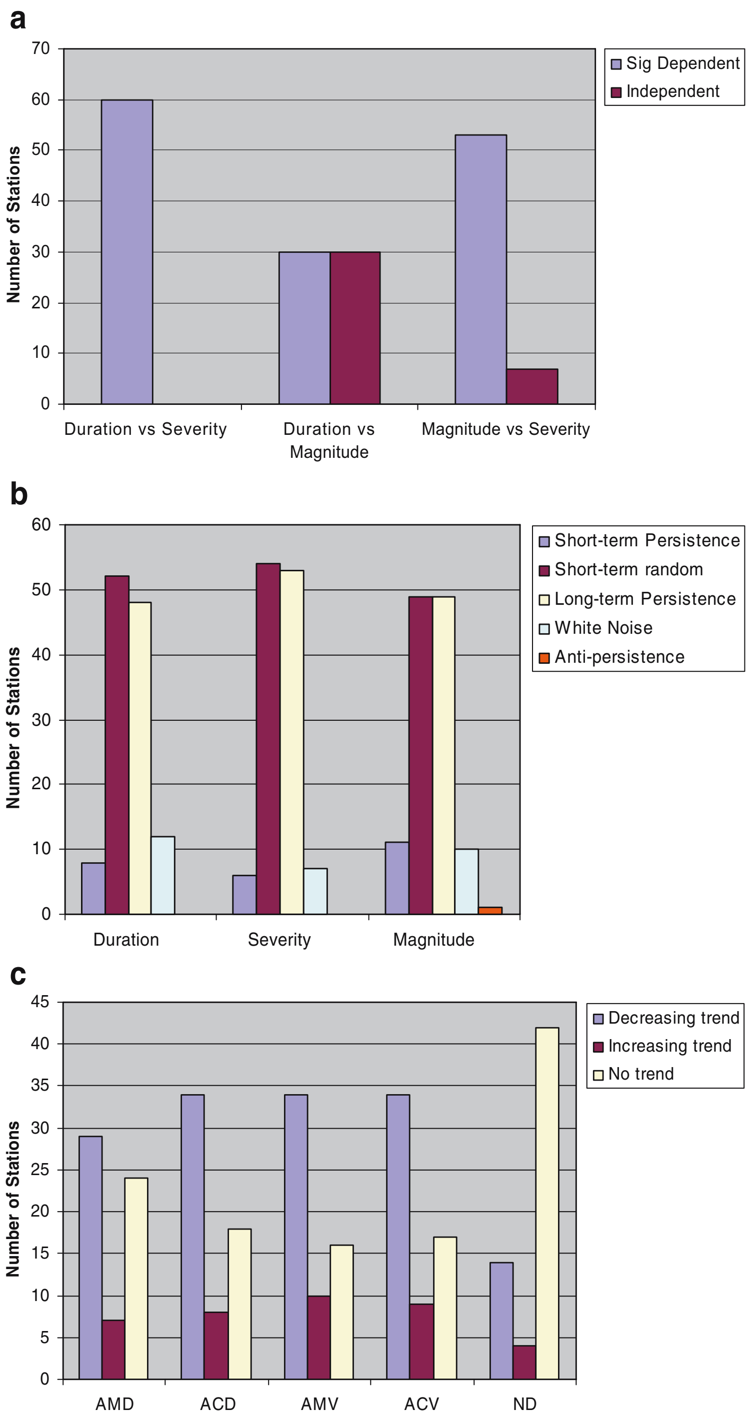



**Fig. 3** The results of the three tests over 1970–2001. **a** correlation between event parameters test, **b** Hurst coefficients and lag-one coefficients, and **c** TFPW- Mann–Kendall test

Hydrological time series often is an AR(1) process (significant serial correlation), which will increase the probability that the Mann–Kendall test will detect a significant trend by the existence of positive serial correlation in the time series. Thus, pre-whitening procedure is necessary to eliminate the influence of serial correlation on the Mann–Kendall test (von Storch 1995). However, the pre-whitening procedure will remove a potion of the detected trend and alter the Mann–Kendall test results. Therefore, Yue et al. (2002; Yue and Pilon 2003) proposed a trend-free pre-whitening (TFPW) procedure used before performing the Mann–Kendall test, refereed to TFPW-MK test in the remaining of this paper. Briefly, the TFPW-MK test procedures are as follows:

(1) Estimate the slope (or trend) of the time series being tested using the Theil–Sen Approach (TSA) (Sen 1968) and then detrend the series;
(2) Compute the Lag-one serial correlation coefficient of the detrended series and then remove the AR(1) from the detrended series. The residual series after applying this procedure is an independent series;
(3) Blend the identified slope (or trend) back to the residual series. The blended series keeps the true trend being detected and is not influenced by the AR(1);
(4) The Mann–Kendall test is performed on the blended series to detect the significance of the trend at $\alpha$=0.05 level for this study.

## 4 Results and Discussions

Table 1 lists the Hurst coefficients for the stations from 1970–2001, 1950–2001 and 1932–2001, respectively. As suggested, the Hurst coefficients change along with the length of the time scales of the study for the same stations. Table 2 shows the values of the mean and standard deviation of the five drought statistical indicators, i.e., AMD, ACD, AMV, ACV and ND, to provide a brief description of the drought characteristics during the three study periods. In the following subsequent sections, the detailed statistical characteristics and trend test results will be presented for each of the three time periods. In addition, temporal and spatial trend patterns will be discussed.

### 4.1 Statistical Characteristics and Trend in Drought for 1970–2001

Figure 3 summarizes the results of the three statistical characteristics, i.e., the correlation, Hurst coefficient and lag-one coefficient, and the TFPW-MK test for the period 1970–2001. Figure 3a presents the pairwise correlation test results among the three parameters of drought: duration, severity, and magnitude. The "independent" columns indicate the number of stations in which the two parameters are not correlated; while the "sig dependent" columns indicate the number in which the two are significantly correlated at a 5% level. Figure 3b demonstrates the test results based on the Hurst coefficients and lag-one coefficients for the three parameters of drought. Particularly, we show here the number of stations with short-term persistence at a significance level of 5%, being short-term random, long-term persistence, white noise, and anti-persistence (which is very uncommon). Figure 3c demonstrates the results of the TFPW-MK test for the drought indicators of AMD, ACD, AMV, ACV, and ND. Particularly, we show here the number of stations with a significantly positive (increasing) trend, those with no trend, and those with a significantly negative (decreasing) trend at a 5% level for the indicators.

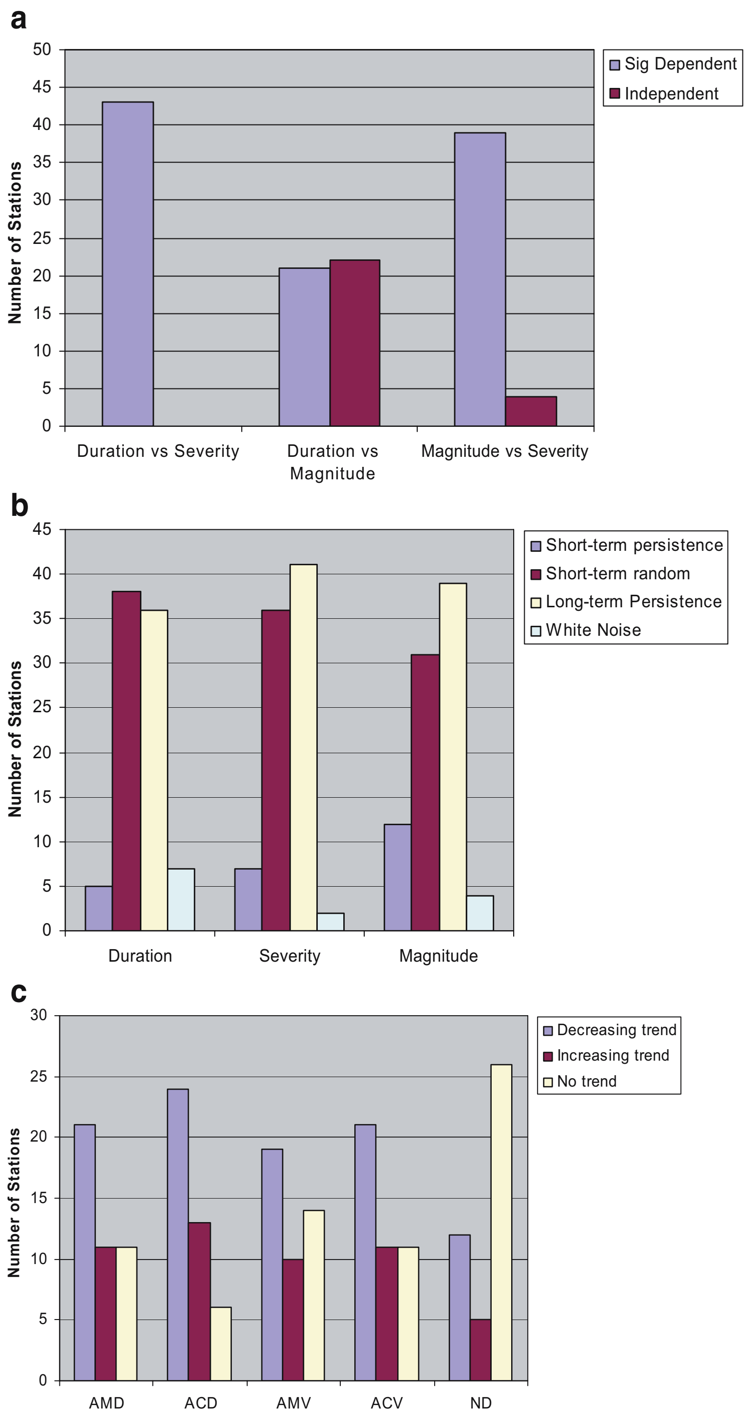



**Fig. 4** The results of the three tests over 1950–2001. **a** correlation between event parameters test, **b** Hurst coefficients and lag-one coefficients, and **c** TFPW- Mann–Kendall test

According to Fig. 3, the duration and magnitude of all the stations are independent of each other, whereas the duration and severity of the most stations are significantly correlated with each other. The magnitude is also closely related to the severity. The Hurst coefficients suggest that the three drought parameters are long-term persistent for a majority of the stations, while only a few stations are white noise series. In contrast, the lag-one coefficients shows that a majority of the stations are short-term random and a few stations are short-term persistent.

The TFPW-MK test on the drought duration indicators (AMD and ACD) suggests only a few stations (less than 10 out of 60) with an increasing trend, half of the remaining stations with a decreasing trend and the rest with no trend. During the period 1970–2001, the number of stations with a negative trend on the AMV and ACV is more than that with a positive trend. The frequency of droughts (ND) does not show a strong tendency in either a negative trend or a positive trend, and a high number with a no-trend still dominate, indicating that the frequency of droughts does not change significantly during 1970–2001.

In summary, the statistical characteristics of drought events during 1970–2001 are: (1) the association between the drought duration and severity is significant; (2) the three parameters are long-term persistent and short-term random; (3) the streamflow droughts become less severe in terms of the annual drought severity and duration for about half of the stations; and (4) the drought frequency does not change over this time period.

### 4.2 Statistical Characteristics and Trend in Drought for 1950–2001

Similarly, over the period 1950–2001 (Fig. 4), the duration and magnitude are highly correlated with the severity. The duration is independent from the magnitude for half of the stations and is significantly correlated with the other half of the stations. Most of the stations are short-term random and long-term persistent. The TFPW-MK test indicates the proportion of the stations with a positive trend increases to about the same to or even higher than the number with no-trend, although a negative trend still dominates on the AMD, ACD, AMV and ACV. Again, the ND does not change in most stations.

### 4.3 Statistical Characteristics and Trend in Drought for 1932–2001

For the longest period 1932–2001, some of the tests results are quite different from the previous periods (Fig. 5). Because of the limited availability of stations and a poorly spatial coverage for the 1932–2001 dataset (nine stations), it is difficult to draw any reliable conclusions based on these results. But some observations can be made: (1) the severity is significantly correlated with the duration and magnitude for all the nine stations, and the duration is significantly correlated with the magnitude for most of the stations; (2) about half of the stations are short-term random and half are short-term persistent; (3) eight or nine stations are long-term persistent; and (4) five to six out of the 9 stations show a negative trend on the AMD, ACD, AMV, ACV, and ND based on the TFPW-MK test, indicating that droughts decrease in terms of severity and frequency over 1932–2001. This decrease also can be observed on the average monthly streamflow time series over the nine stations during 1931–2001 in Fig. 6, in which a slightly increasing slop of the streamflow is shown.

### 4.4 Influence of Time Periods on the Statistical Characteristics of Drought

The influences of the three time scales used on the tests are illustrated by comparing the results of the tests from the different time periods among the nine stations, which appear in

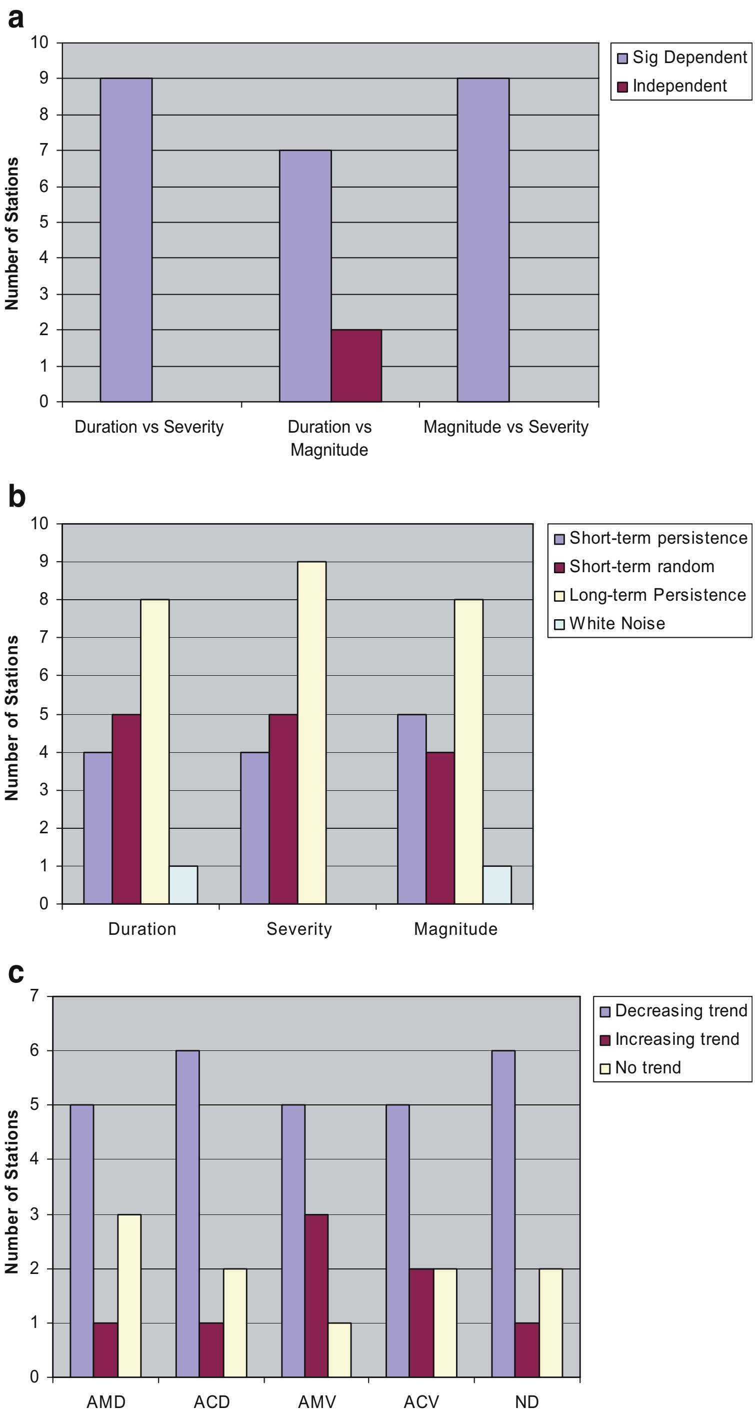



**Fig. 5** The results of the three tests over 1932–2001. **a** correlation between event parameters test, **b** Hurst coefficients and lag-one coefficients, and **c** TFPW- Mann–Kendall test

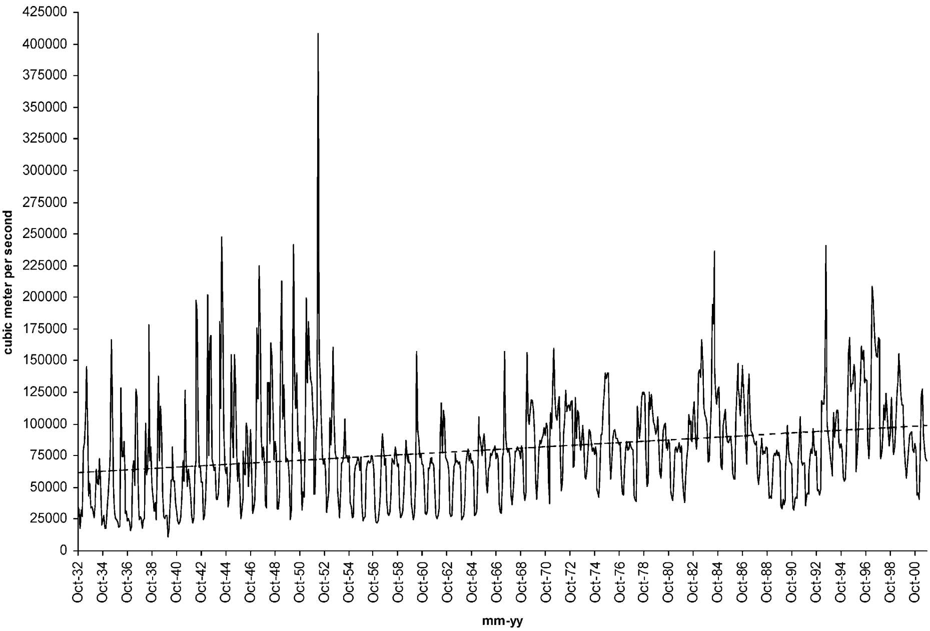



**Fig. 6** Average monthly streamflow time series over the nine stations during 1931–2001. Solid line denotes the streamflow time series; broken line denotes the slop of the streamflow over the time period

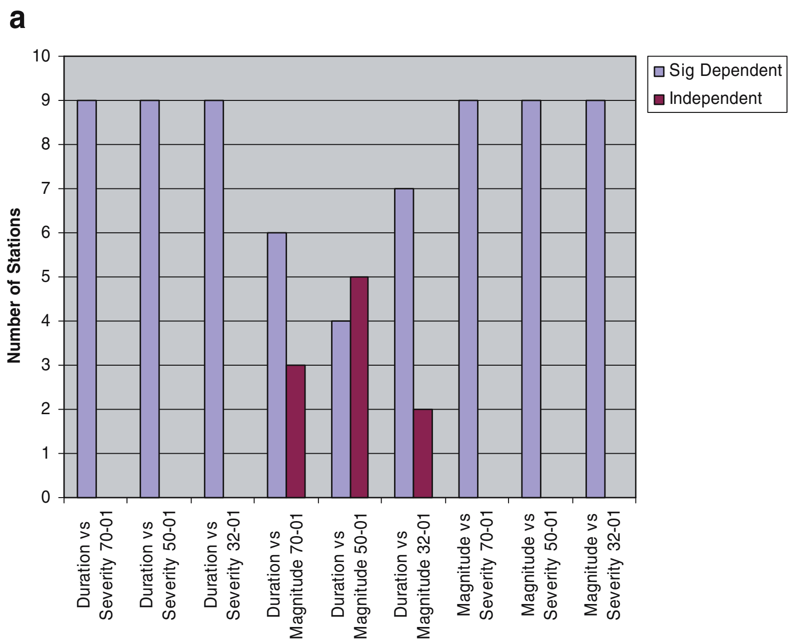
all three time periods (Fig. 7). As shown, except for the correlation test between the duration and magnitude, the correlation test results between the duration and severity, and between the magnitude and severity are consistent over the three time periods, indicating that close relationships between the two pairs dominate the stations (Fig. 7a). The number of stations with short-term persistence varies in different periods (Fig. 7b), while the number of stations with long-term persistence stays about the same over the three time periods (Fig. 7c).

For the TFPW-MK test (Fig. 7d), the stations with an increasing trend for the drought statistical indicators only appear during 1932–2001, except for one station's ACV during 1970–2001. The no-trend generally dominates the shorter periods. As the time scales become longer, some of the stations with no-trend will show either an increasing or decreasing trend. The results suggest that the severity and frequency of the streamflow droughts change as the time scales vary. Thus, the time scales used for the analysis should be carefully chosen for the specific purpose of a study.

## 4.5 Spatial Trend Patterns

Spatial patterns in trends are investigated to reveal if any changes in streamflow drought severity and frequency have occurred in the different time periods. Figure 8 presents the spatial distribution of the trends for the five drought statistical indicators: AMD, ACD, AMV, ACV and ND based on the TFPW-MK test. Because of the spatial coverage limitation, the discussion is limited to the areas where the streamflow stations are available.

It is observed that during 1932–2001, the four stations located in eastern Nebraska (i.e. watersheds of Nemaha, Missouri, Elkhorn and Middle Platte) show consistently negative trends on all five indicators. The one located in the Little Blue watershed shows no trends



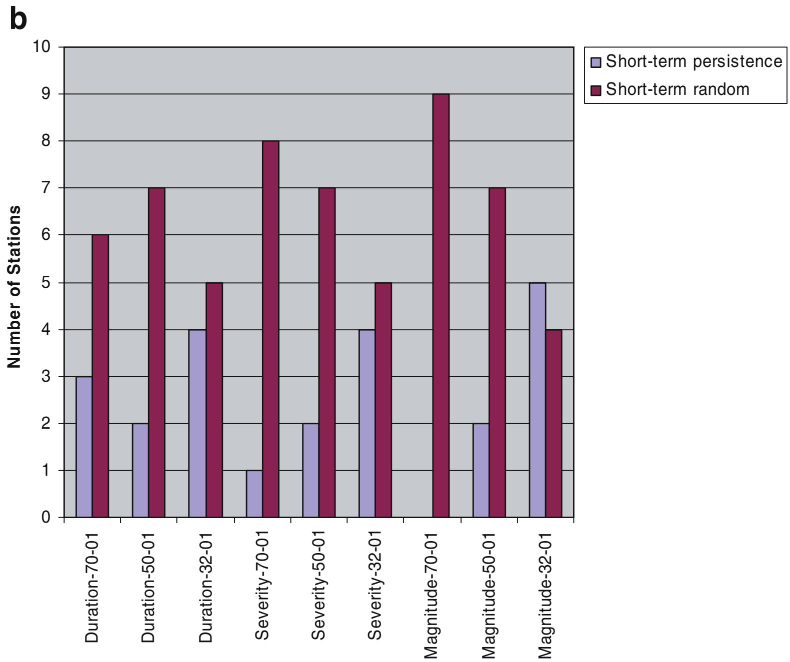




**Fig. 7** Comparison of the test results in the three time periods: **a** correlation between event parameters test, **b** Lag-one Coefficients, **c** Hurst Coefficients, and **d** TFPW- Mann–Kendall test

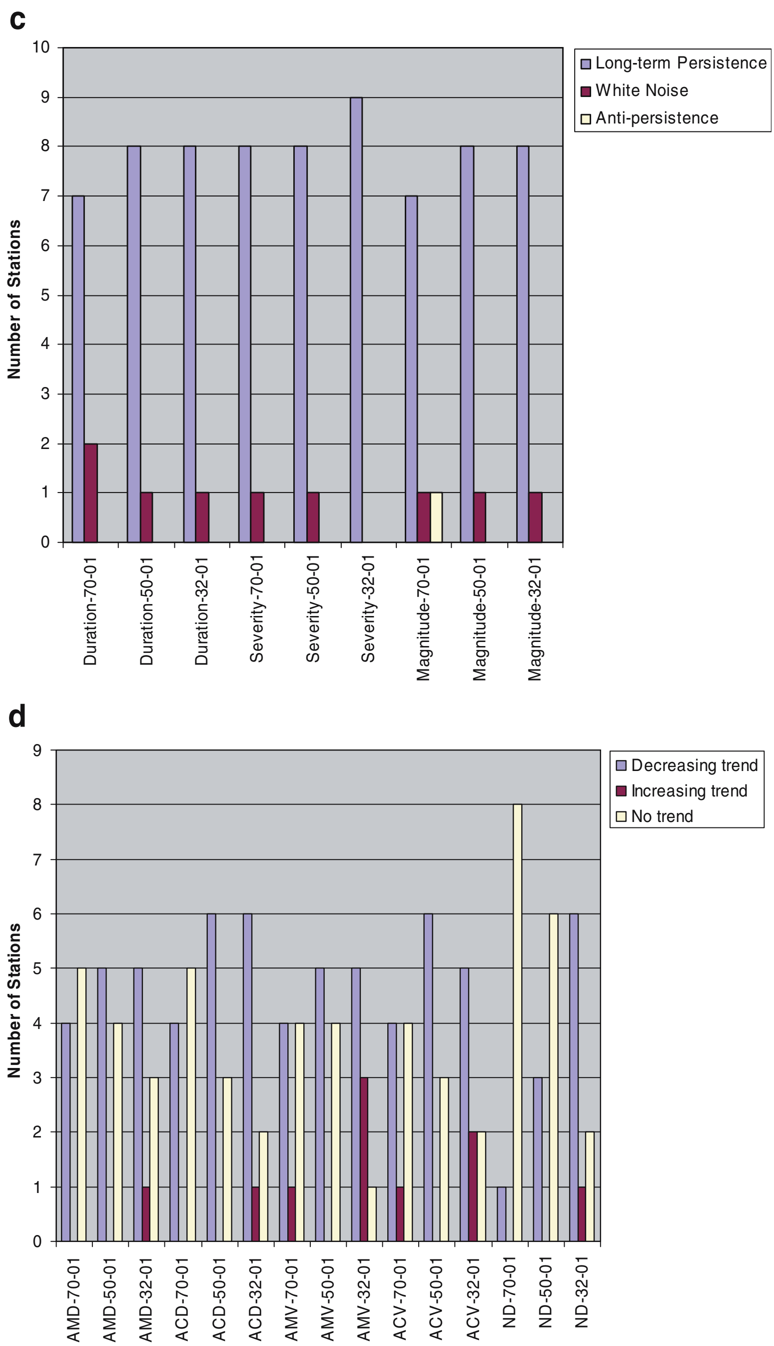



**Fig. 7** (continued)

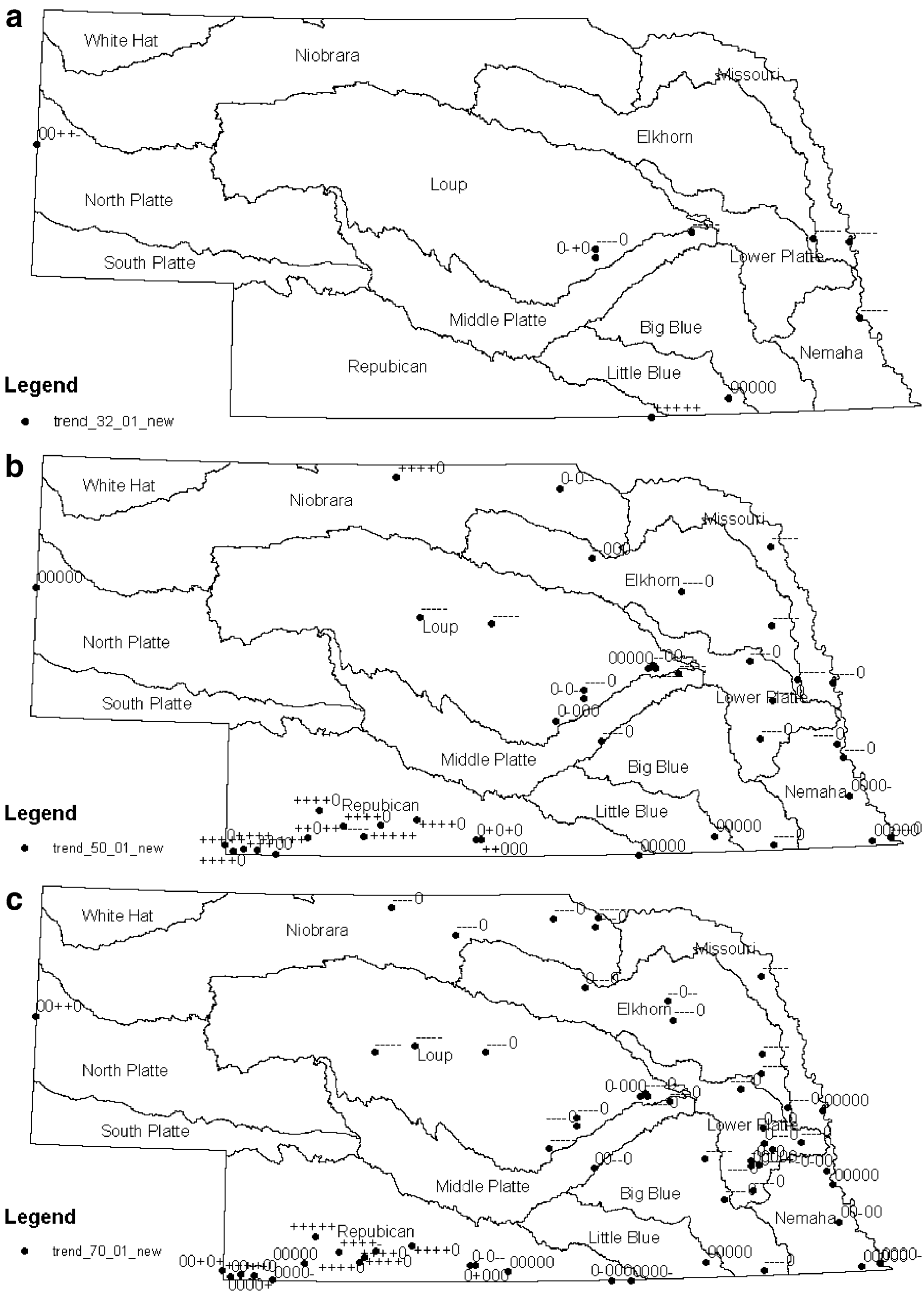



**Fig. 8** Trends over the three periods. Following the stations are the signs of trend for AMD, ACD, AMV, ACV and ND. "+" denotes increasing trend; "–" denotes decreasing trend; "0" denotes no-trend. **a** 1932–2001, **b** 1950–2001, and **c** 1970–2001

and the one located in the Republican watershed shows positive trends on the five indicators. Other stations have mixed trends. Unfortunately, the coverage for this longest period is not extensive enough to come to any reliable conclusions.

For the period 1950–2001, the stations exhibiting the same trend form two clear clusters in space. One cluster is located in the Republican watershed, characterized by a strong positive trend for most of the stations. The other cluster is found in eastern Nebraska, characterized by either a strong negative trend or no trend. The dataset of 1970–2001 has a similar spatial pattern as well. The characteristics of the two clusters are slightly different, however. The number of the stations with no-trend increases in the Republican basin. The characteristics of the cluster in the eastern Nebraska are the same: negative or no trend.

The map of groundwater-level changes indicated that groundwater irrigation has resulted in decline of the water table from 6 to more than 15 m in three counties in southwestern Nebraska since 1950 (CSD 2004). During this period, the number of groundwater wells has increased year after year. Decline of streamflow has been a concern for water resource management in this area. Declining inflow from Colorado and Kansas has contributed in part to the lower streamflow of the Republican River. Further, continued groundwater withdrawal over the last 50 years is another factor for reduction in stream flow (Wen and Chen 2006).

Several combinations of the trends in drought severity, duration and frequency are observed: (1) consistent trends, i.e., the trend signs for the five indicators are the same, either positive, or negative, or no trend; (2) decreased severity and duration (may include no trend) with no changed frequency; (3) increased severity and duration (may include no trend) with no changed frequency; (4) no changed or decreased severity and duration with increased frequency; and some rare cases: (5) increased or decreased severity with no changed duration; and (6) increased or decreased severity with decreased or increased duration (only one case is found). Overall, drought frequency indicator ND is more stable than the other four.

## 5 Conclusions

Streamflow records from Nebraska are grouped into three time periods, ranging from 30 to 70 years. Basic statistical characteristics including correlation between event parameters, Hurst coefficients and lag-one coefficient are computed on the three fundamental drought event parameters: duration, magnitude, and severity. Furthermore, the trend-free pre-whitening Mann–Kendall (TFPW-MK) test is performed on the five drought indicators abstracted from the three parameters: AMD, ACD, AMV, ACV and ND.

Based on the analyses for the periods 1970–2001 and 1950–2001, the statistical characteristics of drought events in Nebraska that are consistent during the two periods include: (1) the association between duration and severity is significant; (2) the three parameters are long-term persistent and short-term random; (3) the streamflow droughts become less severe in terms of the annual drought severity and duration on more than half of the stations; and (4) the drought frequency does not change over the period on most of the stations.

The statistical characteristics and trends for the period 1932–2001 present similarity and difference from the conclusions obtained from 1971–2001 and 1951–2001: (1) the severity is significantly correlated with the duration and magnitude for all the stations; (2) about half of the stations are short-term random, half are short-term persistent, and about all stations are long-term persistent; (3) more than half of the stations indicate droughts decrease in severity and frequency over 1932–2001. These decreasing trends probably might be caused by the severe droughts in 1930s (the Dust Bowl years). However, because of the limited stations and a poorly spatial coverage for dataset of 1932–2001, conclusions based on the results should be used with caution.

Spatial pattern in trend suggest that distinct cluster of stations with trends towards more severe droughts in terms of frequency and severity are found in the Republican watershed over the periods 1971–2001 and 1951–2001. In contrast, in eastern Nebraska streamflow drought severity and frequency become less or remain the same over the time period. The study also demonstrates that temporal resolution is important when conducting the tests on drought parameters. An increased frequency or severity of droughts based on a shorter time scale might turn out to be no change or even decreased trends at a longer time scale.

Climate change and human activities, like change in precipitation record, constructions of dams, and reservoirs, irrigation canals on streams, lead to the changes of streamflow drought in severity and frequency. The complete explanation for the reasons of changes in streamflow drought characteristics is not easy and additional studies are needed. For instance, do trends in precipitation records lead to the trends in streamflow? Are the trends caused by changes in geomorphic characteristics? The results suggest that some systematic factors may play a role in the changes because of the spatial consistency (clusters). We plan to look into periodogram analysis, which has been used to compute periodicity and also persistent rainfall variability (Kottegoda et al. 2004). With knowledge of periodicity and persistence of streamflow, we hope to better define floods (overflow) and droughts (underflow) to improve the quality of our results.

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