Changes in U.S. Streamflow and Western U.S. Snowpack

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Abstract: Hydroclimatological records are increasingly examined for evidence of trends and shifts that may assist in prediction of future climate change scenarios. This study investigates the trend and step changes in U.S. streamflow over a 52-year period (1951–2002) using data from 639 unimpaired streamflow stations categorized according to the hydrologic unit codes. This is particularly relevant since the issue of climate change is of interest to many, and studies have indicated an abrupt change in climate around the year 1976/77. Trends were evaluated using three statistical tests: Spearman's rho, Mann-Kendall, and linear regression, and step changes were evaluated using the rank sum and student's *t* test. The temporal resolution used for the study included water year (Oct–Sept), autumn–winter (Oct–Mar), and spring–summer (Apr–Sept) periods. Additionally, April 1 snow-water equivalent (SWE) data for 121 SNOTEL stations for the period 1941 to 2004 were used to test for the trends in the western U.S. The multiple statistical tests provided robust results for regions with significant changes. Results indicated that the Mississippi and Missouri regions have an increasing trend in streamflow quantity. The Pacific Northwest and South Atlantic-Gulf regions have streamflow decreasing due to a step change in climate. Decreasing trends for the SWE were noted for a number of stations in the states of Oregon and Utah.

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Introduction

The land surface hydrological cycle is effected by extremes in climate (floods and droughts) and causes damage greater than other natural disasters in the United States (Wilhite 1997; Pielke and Downtown 2000; Lakshmi et al. 2004; Huntington 2006). Fluctuations in climate often force water managers to develop plans to mitigate these extremes.

Hydrologic floods and droughts have been studied extensively by the researchers using recorded streamflow and streamflow reconstructions from tree ring data (Lettenmaier et al. 1994; Tarboton 1995; Lins and Slack 1999; Douglas et al. 2000; Groisman et al. 2001; McCabe and Wolock 2002; Pagano and Green 2005). Secular trends in streamflow were evaluated by Lins and Slack (1999) for 395 climate-sensitive streamgaging stations in the conterminous U.S. using the nonparametric Mann-Kendall test. The differences in low, medium, and high flow regimes were computed for selected quantiles of discharge from the 0th to 100th percentile. The results indicated that the conterminous U.S. is getting wetter, but extreme events (e.g., flows) are not increasing in magnitude. McCabe and Wolock (2002) studied the annual minimum, median, and maximum daily streamflow for 400 sites in the conterminous United States. Results indicated an increase in annual minimum and median daily streamflow and less significant changes in annual maximum daily streamflow in the eastern United States. The increases in streamflow and total precipitation resulted from a step change and not from a gradual trend change (McCabe and Wolock 2002). Streamflow studies in the past have used the daily and mean monthly discharge for analysis, but results can be different when using the mean annual or peak flow rates (Lettenmaier et al. 1994; Lins and Slack 1999; McCabe and Wolock 2002).

In the western U.S., snowmelt is the dominant source of streamflow. The majority of the water resources come from the snow pack, which accounts for 50% to 70% of the annual precipitation in the mountainous regions (Hunter et al. 2006). The changes in winter and spring temperatures have effected the arrival of the April–July streamflow peak due to shifts in the timing of snowmelt (Mote 2003; Mote et al. 2005). April 1 snow-water equivalent (SWE) is usually used for evaluating the streamflow in the western U.S., as it can accurately predict the summer streamflow and represents the accumulation of winter snow (McCabe and Dettinger 2002; Mote et al. 2005). Mote (2003) used multiple linear regressions on temperature and precipitation to evaluate trends in the SWE for the Pacific Northwest. Decreasing trends were noted for the Pacific Northwest due to regional increases in temperatures, which also coincided with the increases in precipitation. No conclusions were drawn if the changes occurred due to any step-like shift.

Most studies of historical changes in streamflow have made use of a nonparametric statistical trend test such as the Mann-Kendall (Lins and Slack 1999; Douglas et al. 2000; McCabe and Wolock 2002), but did not account for an abrupt step change in the streamflow (McCabe and Wolock 2002; Rodionov 2004). It is

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important to clearly differentiate between a gradual trend and a step change for climate change studies. This is necessary because the pattern of the trend change can be linear and continuous, whereas step changes are nonlinear, occur abruptly, and may reoccur in the future (McCabe and Wolock 2002). It is well documented that rapid climatic changes were noted during the winter of 1976–1977 in the North Pacific region due to the shift in the ocean-atmosphere system (Kerr 1992; Beamish et al. 1996; Holbrook et al. 1997; Mantua and Hare 2002). These oceanic changes intensified the weather in the subArctic Pacific, which affected the sea surface temperatures. Variations (i.e., increase and decrease in sea surface temperatures) were noted for the Eastern Pacific and Central Pacific regions (Kerr 1992; Beamish et al. 1996). This step-like shift in the mean sea level pressure has been termed as the "climatic regime," following a regime shift in 1977 (Mantua and Hare 2002).

The study presented here evaluates both the trend and step change in U.S. streamflow over three periods (water year, autumn–winter, and spring–summer) for 639 unimpaired stations (maintaining natural conditions) over a 52-year span (1951–2002). The effect of autocorrelation was considered for the corresponding year's streamflow values at each station and the results are presented with and without stations having significant autocorrelations. The periods of autumn–winter and spring–summer were used to distinguish the temporal changes in streamflow. The periods were selected in such a manner that the water year can be divided into two portions and the effect of each period can be analyzed separately. The duration of the periods are explained in the data section.

The majority of previous studies have identified the streamflow changes as a gradual trend change based on a single statistical test. However, there are few studies that evaluate the occurrence of a step change in streamflow. The current research uses multiple statistical tests to identify regions in the conterminous U.S. that have experienced significant trend and/or step changes in streamflow. In addition, trend and step changes were evaluated in April 1 SWE for 121 SNOTEL stations in the western U.S. The results from the study will be useful for water managers in responding to changes in water supply.

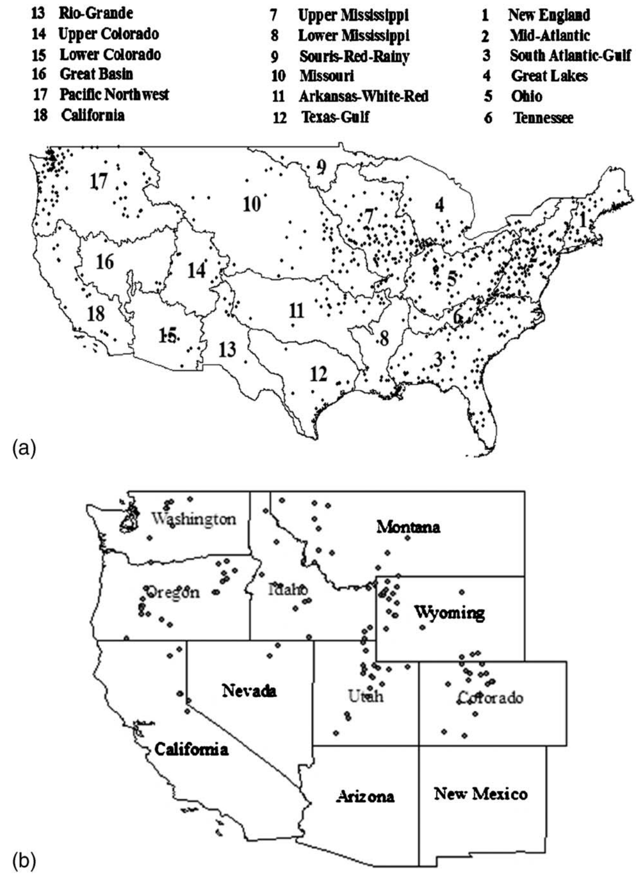

Fig. 1. Schematic of the streamflow and SWE stations (a) location of unimpaired U.S. Geological Survey streamflow stations in the continental United States for the period of 1951–2002; (b) location of SNOTEL sites in the western U.S. for the period of 1941–2004

Data

Streamflow Data

The major data set used in this study to analyze the trend and step changes in U.S. streamflow are unimpaired streamflow data compiled by Tootle et al. (2005). The streamflow data set includes 639 stations with records from 1951–2002 (52 years) [Fig. 1(a)]. The streamflow data consists of average monthly streamflow rates [in cubic feet per second (cfs)], which were averaged for the water year (October of the previous year to September of the current year), autumn–winter (October of the previous year to March of the current year), and spring–summer (April of the current year to September of the current year) and converted into streamflow volumes (km^3). All the stations are archived in the U.S. Geological Survey (USGS) NWISWeb Data retrieval (http://waterdata.usgs.gov/nwis/). The stations were categorized according to the hydrologic drainage basins in the U.S. [Fig. 1(a)] known as hydrologic unit codes (HUC) developed by the USGS (http://water.usgs.gov/GIS/huc.html).

Modified streamflow data set was generated by excluding those stations that had significant autocorrelation for each of the time periods (Fig. 2). For the water year data set, 244 stations were excluded due to significant autocorrelation and the remaining 395 stations were evaluated [Fig. 2(a)]. Similarly, 191 and 84 stations were eliminated in autumn–winter and spring–summer due to significant autocorrelation and the remaining 448 and 555 stations were evaluated [Figs. 2(b and c)].

Snow Water Equivalent Data

April 1 SWE data for 121 SNOTEL sites in the western U.S. were used based on Hunter et al. (2006) [Fig. 1(b)]. The data ranges from 1941 to 2004 and is archived in the NRCS SNOTEL website (http://www.wcc.nrcs.usda.gov/snotel). April 1 SWE is used because it is the most appropriate estimator and forecaster of total runoff in the western U.S. (McCabe and Dettinger 2002).

Methodology

Trend and step changes in the streamflow were evaluated using the Trend software (Chiew and Siriwardena 2005) for individual stations with and without considering autocorrelations during the three time periods. The software is designed to facilitate statistical testing for trend, change, and randomness in hydrological and other time series data.

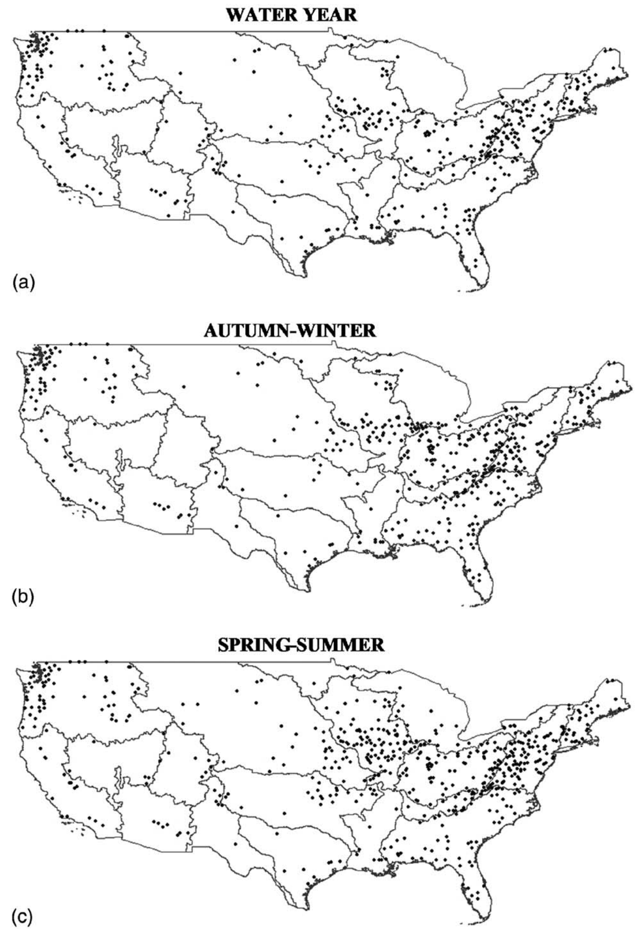

Fig. 2. Locations of unimpaired U.S. Geological Survey streamflow stations in the continental United States excluding stations showing significant autocorrelation (a) water year (395); (b) autumn–winter (448); and (c) spring–summer (555)

Statistical Tests

Three statistical tests (Mann-Kendall, Spearman's rho, and linear regression) were used for trend analysis and two tests (rank sum and student's *t*) for step change analysis (Maidment 1993; Chiew and Siriwardena 2005). For the trend analysis, the Mann-Kendall and Spearman's rho are nonparametric tests, whereas linear regression is a parametric test. For the step analysis, the nonparametric rank sum and parametric student's *t* test were used. For analyzing step changes, 1977 was used as the year showing the step change, as it has been documented by previous researchers (Kerr 1992; Beamish et al. 1996; Holbrook et al. 1997; Mantua and Hare 2002). The tests are rank-based procedures and are not influenced by the use of skewed variables except for student's *t* test. However, still, due to its nonparametric nature, it can be used to determine the step change in the observed data. A trend and step change for a station was termed as increasing or decreasing when all the tests were in agreement (three for trend change and two for step change). The increasing trend and step, or positive change, for a particular streamflow station is termed as high flow and decreasing trend and step, or negative change, as low flow. The use of five different tests allows the comparison of parametric and nonparametric statistical methods.

Standardized streamflow indices (i.e., magnitude) were computed for every station (639) and excluding stations showing significant autocorrelation during the three time periods. The trend magnitude was computed by taking the slope of the time series for a particular station and dividing by the respective station's time series standard deviation. The step change magnitude was computed by subtracting the mean of time series of earlier part of the data (from the first year of the data up to the year before separation) from the mean of the latter part (from the separation year to the final year) of the data dividing by the respective station's time series standard deviation. The whole process was then repeated for the SNOTEL stations to analyze the variability in the western U.S. snowpack. Last, the number of stations having high flows and low flows during the past 52 years were calculated by using a streamflow threshold value of less than 25th percentile flow for low flows and greater than 75th percentile flow for high flows for the three time periods. This analysis was performed in order to evaluate changes in extreme hydrologic conditions (e.g., 25th percentile=low flows and 75th percentile=high flows) in the conterminous United States.

Results and Analysis

Trend and step changes were evaluated for the streamflow stations with and without considering the effect of autocorrelation during the three time periods at a significance level of $p \leq 0.05$ (Figs. 3–5). Upward facing gray triangles represent an increasing trend or step change, and downward facing black triangles represent decreasing trend or step change for the various streamflow locations. The magnitude of the trend or step change is given by the size of the triangles. The magnitude had variable ranges for the trend or step changes. For stations exhibiting increasing and decreasing trend changes, the magnitude ranged from 0.022 to 0.056 and −0.029 to −0.018, respectively. Stations showing step changes had greater range values than those of trend changes. The values ranged from 0.675 to 1.51 and −0.785 to −0.558 for increasing and decreasing step changes, respectively. The small black dots are stations that had no change. The trend and step changes for the SNOTEL sites in the western U.S. are presented using the notations as for the streamflow, but with different magnitude ranges (Fig. 6).

The results are discussed in four ensuing sections. The first two sections highlight the trend and step changes with and without considering the effect of autocorrelation for the entire U.S. using the streamflow data. The next section presents the trend and step changes with and without considering the effect of autocorrelation for the western U.S. using the data for the SNOTEL sites, and last, the streamflow changes occurring over the past 52 years are presented.

Streamflow Trend Changes

An increasing trend in streamflow for the stations in the Great Lakes (4), Upper Mississippi (7), Souris-Red-Rainy (9), and Missouri (10) regions were noted for all the periods [Figs. 3(a), 4(a), 5(a)] using the entire data set. An increasing streamflow trend was also noted for the majority of stations in the Arkansas-White-Red (11) region during autumn–winter [Fig. 4(a)] as compared to the water year [Fig. 3(a)]. A number of stations in the Ohio (5) region showed an increasing trend during the spring–summer [Fig. 5(a)]. A smaller number of stations in the Texas-Gulf (12) and Rio Grande (13) regions showed an increasing trend during the water year and autumn–winter, but not during spring–summer [Figs. 3(a), 4(a)]. A decreasing streamflow trend

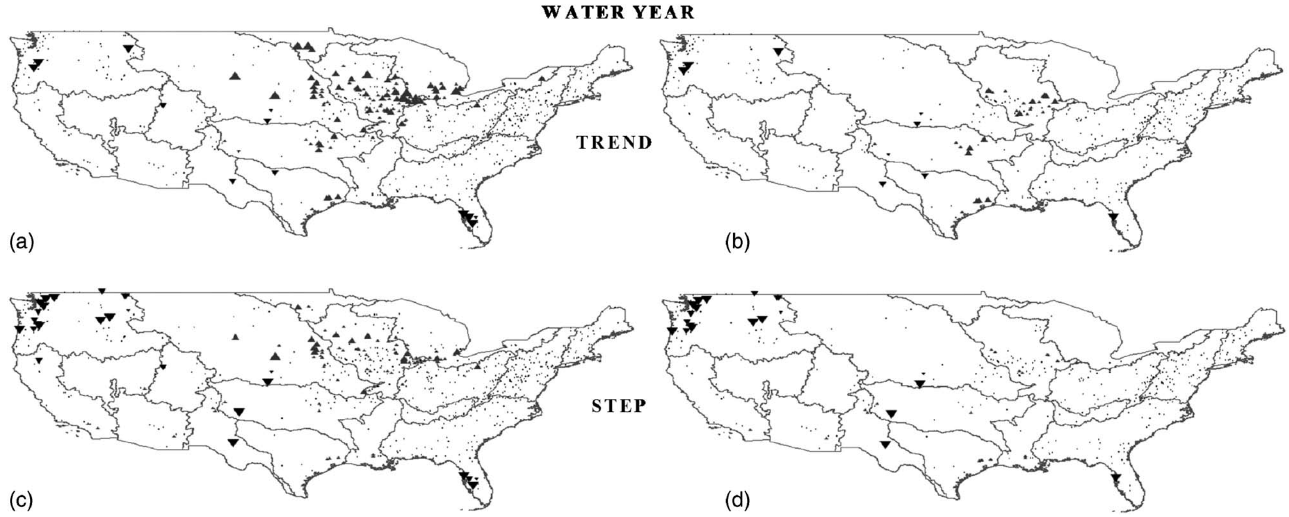

Fig. 3. Water year individual station test results for (a) trend (with autocorrelation); (b) trend (with no autocorrelation); (c) step (with autocorrelation); and (d) step (with no autocorrelation) at $p \leq 0.05$ confidence levels in the continental U.S. where all three statistical tests were in agreement. The direction of the triangles indicates the direction of the change in streamflow. The size of the triangles indicates the standardized magnitudes.

was found for the stations in the Pacific Northwest (17) and South Atlantic-Gulf (3) regions during the water year and spring–summer time periods [Figs. 3(a), 5(a)].

The changes were also analyzed excluding stations showing significant autocorrelations during the three time periods [Figs. 3(b), 4(b), 5(b)]. A significant amount of stations in the Missouri (7) region still showed an increasing trend during the water year and spring–summer [Figs. 3(b), 5(b)]. Increasing trends were also noted for a few stations in the Arkansas-White-Red (11) and Texas-Gulf (12) regions during the water year. The Upper Mississippi (10) region had a few stations showing increasing trend during the spring–summer [Fig. 5(b)]. Decreasing streamflow trends were noted by stations in the Pacific Northwest (17) and South Atlantic-Gulf (3) regions during the water year and spring–summer [Figs. 3(b), 5(b)].

The trend results indicate that the changes are most significant during the water year [Figs. 3(a), 3(b)] and spring–summer [Figs. 5(a), 5(b)] as compared to autumn–winter [Figs. 4(a), 4(b)]. The reduction in spring–summer flow in the Pacific Northwest (17) could be due to decreases in mountain snowpack accumulation during the winter.

Streamflow Step Changes

An increasing streamflow step change was noted for stations in the Upper Mississippi (7) and Missouri (10) regions using the entire data set during the time periods [Figs. 3(c), 4(c), 5(c)]. The majority of stations in the Great Lakes (4) region also indicated increasing step change during water year [Fig. 3(c)] and spring–summer [Fig. 5(c)]. The Pacific Northwest (17) had a significant

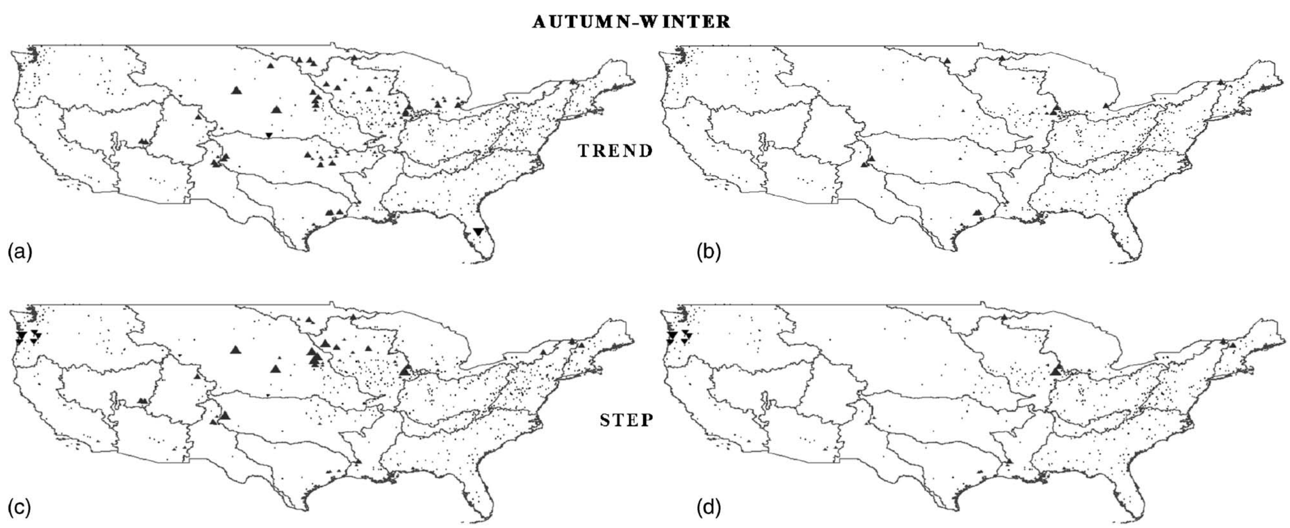

Fig. 4. Autumn–winter individual station test results for (a) trend (with autocorrelation); (b) trend (with no autocorrelation); (c) step (with autocorrelation); and (d) step (with no autocorrelation) at $p \leq 0.05$ confidence levels in the continental U.S. where all three statistical tests were in agreement. The direction of the triangles indicates the direction of the change in streamflow. The size of the triangles indicates the standardized magnitudes.

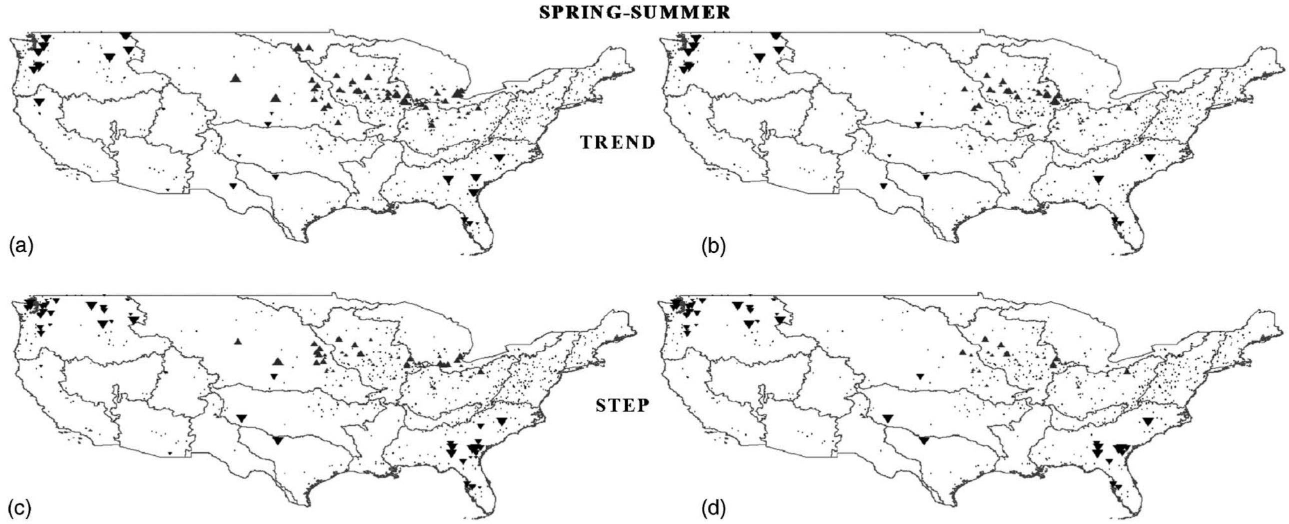

Fig. 5. Spring–summer individual station test results for (a) trend (with autocorrelation); (b) trend (with no autocorrelation); (c) step (with autocorrelation); and (d) step (with no autocorrelation) at $p \leq 0.05$ confidence levels in the continental U.S. where all three statistical tests were in agreement. The direction of the triangles indicates the direction of the change in streamflow. The size of the triangles indicates the standardized magnitudes.

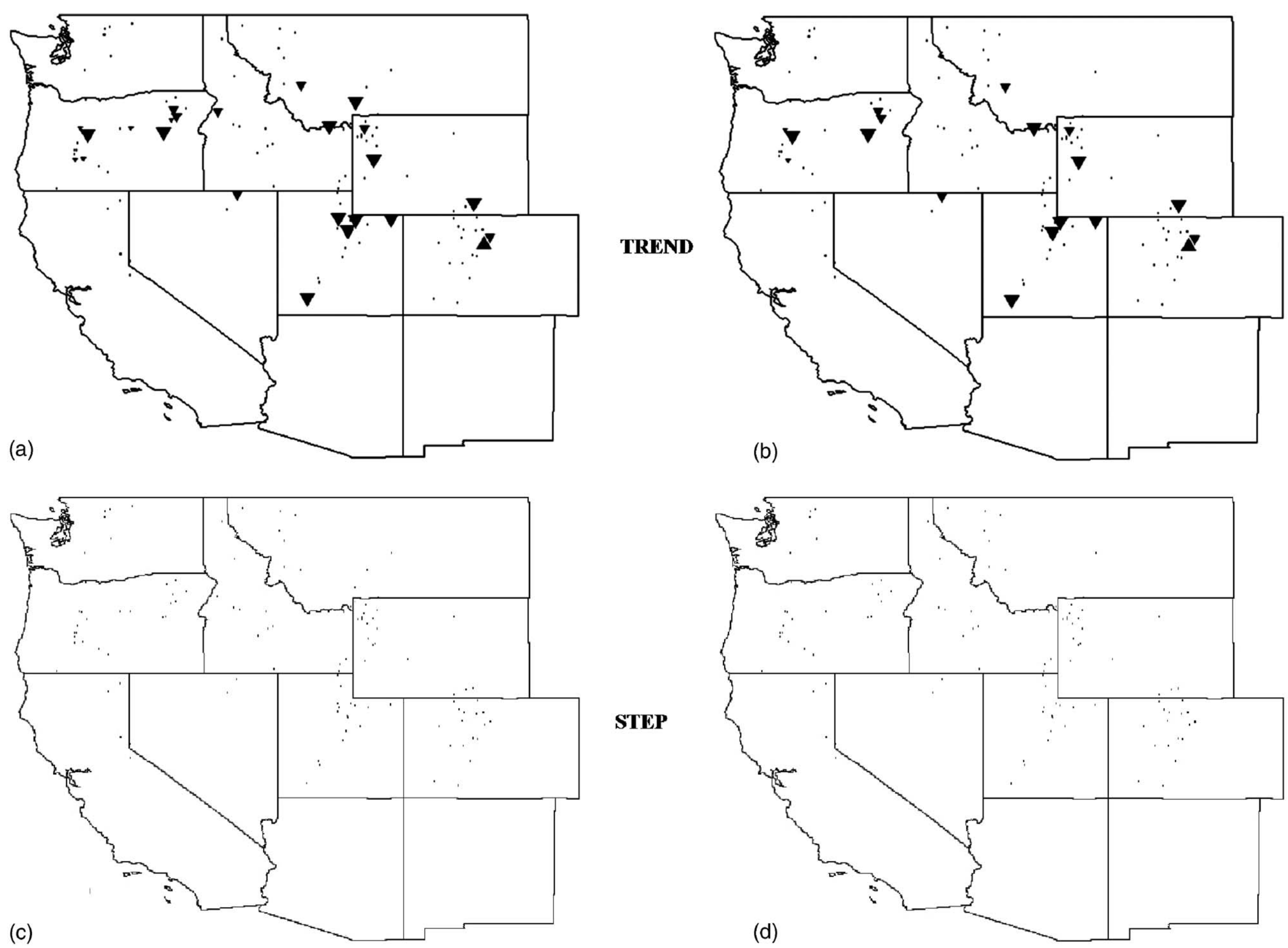

Fig. 6. SWE individual station test results for (a) trend (with autocorrelation); (b) trend (with no autocorrelation); (c) step (with autocorrelation); and (d) step (with no autocorrelation) at $p \leq 0.05$ confidence levels in the western U.S. where all three statistical tests were in agreement. The direction of the triangles indicates the direction of the change in streamflow. The size of the triangles indicates the standardized magnitudes.

Table 1. Increasing (+) or Decreasing (−) Trend and Step Changes in Each Hydrologic Unit Code (HUC) during the Three Time Periods with and without Considering the Effect of Autocorrelation

	With autocorrelation						Without autocorrelation					
	Water year		Autumn–Winter		Spring–Summer		Water year		Autumn–Winter		Spring–Summer	
HUC	Trend	Step	Trend	Step	Trend	Step	Trend	Step	Trend	Step	Trend	Step
1												
2												
3	−	−			−	−	−				−	−
4	+	+	+		+							
5					+							
6												
7	+	+	+	+	+	+	+	+			+	+
8												
9	+		+		+							+
10	+	+	+	+	+	+					+	
11	+		+				+					
12	+		+				+					
13	+		+									
14												
15												
16												
17	−	−			−	−	−	−			−	−
18												

number of stations indicating a decreasing streamflow step change during the water year [Fig. 3(c)] and spring–summer [Fig. 5(c)] as compared to autumn–winter [Fig. 4(c)]. The stations in the South Atlantic-Gulf (3) also showed decreasing step change for the water year [Fig. 3(c)] and spring–summer [Fig. 5(c)] but not for the autumn–winter.

When excluding the stations showing significant autocorrelation for the three time periods, there was a difference in the step change results. An increasing step change was only noted for streamflow stations in the Upper Mississippi (7) region during spring–summer [Fig. 5(d)] and water year [Fig. 3(d)], and not during autumn–winter. A few stations showed increasing step change in the Missouri (9) region during the spring–summer [Fig. 5(d)]. More stations showed decreasing streamflow step changes in the Pacific Northwest (17) region during the water year [Fig. 3(d)] and spring–summer [Fig. 5(d)] as compared to the autumn–winter period [Fig. 4(d)]. The stations in the South Atlantic-Gulf (3) region showed a decreasing step change during the spring–summer time period [Fig. 5(d)]. Similar to the trend analyses, the step analysis also indicated that the changes are most significant during the water year [Figs. 3(c), 3(d)] and spring–summer [Figs. 5(c), 5(d)].

Tables 1 and 2 summarize the increasing (+) and decreasing (−) streamflow changes with and without considering the effect of autocorrelation during the three time periods for each HUC. It is noteworthy that changes are more significant during the water year and spring–summer, as compared to the autumn–winter (Table 2). Tables 1 and 2 also indicate the significance of autocorrelation in the present study and how the results change when excluding stations showing significant autocorrelation during the three time periods. The number in parentheses indicates stations showing a change after excluding the stations showing significant autocorrelation (Table 2). The maximum numbers of stations showing significant autocorrelation were present during the water year (244) and decreased from autumn–winter (191) to spring–summer (84). Of the remaining stations, more significant results (increasing or decreasing) were noted during the water year and spring–summer than in autumn–winter. It is also noteworthy that there are more stations indicating increasing streamflow trend and step changes as compared to the decreasing change. This implies that the conterminous United States has been getting wetter during the duration and period of record.

Trend and Step Changes for SNOTEL Sites

The trend and step change for the western U.S. snowpack were analyzed for 121 SNOTEL sites and also excluded stations showing significant autocorrelation between the various years SWE

Table 2. Number of Stations with Trend and Step Changes during the Three Time Periods with and without Considering the Effect of Autocorrelation. The Number inside the Parentheses Indicates the Number of Stations Showing Changes after Excluding Stations Showing Significant Autocorrelation.

Period	Number of stations without autocorrelation	Streamflow increasing		Streamflow decreasing	
		Trend	Step	Trend	Step
Water year	639 (395)	121 (31)	85 (19)	13 (9)	29 (24)
Autumn–Winter	639 (448)	90 (29)	54 (18)	3 (0)	7 (5)
Spring–Summer	639 (555)	84 (53)	52 (31)	27 (21)	52 (44)

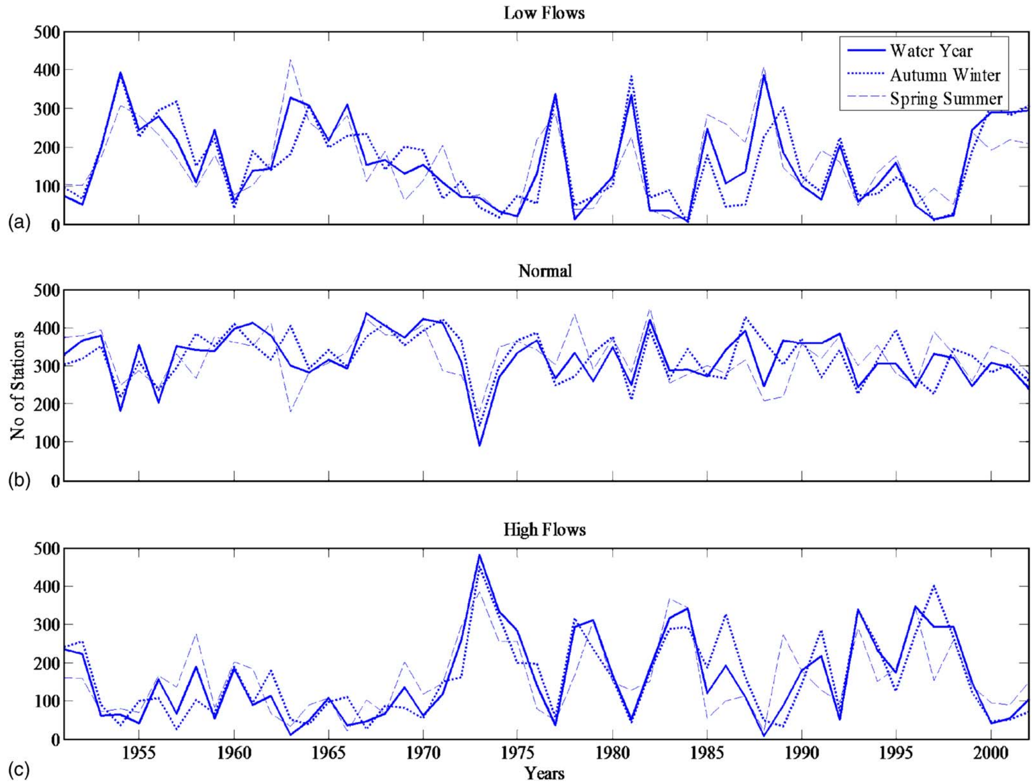

Fig. 7. Summary of the number of U.S. stations during water year, autumn–winter and spring–summer having (a) low flows (<25th percentile); (b) normal; and (c) high flows (>75th percentile) conditions from 1951–2002

(Fig. 6). An increasing trend for the SWE was found for a single station in Colorado [Fig. 6(a)] with a magnitude of 0.26. The decreasing trend for SWE was noted in the states of Oregon, Utah, and west Montana [Fig. 6(a)] with magnitudes ranging from −0.028 to −0.013, respectively. Eight stations were eliminated since they had significant autocorrelation [Figs. 6(b), 6(d)]. The single station in Colorado that noted increasing trend change was still present [Fig. 6(b)] after eliminating stations with significant autocorrelation. The decreasing trend for the SWE was still noted at sites in Oregon and Utah [Fig. 6(b)]. Step changes were found insignificant in SWE during the present study [Figs. 6(c), 6(d)]. Individual test (i.e., student's t and rank sum) indicated increasing/decreasing step changes for various SNOTEL sites, but the agreement of the test was not noted at any of the sites. So, this resulted in the nonoccurrence of step changes in the SWE values.

The SNOTEL sites analysis agreed with streamflow analysis in indicating decreasing trends in SWE (Fig. 6) and streamflow (Figs. 3–5) for the northwestern United States. However, streamflow results indicated changes as both trend and step for the western U.S. during the three time periods. The changes in SWE were only due to trend change.

Streamflow Comparison over a Period of 52 Years (1951–2002)

The number of stations having low flows (<25th percentile), high flows (>75th percentile) and normal conditions are shown in Fig. 7. The early part of the record (pre1977) contained more low flows [Fig. 7(a)] as compared to stations having high flows and normal conditions, which has also been established by McCabe and Wolock (2002). There has been a gradual decline in the number of stations with normal conditions after 1977 [Fig. 7(b)]. This corresponds with temperature studies that showed climate change impacts and the potential for impacting streamflow (Holbrook et al. 1997; Mantua and Hare 2002). Last, the number of stations having low flows and high flows has increased after 1977 [Figs. 7(a and c)], which could be due to a climate regime shift.

Conclusions and Discussion

The current research focused on a robust approach using multiple statistical tests for evaluating the trend and step changes in streamflow at a confidence level of $p \leq 0.05$ for the 639 unimpaired streamflow stations in the conterminous United States during three time periods. A number of stations were eliminated in the analysis, as the results were based on the agreement of all the trend or step tests for a particular location and not on a single test. Furthermore, the presence of significant autocorrelation between the various years' streamflow values eliminated some stations. The majority of stations in the regions of Great Lakes (4), Upper Mississippi (7), Souris-Red-Rainy (9), and Missouri (10) had considerable high flows due to a gradual trend change in the past 52 years using the entire data set. The number of stations showing trend and step changes decreased when stations showing significant autocorrelation were eliminated during the three time periods. The streamflow stations only in the eastern regions of the U.S. [i.e., Missouri (7) and part of Upper Mississippi (10)] showed increasing trends during the water year and spring–summer when taking into account the autocorrelation. This agrees with Lins and Slack (1999) that showed the eastern U.S. is getter wetter but less extreme. Groisman et al. (2001) reported increases in high flows in the conterminous U.S., particularly in the eastern part. The increase in the eastern U.S streamflow statistics also coincides with the increases in precipitation in the eastern United States (Karl and Knight 1998). McCabe and Wolock (2002) showed an increase in the eastern U.S. high flows, but their timing was different and the increases were a result of step increases, rather than a gradual trend, as indicated in the present study. The present study used mean monthly flows averaged over different time periods, whereas McCabe and Wolock (2002) used maximum daily streamflows. In addition, the results are based on multiple tests and not on a single test as used by McCabe and Wolock (2002).

The decreasing streamflow for the Pacific Northwest (17) and South Atlantic-Gulf (3) may be due to a step change, as compared to gradual trend change during the water year [Fig. 3(c)] and spring–summer [Fig. 5(c)], because both regions have stations exhibiting decreasing step changes using the entire data set and when stations showing significant autocorrelation are excluded. Lins and Slack (1999) and Mote (2003) showed a decreasing trend in the streamflow for Pacific Northwest (17), but did not account for any step change. For the conterminous U.S., the changes are prominent during the water year and spring–summer and are gradual trend changes. This could reflect more precipitation in the form of rainfall instead of snowfall. The SWE had decreasing trend in the states of Oregon and Utah and no signs of any step changes were found in the data. It is also noteworthy that the results of this study suggest that the changes in streamflow for the Pacific Northwest (17) and South Atlantic-Gulf (3) are due to an abrupt step change and not due to a gradual change over the past 52 years. The interpretation of step and gradual trend changes are important for climate change studies, as they may help the water resource managers in predicting future climate scenarios. In response, this may help in modifying the operating rules for extreme events and mitigate the impact of such events. Further work can be done by incorporating the various climatic observations, such as the precipitation, evaporation, and latent heat, which might be helpful in providing a wider perspective to the present results.

Acknowledgments

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