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Using wavelet to analyze periodicities in hydrologic variables

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Abstract

The trend and shift in the seasonal temperature, precipitation and streamflow time series across the Midwest have been analyzed, for the period 1960-2013, using the statistical analyses (Mann-Kendall test with and without considering short term persistence (MK2 and MK1, respectively) and Pettitt test). The paper also utilizes a relatively new approach, wavelet analysis, for testing the existence of trend and shift in the time series. The method has the ability to decompose a time series in to lower (trend) and higher frequency components (noise). Discrete wavelet transform (DWT) has been employed in the present study with an aim to find which periodicities are mainly responsible for trend in the original data. The combination of MK1, MK2 and DWT along with Pettitt test hasn't been extensively used up to this time, especially in detecting trend and shift in the Midwest. The analysis of climate division temperature and precipitation data and USGS naturalized streamflow data revealed the presence of periodicity in the time series data. All the incorporated time series data were seasonal to analyze the trends and shifts for four seasons-winter, spring, summer and fall independently. D3 component of DWT were observed to be influential in detecting real trend in Temperature, precipitation and streamflow data, however unlike temperature, precipitation and streamflow showed decreasing trend as well. Shift was relatively observed more than trend in the region with dominance of D3 component in the data. The result indicate the significant warming trend which agrees with the "increasing temperature" observations in the past two decades, however a clear explanation for precipitation and streamflow is not obvious.

Introduction

Climate change and its impacts are drawing attention of research communities (Kalra and Ahmad, 2011, Sagarika et al., 2015a). Different studies have detected the effects of changing climate change on the hydrologic cycle and hydrological parameters such as temperature, precipitation and streamflow (Karl and Riebsame, 1989; Zhang et al., 2001; Christensen et al., 2004; Milliman et al., 2008; Kalra and Ahmad, 2012; Thakali et al., 2016). Increase in temperature affects several hydrological variables such as changing precipitation patterns, amplification in melting of snow and ice, increasing evaporation resulting in alteration of soil moisture and runoff (Xu et al., 2009; Nijssen et al; 2001; Dawadi and Ahmad, 2012; Kalra et al., 2013 a&b; Dhakal and Chevalier, 2015, Zhang et al., 2016). Increase in streamflow as a result of warming temperature and increasing precipitation is one of the most significant consequences of climate change (Kalra et al., 2013c; Zhang et al., 2014). As a result of climate change the trends in streamflow and its indicators were detected while, the significance of the trend were region

specific (IPCC, 2007). These impacts of climate change induce hydrological issues like flood and drought in different region. The comprehension of the changes in the hydrological parameters and the associated socio-economic and ecological impacts can help the water managers and policy makers to design and implement technological remedies as well as formulate institutional arrangements accordingly (Dhakal and Chevalier, 2016).

Water managers have increasing interest in evaluating the impacts of global warming on water resources (Carrier et al., 2013; Paz et al., 2013; Maheswari et al., 2014; Sagarika et al., 2015b; Ghimire et al., 2016). Researchers have suggested the change in hydrologic variables such as temperature, precipitation, and streamflow by identifying the presence of shifts and trend in these variables (Lattenmaier et al., 1994; Milly et al., 2005). Documented literature have identified statistical trends in temperature, precipitation and runoff, attributing climate change as the cause (Lettenmaier et al., 1994; Cayan et al., 2001; McCabe and Wolock, 2002; Kalra et al., 2008; Tamaddun et al., 2016b). Trends are the gradual increase/decrease in the time series data. Different studies have evaluated the statistical trends and steps in the runoff attributing earlier snowmelt, change in precipitation and its timing as the cause (Mote et al., 2004; Huntington, 2006; Hamlet et al., 2007; Kalra et al., 2008; Stewart, 2009). These causes also trigger droughts in summer by shifting the hydrograph earlier in time. Association of trend in increased streamflow to increasing temperature and precipitation in different parts of the world is another major finding available in the literature (Lins and Slack, 1999; Zhang et al., 2001; Birsan et al., 2005; Xu et al., 2009; Gautam et al., 2010; Kalra and Ahmad, 2011). In addition to the trend there are abrupt changes in a time series data known as shift. Trend analysis by incorporating the shift in the time series is getting popular in recent studies (Villarini et al., 2009). Considering the shift during trend analysis prevents overestimation of trends because of unconsidered shifts.

For better estimation of future temperature, precipitation, and streamflow past changes in these values should be comprehended. Along with trend and shift analysis, previous researchers have incorporated wavelet analysis to understand the past events of different periodicities (Nalley et al., 2012). Wavelet analysis can be applied for both continuous and discrete datasets for comprehending non-stationarity of the data at different periodicity (Daubechies 1990). According to Labat (2008), discrete wavelet transform (DWT) can detect hidden trends in the time series by disintegrating the data into other subsets of different frequencies; thus considering different periodicities in the data set. Previously, DWT has been used in evaluating correlation among hydroclimatic variables (Tammadun et al., 2016a) and determining trends in hydrological data and also in forecasting in combination with other statistical tools (Kulkarni 2000; Shafaei and Kisi 2016; Nourani et al., 2009).

The current study incorporates Mann- Kendall (MK) test with and without considering short term persistence (MK2 and MK1, respectively) for trend analysis in Midwestern US- agricultural heartland of US. The study uses Pettit test for shift analysis and further utilizes DWT to decompose the time series to obtain the trend by segregating the high frequency noise.

Study Area and Data

Midwest being among agriculturally productive regions has attracted different researchers and water managers for accessing the impacts of changing hydroclimatic variables (Pathak et al., 2016a). Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota and Wisconsin are the 12 states of Midwest in alphabetical order. There are 144 climate division (CD) in Midwestern U.S. as shown in Fig. 1. The temperature and precipitation data between 1960 and 2013 (54 years) for each CD were obtained from National Climatic Data Center (NCDC, <http://www.esrl.noaa.gov/psd/data/timeseries/>). The continuous streamflow data from 1960 to 2013 for 88 streamflow station were obtained from USGS (<http://waterdata.usgs.gov/nwis/sw/>). The spatial location of these streamflow stations is also shown in Fig. 1. The streamflow stations incorporated in the study are unimpaired, maintained under Hydro-Climatic Data Network 2009 (Lins, 2012).

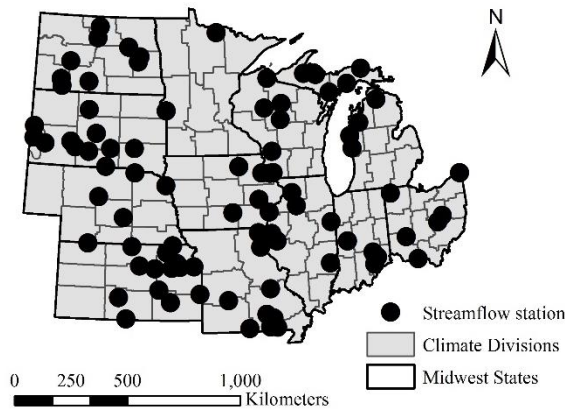


Figure 1: Map of Midwestern US with the streamflow stations and climate divisions incorporated in the study.

Methodology

Use of MK test is popular in plethora of researches as the test is non-parametric and analyses the time series data that do not follow any distribution (Lins and Slack, 1999; Villarini et al., 2009; Sagarika et al., 2014). For more details of MK test readers are referred to (Mann, 1945; Kendall, 1975). The Pettitt test utilized in the study is incorporated to find shifts in the time series and the detailed description of this test can be obtained from Pettitt (1979). All the tests specified above are simultaneously implemented with the DWT to obtain different modes of periodicities and respective trends and shift in the time series (Nalley et al., 2012; Pathak et al., 2016b).

Results and Discussions

The results of the study are presented in different sections. First the MK1 trend of temperature and precipitation for different dyadic scales and seasons is presented followed by MK2 trends. Next the Pettitt test results for temperature and precipitation are discussed. Finally, the trend and shift in streamflow is explained.

MK1 trend in temperature and precipitation at different dyadic scale

The MK test results without considering short term persistence are summarized in Fig. 2. The figure represents the MK1 results for both temperature and precipitation for four seasons and four dyadic scales D0, D1, D2 and D3 (2, 4, 8 and 16 years). Here four dyadic scales D0, D1, D2 and D3 are original time series, first wavelet component, second wavelet component, and third

wavelet component, respectively. Fig. 2a, b, c and d represents spatial distribution of MK1 trend during winter, spring, summer and fall respectively.

As shown in Fig.2 a, b, c and d; during spring, summer, winter, and fall 106, 65, 79 and 9 CD, respectively showed positive trend in temperature for D0. While 29, 12, 9 and 26 CD for precipitation showed increasing trend for winter, spring, summer and fall, respectively, for original time series. While, one CD in North Dakota showed decreasing trend in precipitation during original time series. All CD of the original time series of temperature revealed decreasing trend during winter. More number of CD revealed increasing trend in both temperature and precipitation at higher dyadic scales. From Fig. 2 it is evident that maximum increasing trend in temperature is observed during winter while comparatively less number of CD revealed increasing trend in fall. For winter south east region of Midwest showed decreasing trend in precipitation and the number of CD following increasing trend increased at higher dyadic scales. The minimum increasing trend in precipitation was observed during summer. During higher dyadic decomposition of fall precipitation significant CD were observed showing decreasing trend.

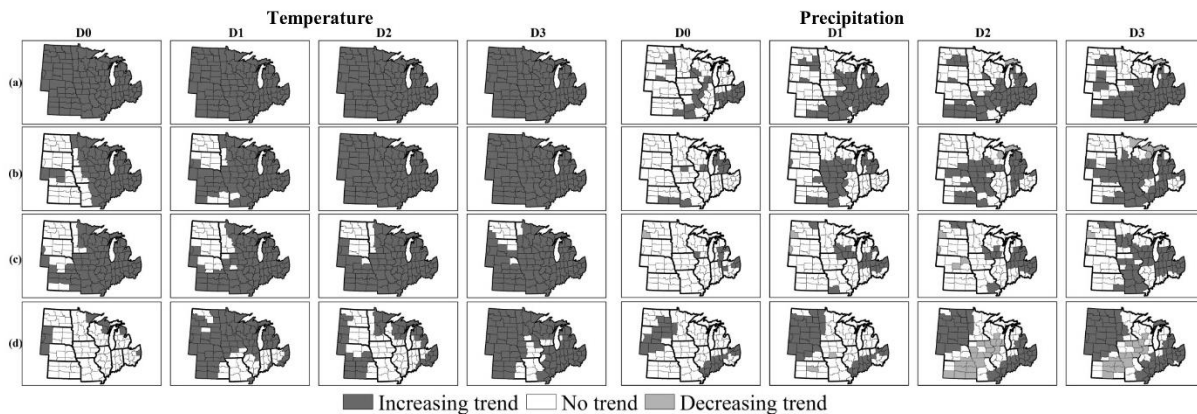


Figure 2: MK1 trend spatial plot representing the climate divisions showing MK1 trend in temperature and precipitation at 90% significance during (a) winter, (b) spring, (c) summer and (d) fall.

MK2 trend in temperature and precipitation at different dyadic scale

The short term persistence was observed in significant number of CD and the one showing short term persistence increased at higher dyadic scales. Thus, to have better estimation of trends MK2 test was performed which takes into account for short term persistence. The MK test results considering short term persistence are summarized in Fig. 3. The figure represents the MK2 results for both temperature and precipitation for four seasons and four dyadic scales D0, D1, D2 and D3 (2, 4, 8 and 16 years). Fig. 3 a, b, c and d represent spatial distribution of MK2 trend during winter, spring, summer and fall, respectively.

As shown in Fig. 3 a, b, c and d; during spring, summer, winter and fall all 106 CD showed increasing trend in original time series of temperature (D0). While 29, 12, 9 and 26 CD for precipitation showed increasing trend for winter, spring, summer and fall, respectively, for original time series. Similar to MK1, one CD in North Dakota showed decreasing trend in precipitation during original time series. The number of CD showing increasing trend increased at higher dyadic scales. For winter, south east region of Midwest showed increasing trend in precipitation and the number of CD showing increasing trend increased at higher dyadic scales.

The minimum increasing trend in precipitation was observed during summer. During higher dyadic decomposition of fall precipitation significant CD were observed showing decreasing trend. Most of the results of MK2 were similar to MK1 results while some new stations showed trends during MK2 test when short term persistence was taken into account.

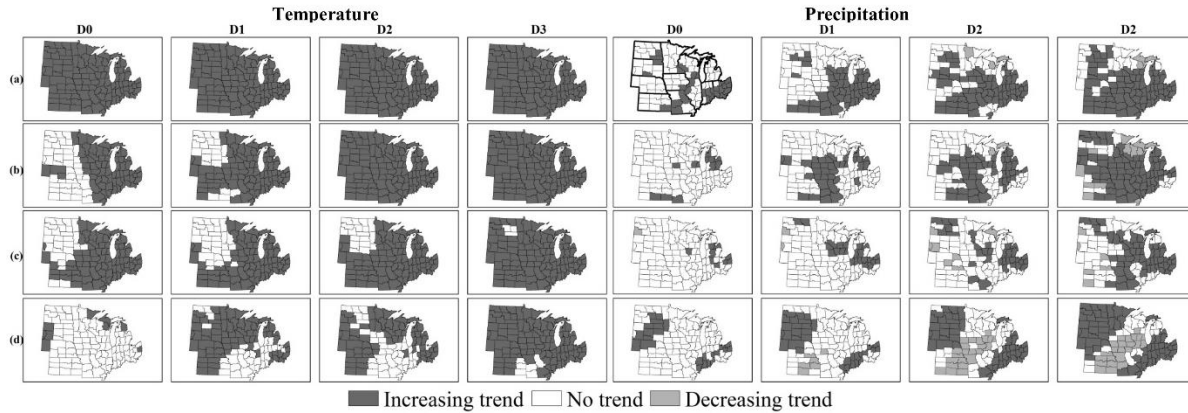


Figure 3: MK2 trend spatial plot representing the climate divisions showing MK2 trend in temperature and precipitation at 90% significance during (a) winter, (b) spring, (c) summer and (d) fall.

Shift results in temperature and precipitation at different dyadic scale

The Pettitt test results are summarized in Fig. 4. The figure represents the Pettitt results for both temperature and precipitation for four seasons and four dyadic scales D0, D1, D2 and D3. Fig. 4 a, b, c and d represents spatial distribution of shift during winter, spring, summer and fall, respectively.

During winter, spring, summer and fall 106, 75, 48 and 82 CD, respectively showed positive shifts in original time series of temperature (D0). While 20, 9, 7 and 27 CD for precipitation showed increasing shift for winter, spring, summer and fall, respectively, for original time series. While, one CD for both summer and fall in Minnesota and Kansas showed decreasing shift in precipitation during original time series. All CD of the original time series of temperature showed increasing shift during winter. The number of CD showing increasing shift in both temperature and precipitation increased at higher dyadic scales. From Fig. 4 it is inferred that maximum decreasing shift in temperature is observed during winter while comparatively less number of CD showed increasing shift during summer. The minimum increasing shift in precipitation was observed during summer. During higher dyadic decomposition of fall precipitation significant CD were observed showing decreasing shift.

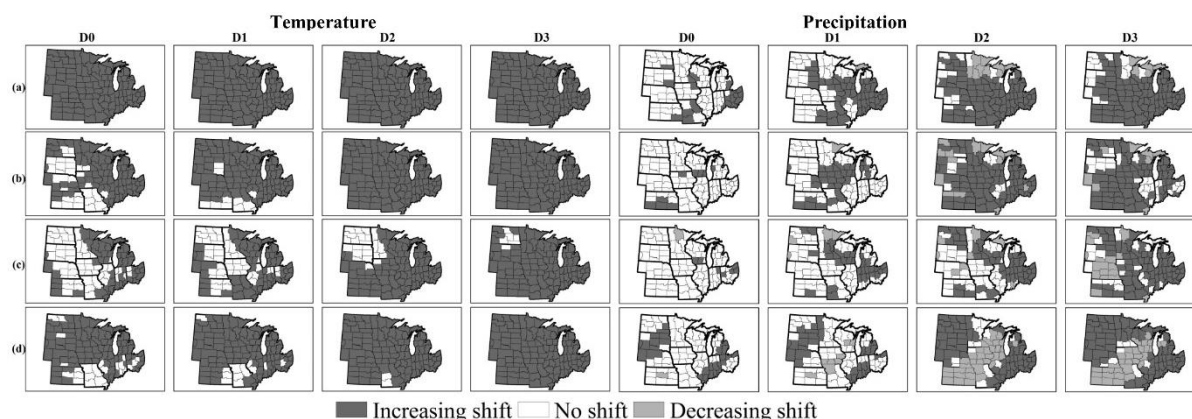


Figure 4: Spatial plot representing Pettitt's test results for all climate divisions of Midwestern US for both temperature and precipitation at 90% significance during (a) winter, (b) spring, (c) summer and (d) fall.

Trend and shifts in streamflow at four dyadic scales

Tab. 1 summarizes the results of both trend and shifts observed in Midwestern US. The numbers in the table are the number of streamflow stations exhibiting the trend and shifts at 90% significance. Similar to previous sections the trend and shift analysis for streamflow were also performed simultaneously with DWT resulting trends and shifts at four dyadic scales for all four seasons. From the table it is noted that, less number of stations showed increasing/decreasing trends (with and without considering short term persistence) and shift at original time scales. In contrast, higher number of streamflow stations showed both trends and shifts at higher dyadic decomposition.

Table: 1. Table showing number of streamflow stations showing MK1 and MK2 trend along with shift during winter, spring, summer and fall for four dyadic scales D0, D1, D2 and D3.

		D0(+/-)	D1(+/-)	D2(+/-)	D3(+/-)
Trend (MK1)	Winter	22/2	32/3	35/14	40/9
	Spring	13/9	30/9	37/14	43/16
	Summer	23/5	44/9	49/11	51/13
	Fall	22/5	31/6	35/20	34/17
Trend (MK2)	Winter	20/3	33/4	37/17	49/15
	Spring	13/9	28/9	40/14	56/19
	Summer	23/6	44/10	53/11	56/15
	Fall	21/6	31/9	36/25	41/23
Pettitt's test (shift)	Winter	24/4	34/11	49/23	57/14
	Spring	15/11	29/12	42/17	60/21
	Summer	24/10	51/11	55/14	60/19
	Fall	31/7	36/12	43/24	43/28

+ increasing trend and shift

- decreasing trend and shift

The variables used in the study vary spatially (Carrier et., 2016) hence, the spatial assessment of trends and shift helps in understanding this variation. The results of trend and step analysis confirm the findings of Kunkel et al., (2013) which suggest increase in temperature during

months of winter and spring. Again, significant number of CD showed rising temperature during fall and summer and the trend and shift analysis were more significant at higher wavelet decompositions. Evaluated trends and shifts in precipitation were consistent with Partal and Kucuk (2006) suggesting the trend in precipitation varies spatiotemporally and the trend and shifts at higher periodicity could be relied upon. Less number of CD showed short term persistence in original time series for both temperature and precipitation. The short term persistence was significant at higher dyadic scales as compared to original time series. Considering the short term persistence further tweaked the trend results to some extent and the difference in MK1 and MK2 results were comparatively more significant at higher dyadic scales. While, the MK1 and MK2 results were almost similar at lower dyadic scales.

In contrast to both temperature and precipitation significantly large number of streamflow stations showed both increasing and decreasing trends and shifts. Further, the number of streamflow station showing increasing or decreasing trend and shift increased with increase in periodicity. The results supports the findings of Nalley et al., (2012) suggesting the significance of timescales in detecting trends in streamflow. The study by Nalley et al., (2012) also inferred the detections of trends in the stations which never showed trend in original time series by incorporating DWT. The trend in streamflow can be attributed to observed trend in temperature and precipitation. In contrast to temperature and precipitation, streamflow data showed short term persistence and it further increased with the increase in periodicity. Thus, the results of MK1 and MK2 were distinct at higher dyadic scales.

Conclusion

The findings of the current study can be summarized as:

1. The trends and steps in temperature, precipitation and streamflow were detected.
2. The decomposition of original time series into time series of different periodicities helped in detecting underlying trends and shifts, which would have remained undetected otherwise.
3. The temperature in Midwest is increasing, especially in winter. This in turn is leading to change in precipitation spatially at different temporal scales. The increasing and decreasing trends and shifts in precipitation result in the increasing and decreasing trends and shift in streamflow.
4. The presence of short term persistence in the streamflow was further noted. It was observed that D3 component was dominant in detecting the trend and shift in temperature, precipitation and streamflow.
5. The increasing temperature trends were significant throughout the Midwest while, the trends in precipitation and streamflow were observed significantly in southeast and western region of Midwestern United States.

The different periodicities in the time series data evaluated in the study helped in detecting hidden trends and shifts. This could be helpful to the water managers and hydrologic forecasters. Future study can account for the attribution of observed trends and shifts.

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