Journal of Hydrology 517 (2014) 36–53

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Evaluating the effect of persistence on long-term trends and analyzing step changes in streamflows of the continental United States

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ARTICLE INFO

Article history:
Received 19 September 2013
Received in revised form 6 April 2014
Accepted 3 May 2014
Available online 14 May 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Bruno Merz, Associate Editor

Keywords:
Streamflow
Trend detection
Shift
Persistence
Climate variability

SUMMARY

Streamflow is a very good indicator of long-term hydroclimatic changes. From a water management perspective, the identification of gradual (trend) and abrupt (shift) changes in streamflow are important for planning purposes. This study investigated the detection of comprehensive change, gradual and abrupt, in 240 unimpaired streamflow stations, categorized according to the hydrologic regions in the continental United States. The changes in streamflow volume were analyzed for water–year, autumn, winter, spring, and summer from 1951 to 2010, a 60-year period. The non-parametric Mann–Kendall test, with variations accounting for short term and long-term persistence, was used to evaluate the trends; the non-parametric change-point Pettitt test was used to evaluate the shifts. The field significance was evaluated using the Walker test. The trend results indicated increasing streamflow patterns in the majority of the eastern U.S. regions – the Upper Mississippi, Missouri, Great Lakes and Texas Gulf were field significant – and dominant decreasing streamflow trends in the Pacific Northwest region. The use of different Mann–Kendall test helped in evaluating the spatial distribution of short-term and long-term persistence and their effect on trends. The Pettitt test analysis indicated that statistically significant shifts occurred during the early 1970s and late 1980s. Similar to the trend results, the Midwest as well as the central and southern U.S. had significantly increasing shifts; the Pacific Northwest, Tennessee (winter season only), and South-Atlantic Gulf (spring season only) had decreasing shifts in streamflow. The findings may assist water managers in better planning and management of water resources under climate variability and change.

1. Introduction

With the rapid increase in population, the stress on water resources has increased manifold (Qaiser et al., 2013; Shrestha et al., 2011; Ahmad and Prashar, 2010; Wu et al., 2013). Further, water managers have been concerned about the anticipated impacts of climate variability and change on water resources (Dawadi and Ahmad, 2012; Vedwan et al., 2008; Kalra and Ahmad, 2012; Dawadi and Ahmad, 2013). Increased variability in streamflow due to changing climate has resulted in altering the hydrological cycle (Puri et al., 2011; Stephen et al., 2010; Ahmad et al., 2010; Ahmad and Simonovic, 2006). In snow-fed basins, an increase in spring temperatures has led to earlier summer streamflow peaks (Arora and Boer, 2001; Voss et al., 2002; Stewart et al., 2005; Hamlet and Lettenmaier, 2007); moreover, low annual flows have increased in the northeast U.S. in the last century, and have become less extreme (Lins and Slack, 1999; EPA climatic indicators, 2012).

Changes in climate variability enhance the uncertainties in the availability of fresh water for future generations (Middelkoop et al., 2001). Thus, water managers face the challenge of meeting future water demands with existing water infrastructure that may be inadequate in the future (Qaiser et al., 2011; Ahmad and Simonovic, 2001). In addition, stress is increasing to meet environmental flow requirements and provide water for the energy needs (Shrestha et al., 2012; Venkatesan et al., 2011a; Venkatesan et al., 2011b; Melesse et al., 2011).

Changes in the hydrological cycle can result from both climate variability and anthropogenic interference. These changes may be gradual (trend) or abrupt (shift). Changing hydrology may lead to under-designed or over-designed projects (Forsee and Ahmad, 2011; Mosquera-Machado and Ahmad, 2007; Ahmad and Simonovic, 2000a), which may not meet long-term needs; thus, the traditional assumption of stationarity for hydraulic designs requires review (Milly et al., 2008). To address these issues, this

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http://dx.doi.org/10.1016/j.jhydrol.2014.05.002
0022-1694/

study focuses on evaluating trend and step changes in streamflow while taking into account streamflow persistence, which affects long-term trends.

Study of the changes in streamflow, using unimpaired stations, helps to minimize the effect of anthropogenic influences on land use, flow storage, and diversions; the resulting change can be attributed to variability and climate change. Various studies have predicted future warming, bringing change in timings as well as increasing the quantity of monthly precipitation; reducing winter precipitation and snowpack accumulation in the western U.S.; decreases in high flows in the eastern U.S., and shifting summer peak streamflow towards winter, thus increasing the flood and drought risks in western United States (Aguado et al., 1992; Dettinger and Cayan, 1995; Hamlet and Lettenmaier, 1999; Nijssen et al., 2001; Stewart et al., 2005; Hamlet et al., 2007; Hayhoe et al., 2007). Analyses on the global pattern of climate trends concur with evidence of a warming climate (Dettinger and Diaz, 2000; Easterling et al., 2000; Milly et al., 2002; Milly et al., 2005; Adam et al., 2009).

A great deal of research is taking place to understand the interdependency between climate variability, and streamflow (Hamlet and Lettenmaier, 1999; Kalra and Ahmad, 2011; Carrier et al., 2013; Kalra et al., 2013a, b). However, there is a need to understand the changing patterns of streamflow over time, which can improve planning and operational strategies for sustainable use of available water resources (Frederick and Major, 1997; Mirchi et al., 2012; Ahmad and Simonovic, 2000b).

In the past, significant efforts have been made to study the long-term trends in streamflows over the continental United States. Several studies have shown an increase in annual moderate-to-low streamflows and a less significant increase in peak streamflows (Lettenmaier et al., 1994; Lins and Slack, 1999; McCabe and Wolock, 2002; Kalra et al., 2008). Lettenmaier et al. (1994) used monthly records of 1009 unimpaired streamflow stations in the continental U.S. for a period of 40 years (1948–1988); they found increases in streamflows from November to April that concentrated in the north-central states. Lins and Slack (1999) conducted a trend analysis on daily discharges from 395 streamflow stations of the Hydro-Climatic Data Network for varying years, and identified decreasing trends in the Pacific Northwest and Southeast region. For the eastern United States, Small et al. (2006) indicated that increases in fall precipitation increased the low flows; on the other hand, high flows were not related statistically to trends in spring precipitation. Groisman et al. (2001) studied 385 stations from the HCDN and found increasing trends in peak streamflows in the eastern U.S. resulting from increasing precipitation; however, they found negligible change in the western United States. The differences in the results are due to the different techniques used in these studies.

Regarding regional studies on streamflow changes, in Pennsylvania, Zhu and Day (2005) found strong downward trends in the daily streamflow volume. Gebert and Krug (1996) found that annual low flows increased and flood peaks decreased in southwestern Wisconsin, which varied from northern Wisconsin. Easterling et al. (2000) and Groisman et al. (2001) found an escalation in climate events, such as heavy precipitation, floods, and droughts, indicating abrupt climate patterns. In the 20th century, the droughts of 1930s and 1950s were identified as the most severe for large areas; the droughts of early 2000s in the western U.S. were identified as the most extreme for small areas (Andreadis et al., 2005).

So far, the documented literature has been valuable with regard to streamflow change studies. However, various unrealized forcing mechanisms, such as short-term and long-term natural variability, need to be considered while analyzing a hydrological time series. The hydro-climatic variables have a propensity to be present in clusters during certain periods of time, i.e., droughts or floods; this is termed ‘scaling’ or ‘persistence’. Short-term persistence (STP), the most common and simple example, has been addressed in many studies using the autoregressive-1 model. The presence of long-term persistence (LTP), first identified by Hurst (1951) in a study on the Nile River, can considerably influence trends determined with independence and STP assumptions (Cohn and Lins 2005).

LTP can be postulated to exhibit the continual variability of several factors influencing climate and ultimately streamflow, such as solar forcing, volcanic activity, greenhouse gases, carryover storage of water in lakes, soil properties, and oceanic-atmospheric oscillations. As stated by Koutsoyiannis and Montanari (2007), the recorded data could be a small segment of a longer cycle of natural processes that, under current circumstances, are unidentified by currently available observations. Therefore, a longer observation period can provide more realistic information of the process under investigation. Each watershed has its own characteristic hydrology, which is the basis of hydrologic spatial variability.

Vogel et al. (1998) studied the variation of persistence across the U.S., and identified larger regions with the homogenous property of persistence. The presence of LTP can significantly deviate the mean from actual trends; thus, it is essential to investigate LTP’s effect on trends. Burn and Elnur (2002) analyzed trends of hydrologic and meteorological variables in Canadian catchments, using serial and cross-correlation; they observed an earlier onset of spring-melt conditions, and suggested that hydrological variables accentuate patterns existing in meteorological variables acting as input. Kalra et al. (2008) analyzed 639 unimpaired U.S. streamflow stations data for 52 years for trends with lag-1 autocorrelation; they observed decreasing streamflow trends in the Pacific Northwest and South-Atlantic Gulf, resulting from an abrupt step change followed by a gradual decreasing trend. In the analysis of streamflow in Indiana, Kumar et al. (2009) used lag-1 autocorrelation, complete autocorrelation structure, and LTP. Similarly, Ehsanzadeh and Adamowski (2010) conducted a study identifying the STP and LTP influence on streamflow trends in Canada. Other studies have suggested that trends are influenced by the nature of streamflow statistics, annual/seasonal statistics, the time period, and take into consideration the correlation structure (Koutsoyiannis, 2003; Kumar et al., 2009).

The literature has highlighted the importance of studying long-term trends in streamflow; however, addressing the effect of LTP while identifying trends has not received prominence in studies of the continental United States. To evaluate the impact of climate change, the distinction between trends and shifts is important. When there is a sharp increase or decrease in any hydrological variable, abrupt changes, also known as shifts, may be associated with extreme hydrologic events, such as storms, floods, or droughts, along with changes in ecosystems. For example, the winter of 1976–1977, in the North Pacific was extreme due to a shift in the ocean–atmosphere system (Kerr, 1992; Beamish et al., 1997; Holbrook et al., 1997; Mantua and Hare, 2002). During that period, a shift was observed in the mean sea-level temperature (Mantua and Hare, 2002). Sudden changes in the inland surface water may be result of these climate extremes.

A trend is anticipated to extend into the future, whereas the occurrence of a shift can lead the streamflow towards a completely different regime. Generally, these changes are unpredictable unless the causes are known. Previous studies on shift detection in the U.S. have been conducted by using a pre-defined known year and by comparing the means or medians in the data before and after that time (Kalra et al., 2008; Miller and Piechota, 2008). This method has limitations when a large number of stations are considered because the shift period may not coincide; hence, it is difficult to pre-define a particular shift period. The presence of a shift