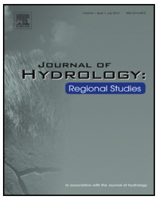
Journal of Hydrology: Regional Studies 4 (2015) 713–731

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

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



Long-term trends in climate and hydrology in an agricultural, headwater watershed of central Pennsylvania, USA[☆,☆☆]

Haiming Lu[a,*], Ray B. Bryant[b], Anthony R. Buda[b], Amy S. Collick[b], Gordon J. Folmar[b], Peter J.A. Kleinman[b]

[a] *Nanjing Hydraulic Research Institute, State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, 223 Guangzhou Road, Nanjing 210029, China*
[b] *USDA-ARS, Pasture Systems & Watershed Management Research Unit, Building 3702, Curtin Road, University Park, PA 16802, USA*

ARTICLE INFO

Article history:
Received 15 January 2015
Received in revised form 2 October 2015
Accepted 6 October 2015
Available online 1 December 2015

Keywords:
climate change
agriculture
water resources
long-term trends
precipitation
temperature
streamflow
watershed

ABSTRACT

Study region: The WE-38 Experimental Watershed, which is a small (7.3 km^2) basin in the Ridge and Valley physiographic region of east-central Pennsylvania.
Study focus: We used non-parametric Mann-Kendall tests to examine long-term (1968 to 2012) hydroclimatic (precipitation, temperature, streamflow) trends in WE-38 in the context of recent climate change across northeastern US.
New hydrological insights for the region: Annual mean temperatures in WE-38 increased 0.38 °C per decade, leading to an expansion of the growing season (+2.8 days per decade) and a contraction of frost days (-3.6 days per decade). Consistent with increased temperatures, annual actual evapotranspiration rose significantly (+37.1 mm per decade) over the study period. Precipitation also trended upward, with October experiencing the most significant increases in monthly total rainfall (+8.2 mm per decade). While augmented October precipitation led to increased October streamflow (+5.0 mm per decade), the trend in WE-38 streamflow was downward, with the most significant declines in July (-1.2 mm per decade) and February (-7.5 mm per decade). Declines in summertime streamflow also increased the duration of hydrological droughts (maximum consecutive days with streamflow < 10th percentile) by 1.9 days per decade. While our findings suggest some challenges for producers and water resource managers, most notably with increased fall rainfall and runoff, some changes such as enhanced growing seasons can be viewed positively, at least in the near term.

[☆] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

[☆☆] The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20,250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

[*] Corresponding author. Nanjing Hydraulic Research Institute, State Key Laboratory of Hydrology–Water Resources and Hydraulic Engineering, 225 Guangzhou Road, Nanjing 210029, China. Tel.:+ +86 25 85828519; fax: +86 25 85828555

E-mail address: hmlu@nhri.cn (H. Lu).

http://dx.doi.org/10.1016/j.ejrh.2015.10.004

1. Introduction

Climate change has emerged as a key issue facing agriculture and water resources in the twenty-first century (Porter et al., 2014; Jiménez Cisneros et al., 2014). According to the most recent report by the Intergovernmental Panel on Climate Change (IPCC), the mean surface temperature of the earth system (land and ocean) increased 0.85 °C from 1880 to 2012 (IPCC, 2013), leading to a worldwide prolonging of warm weather periods and a contraction of cold spells. The intimate link between surface air temperature and atmospheric water vapor has also intensified earth's hydrologic cycle (Huntington, 2009), resulting in increased precipitation amounts and intensities, particularly in the Northern Hemisphere (IPCC, 2013). Because shifts in climate are highly variable, there is widespread concern and uncertainty about the specific effects of climate and hydrologic change on agriculture and water resources, particularly at regional and local scales (Walsh et al., 2014; Hatfield et al., 2014).

In the humid northeastern USA, climate change concerns revolve around increases in annual and seasonal temperatures, changes in seasons, and greater variability in weather patterns that adversely impact agriculture. For instance, annual mean temperatures in the northeast have been increasing 0.09 °C per decade since 1900, yielding a total temperature increase of 1.11 °C (Kunkel et al., 2013). Remarkably, minimum temperatures have been warming faster than maximum temperatures, especially during the winter season (Burakowski et al., 2008; Brown et al., 2010). In response to warming temperatures, growing seasons have expanded in length across the northeast region at rates of up to 50 days per decade (Brown et al., 2010), while cold spells and frost days have largely truncated. In addition, there has been a general increasing trend in actual evapotranspiration nationally (Szilagyi et al., 2001; Walter et al., 2004), as well as across the northeast (Yang et al., 2014a).

Past climate change in the northeastern US has also altered precipitation patterns and watershed hydrology, especially with regard to extreme events (Walsh et al., 2014). On an annual basis, total precipitation has risen significantly since 1900 at rates approaching 9 mm per decade. Most notably, extreme precipitation events (defined as the heaviest 1% of all daily events) have increased faster in the northeastern US than anywhere in the nation (Groisman et al., 2013). Paradoxically, the increase in extreme rainfall has not led to a corresponding increase in the magnitude of river flooding (Hirsch and Ryberg, 2012; Peterson et al., 2013) because the majority of increased rainfall has occurred in fall when streamflows are lowest (Small et al., 2006). In general, streamflow has increased across the eastern US (Sagarika et al., 2014; Yang et al., 2014b) in response to increased precipitation totals. However, the expansion of rain-free episodes (Groisman and Knight, 2008) in recent decades has also increased the risk of low flow periods during summer and fall.

To date, much of the research on past climate change impacts on agriculture and water resources has focused on regional and national scale assessments (Horton et al., 2014; Walsh et al., 2014). While these assessments are clearly important, they tend to average the effects of changing conditions over large spatiotemporal scales and ignore specific impacts at local scales that have relevance for agricultural and water resources managers. Numerous studies of historical changes in climate and hydrology have been conducted across the northeastern USA, with particular emphases on forested regions in New England (Huntington, 2003; Hodgkins et al., 2003; Campbell et al., 2011; Hamburg et al., 2013) and in New York (Burns et al., Insaf et al., 2013; Matonse and Frie, 2013). Notably absent are studies from the central Appalachian region of Pennsylvania (Douglas et al., 2013) where agricultural production is regionally important. Characterizing the effects of recent climate warming on representative, upland agricultural watersheds in the central Appalachians is critical for improved management of local agriculture and water resources, as well as for downstream aquatic ecosystems and ultimately, the Chesapeake Bay (Najjar et al., 2010; Zhang et al., 2013).

In this paper, we present a holistic, long-term (1968 to 2012) analysis of climate and hydrologic trends (annual, seasonal, and monthly) in the WE-38 watershed, an intensively monitored upland basin in the Appalachian Mountain region of east-central Pennsylvania. The WE-38 watershed is one of 23 benchmark experimental watersheds maintained by the US Department of Agriculture's Agricultural Research Service (ARS) and is part of several major long-term research efforts, including the Conservation Effects Assessment Project (CEAP; Bryant et al., 2011) and the Long-Term Agroecosystem Research (LTAR) Network (Walbridge and Shafer, 2011; Bryant et al., 2012). Long-term records of precipitation and streamflow in WE-38 stretch back to 1968, shortly after the watershed was formally established by USDA-ARS in 1966, with detailed temperature records in the watershed extending to 1978. The length (35 to 45 years) and quality (Bryant et al., 2011) of these records make WE-38 an ideal place to evaluate long-term climatic and hydrologic trends in the context of recent changes in regional and global climate.

2. Materials and methods

2.1. Study watershed

The WE-38 watershed is a 7.3 km^2 subcatchment of Mahantango Creek (420 km^2) located in the Ridge and Valley physiographic region of east-central Pennsylvania (Fig. 1). The climate of WE-38 is temperate and humid, with a mean annual temperature of 10.1 °C, annual precipitation averaging 1080 mm, and streamflow representing about 46% of total precipitation (Bryant et al., 2011). Land use and geology in WE-38 ranges from mature forest cover on sandstone ridges (350-510 m elevation) to mixed cropland and pasture in valleys (125-300 m elevation) underlain by shale and siltstone. Uplands (ridges, hillsides) feature residual soils derived from sandstones and shales that are well-drained and possess high infiltration capacities. In contrast, soils in lower landscape positions and valley bottoms are typically derived from colluvial

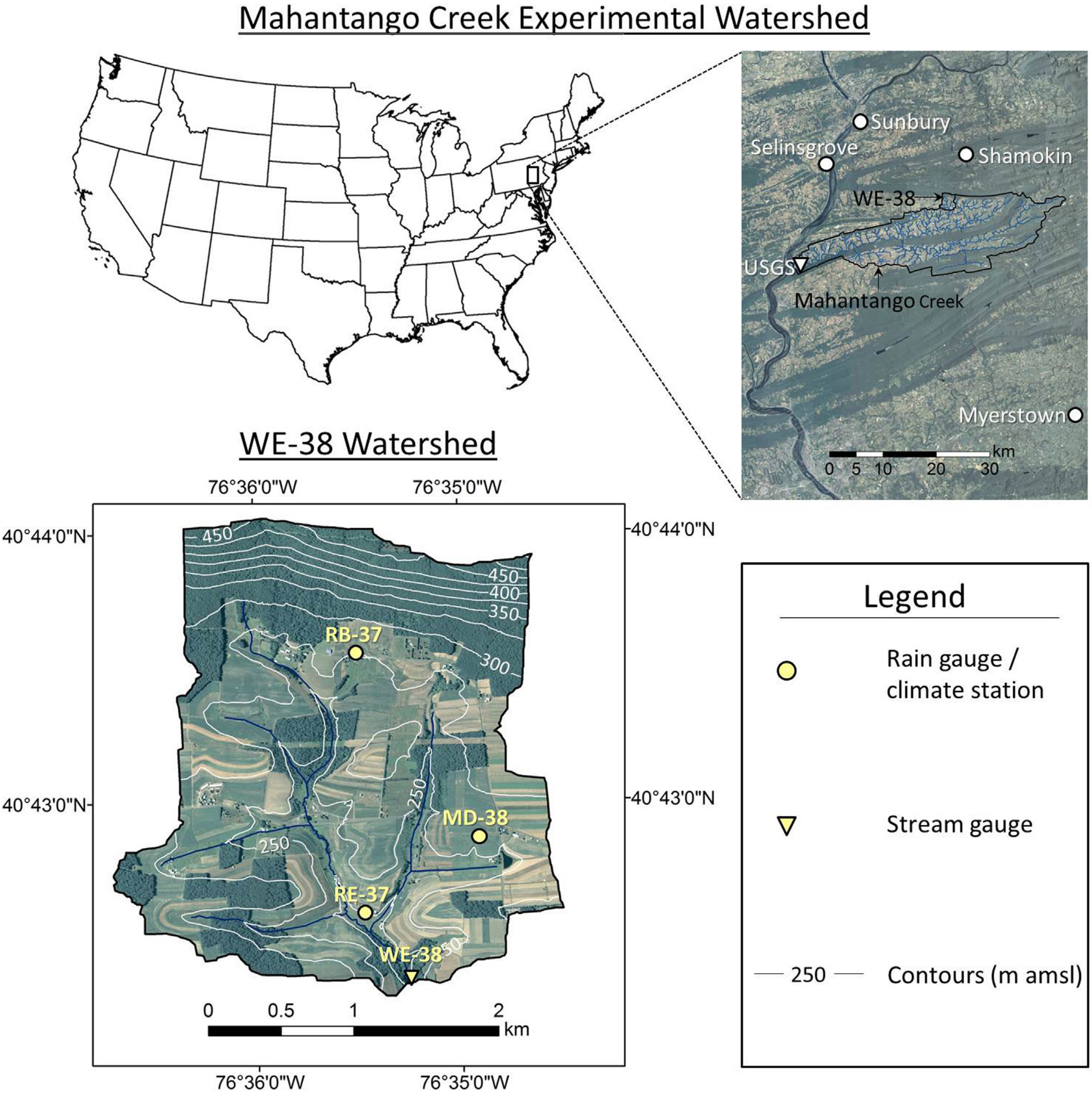


Fig. 1. Maps showing the location of the WE-38 watershed, as well as the monitoring sites used in the analysis of long-term trends.

deposits and are characterized by poor drainage, perched water tables, and frequent runoff generation by saturation excess (Buda et al., 2009; Gburek et al., 2006).

2.2. Precipitation data

We assembled long-term (1968 to 2012) rainfall records using continuous (5-min) data from two permanent rain gauges in WE-38 (Fig. 1). The rain gauges encompass the range in elevations of the agricultural component of WE-38, with the northern gauge (RB-37) located at 279.1 m above mean sea level (amsl) in cropland and the southern gauge (RE-37) at 222.2 m amsl in pasture. Both gauges are situated in large open areas and have seen little change in management over the period of measurement. From 1968 until 1996, accumulated rainfall was measured at each gauging location using Fischer and Porter digital punch paper weighing rain gauges (Buda et al., 2011a). After 1996, the Fischer and Porter systems were replaced with Interface (Model SSB-AJ-100) load cells that were connected to Campbell CR10X dataloggers. The transition from Fischer and Porter to load cell systems increased the precision of rainfall measurement by one order of magnitude (2.5 mm to 0.254 mm).

2.3. *Temperature data*

We acquired long-term (1978 to 2012) air temperature data from a climate station in the east-central portion of WE-38 (Fig. 1). The climate station (MD-38) is located at an elevation of 254.4 m amsl and is set within a cropped field that is typically rotated between corn and soybeans. Daily data on maximum and minimum air temperatures (°C) were available from 1978 through 1996, while continuous (5-min) air temperature data were obtainable from 1996 forward. Briefly, maximum and minimum air temperature measurements were made once per day using a combination of separate liquid-in-glass maximum (mercury) and minimum (alcohol) thermometers and a Belfort (Model #5-594) hygrothermograph, all of which were housed within a standard National Weather Service shelter (McGuiness et al., 1979; National Weather Service, 1989). On working days, technicians visited the site each morning between 0800 and 0900 hrs and recorded maximum and minimum air temperatures to the nearest 0.5 °C. On non-working days (weekends and holidays), technicians determined maximum and minimum air temperature to the nearest 0.5 °C by reading the continuous air temperature trace provided by the hygrothermograph. In 1996, the air temperature measurement system was automated by connecting a Vaisala (Model #HMP35C) air temperature and relative humidity sensor to a Campbell CR10X datalogger. Air temperature was measured every 5 min to the nearest 0.4 °C, with maximum and minimum daily temperatures determined from the 5-min data. The temperature and relative humidity sensors were calibrated annually to maintain accuracy and precision.

2.4. *Streamflow data*

We compiled continuous (5-min) streamflow data from a gauging station located at the outlet of WE-38 (Fig. 1). The gauging station features a concrete, 1.22 m high, 5:1 broad-crested V notch weir (measuring high flows ranging from 0.155 m^3 s^{-1} to 15 m^3 s^{-1}) in tandem with a metal, 0.46 m, 90° sharp-crested V notch weir (measuring low flows < 0.155 m^3 s^{-1}) (Buda et al., 2011b). Streamflow in the broad-crested and 90° V notch weirs is determined using standard rating curve equations. From 1968 until 1997, gauge height was measured in separate stilling wells (one for each weir) using a Fischer and Porter float-and-pulley water level recorder system. From 1997 onward, gauge height was monitored via float-and-shaft recorder systems connected to a Campbell Scientific CR10X datalogger. Both systems measured gauge height to the nearest 3 mm. Rating curves, gauge height measurements, and weir integrity are regularly maintained and updated as needed.

2.5. *Missing data*

We used standard data augmentation techniques to infill occasional data gaps that resulted from site damage, equipment failure, routine maintenance, or extreme events (Buda et al., 2011a,b). We applied simple station averaging methods (McCuen, 1998; Dingman, 2002) to replace missing daily precipitation values at RB-37 and RE-37. To predict missing daily streamflow values at WE-38, we developed a series of regression equations relating daily streamflow at the WE-38 weir to daily streamflow measured by the US Geological Survey at the outlet of Mahantango Creek (USGS Gauge #01555500) (Fig. 1). Predictive equations were established for four different flow intervals at WE-38 (low: 0-14 m^3 s^{-1}, medium: 14-28 m^3 s^{-1}, high: 28-57 m^3 s^{-1}, very high: >57 m^3 s^{-1}) using 45 yrs of concurrent daily streamflow at both sites (e.g., Hirsch, 1979). Missing 5-min rainfall and temperature records at single sites were replaced by linear interpolation for data gaps less than 5 hrs (gaps greater than 5 hrs were not filled). Data from Engman et al. (1974) were used to infer total rainfall and peak streamflow resulting from the remnants of Tropical Storm Agnes (June 21-23, 1972), one of the largest events in the data record.

2.6. *Regional data sets*

We examined climatic and hydrologic records from other measurement stations in the area in order to place the results from WE-38 in context with longer-term regional trends (i.e., those that extend prior to the beginning of our monitoring program in 1968). We acquired long-term air temperature and precipitation (rainfall, snowfall, snow depth) data from four nearby climate stations in central Pennsylvania (Fig. 1): Selinsgrove 2S (25 km NW of WE-38; 1975 to 2012), Sunbury (24 km NW of WE-38; 1926 to 1975, 1998 to 2012), Shamokin (10 km NE of WE-38; 1944 to 1994) and Myerstown (45 km SE of WE-38; 1941 to 2012). All four stations are part of the Global Historical Climatology Network (GHCN)-Daily, which is an integrated database of daily climate summaries from land observation stations across the world. These data sets were downloaded from NOAA's National Climatic Data Center website (http://www.ncdc.noaa.gov/). We also assembled 84 yrs (1929 to 2012) of daily mean streamflow data from the USGS gauging station (USGS Gauge #01555500; http://waterdata.usgs.gov/nwis) on Mahantango Creek (Fig. 1), which defines a 420 km^2 watershed that includes WE-38.

Table 1
Metrics used to summarize long-term trends in climate and hydrology in the WE-38 watershed

Category	Name of metric	Definition	Units	Reference(s)
Temperature	Mean temperature	Daily mean temp averaged over specified time intervals (monthly, seasonal, annual)	°C	
	Minimum temperature (T_{min})	Daily min temp averaged over specified time intervals (monthly, seasonal, annual)	°C	
	Maximum temperature (T_{max})	Daily max temp averaged over specified time intervals (monthly, seasonal, annual)	°C	
	Diurnal temperature range	Difference between daily T_{max} and T_{min} averaged over specified time intervals (monthly, seasonal, annual)	°C	Karl et al. (1993)
	Growing degree days	Annual accumulation of daily mean temp $[(T_{max} + T_{min})/2]$ deviations greater than 10 °C	GDD	McMaster and Wilhelm (1997)
	Warm season	Period of time when daily mean temp consistently >0 °C	d	Schwartz et al. (2006)
	Growing season	Period of time before and after July 1 each year with daily mean temp consistently >5 °C	d	
	Summer season	Period of time when daily mean temp consistently >13 °C	d	Schwartz et al. (2006)
	Cold season	Period of time when daily mean temp consistently <-5 °C	d	Schwartz et al. (2006)
	Last freezing date	Last -2.2 °C freeze date in spring	JD[a]	Schwartz et al. (2006)
	First freezing date	First -2.2 °C freeze date in autumn	JD	Schwartz et al. (2006)
	Summer days	Annual count of days when daily max temp > 25 °C	d	Zhang et al. (2011)
	Tropical nights	Annual count of days when daily min temp > 20 °C	d	Zhang et al. (2011)
	Frost days	Annual count of days when daily min temp < 0 °C	d	Zhang et al. (2011)
	Icing days	Annual count of days when daily max temp < 0 °C	d	Zhang et al. (2011)
Precipitation	Total precipitation	Precip summed over specified time intervals (daily, monthly, seasonal, annual)	mm	
	Max daily precipitation	Max daily precip value within a specified time interval (monthly, seasonal, annual)	mm d^{-1}	
	Max daily 1-hr precipitation	Max 1-hr precip value (using a 1-hr moving window over 5-min data) within a specified time interval (monthly, seasonal, annual)	mm hr^{-1}	
	Trace precipitation	Days with precip < 2.5 mm d^{-1}	d	Groisman et al. (2012)
	Light precipitation	Days with precip within a 2.5 to 12.7 mm d^{-1} range	d	Groisman et al. (2012)
	Moderately heavy precipitation	Days with precip within a 12.7 to 25.4 mm d^{-1} range	d	Groisman et al. (2012)
	Heavy precipitation	Days with precip within a 25.4 to 76.2 mm d^{-1} range	d	Groisman et al. (2012)
	Very heavy precipitation	Days with precip > 76.2 mm d^{-1}	d	Groisman et al. (2012)
Stream flow	Streamflow depth	Daily discharge volume divided by watershed area summed over specified time intervals (monthly, seasonal, annual)	mm	
	Low streamflow	Max number of consecutive days in each year during which mean daily streamflow is lower than the tenth percentile	d	Campbell et al. (2011)

[a] Julian date

2.7. Indices of climate and hydrologic change

We calculated a number of different indices using precipitation, temperature, and streamflow data in order to describe how the climate and hydrology of WE-38 changed during the 45-yr study period (see Table 1 for a list of indices, definitions, and references). The indices used in this study fell into roughly three main categories: (1) measures of extreme values (maxima and minima) and central tendency (means), which describe, for example, the maximum or minimum daily temperature, or the annual mean precipitation; (2) threshold indices, which tally the number of days or identify the specific date when a fixed temperature or precipitation threshold is exceeded, for instance, growing season or last freezing date; and (3) percentile-based threshold indices, which describe the exceedance rates (e.g., number of days) above or below a certain threshold such as low streamflow (e.g., consecutive days with streamflow less than the 10th percentile of the distribution), which is useful for characterizing drought periods.

In addition to the indices described above, we also sought to assess long-term changes in potential and actual evapotranspiration in the WE-38 watershed. We calculated potential evapotranspiration using a modified version of the Priestly-Taylor method (Priestly and Taylor, 1972) that requires maximum and minimum daily temperature, latitude, and day-of-year as inputs. The modified potential evapotranspiration routines are based on research by Walter et al. (2005) and Archibald and Walter (2014) and are included in the EcoHydRology R package developed by Fuka et al. (2013). A key advantage of using the Priestly-Taylor method to estimate potential evapotranspiration is that it is less sensitive to temperature changes than other methods, which is important as temperature is not the main driver of potential evapotranspiration (Shaw and Riha, 2011). Actual evapotranspiration was inferred by the water balance equation, which is solved by subtracting annual mean runoff from annual mean precipitation. The key assumption in applying this method is that no considerable changes in watershed storage occurred during the year and that all groundwater discharge is captured in watershed runoff (Huntington and Billmire, 2014). All water balance calculations were done on a calendar year basis to be consistent with the assessment of trends in precipitation and temperature. We compared water balance trends by calendar year against those derived from a traditional water-year (October 1 to September 30) and found that the trends were highly consistent.

Finally, we relied on existing, published methods to ascertain recurrence intervals of notable rainfall and streamflow events in the WE-38 watershed during the period of record. For rainfall recurrence intervals in WE-38 (centroid = 40.73°, -76.59°), we used specific precipitation frequency estimates for Pennsylvania provided by NOAA's Atlas 14 Volume 2 (Bonnin et al., 2006). To determine the recurrence interval of annual peak streamflows in WE-38, we used design equations developed for Pennsylvania by Flippo (1977), which are part of a national program providing predictive equations for flood frequencies in ungauged streams throughout the US (Ries III, 2007). The equations developed by Flippo (1977) predict streamflow rates corresponding with recurrence intervals of 2.33-, 10-, 25-, 50-, and 100-yr storms, which were then used to quantify the number of flow events in each year that met these criteria. For years with significant periods of missing 5-min streamflow data (e.g., 1982, 1992, 2002), we used daily mean streamflows predicted by the regression relationship between Mahantango Creek and WE-38 as a conservative estimate of high flows resulting from storms in WE-38.

2.8. Data organization and statistical analysis

Prior to conducting formal statistical analyses of long-term trends, we organized all climate and hydrologic data, as well as the indices derived from these data, into three temporal scales: monthly, seasonal (winter, spring, summer, fall, growing, non-growing), and annual. The four seasons were defined as follows: winter = December, January, and February; spring = March, April, and May; summer = June, July, and August; fall = September, October, and November. In addition, we also assessed climate and hydrologic trends over fixed-length growing and non-growing seasons based on average conditions in the region. These terms should not be confused with our evaluation of trends in growing season length (Table 1), which was allowed to fluctuate based on the period of time when temperatures were consistently above 5 °C. In this case, the average growing season in east-central Pennsylvania was operationally defined as the period beginning with the average date of the last freeze in spring (April 15) and ending with the average date of the first freeze in fall (October 15). Non-growing season was defined as the remaining six month period from October 16 to April 14.

We evaluated monthly, seasonal, and annual trends in climate and hydrology using the rank-based, non-parametric Mann-Kendall test (Hirsch et al., 1982; Helsel and Hirsch, 2002). The Mann-Kendall test is commonly used by hydrologists in long-term trend assessments because it does not assume a normal distribution, is insensitive to outliers, and reliably detects monotonic linear and non-linear time series trends. Notably, the Mann Kendall test does assume that there is no significant serial correlation in any of the time series, which we confirmed using Durbin-Watson tests (Durbin and Watson, 1950, 1951). The rate of change for each time series was determined using the Theil-Sen slope method (Theil, 1950; Sen 1968), which calculates the median slope of all possible pairs of points in the data set. For graphical presentation, we plotted robust locally weighted scatterplot smooth (LOWESS) regression lines (Cleveland, 1979), as well as an 11-yr moving average (e.g., Matonse and Frei, 2013). Mann-Kendall tests and Theil-Sen slope calculations were completed using the wq package (Jassby and Cloern, 2010) within the R software environment (version 3.1.1, R Development Core Team, 2013), while Origin software (OriginLab, Northampton, MA) was used to plot the LOWESS regression lines and the moving average trends. All trends shown in the tables of results are expressed as the rate of change per decade, except in Table 5. All trends were considered statistically significant at $\alpha = 0.10$.

3. Results and discussion

3.1. Temperature

Temperature patterns in the WE-38 watershed were generally consistent with those observed in the northeastern US, as well as nationally. The year 2012 was the warmest year on record (annual mean temperature = 11.7 °C) in WE-38 as well as for the US as a whole (Walsh et al., 2014). Notably, six of the warmest years on record in WE-38 have occurred since 2001, which is supported by evidence from regional and national assessments of past climate change (Walsh et al., 2014). In contrast, six of the ten coolest years on record in WE-38 occurred prior to 1990, with 1978 being the coldest (annual mean temperature = 8.7 °C).

Table 2
Trends in temperature at various temporal scales in the WE-38 watershed (1978 to 2012). Slopes are expressed as a rate of change per decade. Slopes in bold and italics show trends with statistical significance at p < 0.1

Period		Mean temp.		Min temp.		Max temp.		DTR	
		slope °C	p-value	slope °C	p-value	slope °C	p-value	slope °C	p-value
Spring	Mar	***0.52***[*]	***0.10***	***0.42***	***0.07***	***0.63***	***0.08***	***0.32***	***0.05***
	Apr	***0.60***	***0.01***	***0.41***	***0.03***	***0.77***	***0.00***	***0.31***	***0.07***
	May	0.26	0.21	0.29	0.11	0.16	0.36	-0.31	0.11
Summer	Jun	***0.51***	***0.00***	***0.77***	***0.00***	0.17	0.23	***-0.56***	***0.01***
	Jul	0.25	0.15	***0.46***	***0.02***	0.18	0.27	-0.11	0.23
	Aug	0.16	0.23	***0.32***	***0.06***	0.10	0.29	***-0.35***	***0.08***
Fall	Sep	***0.41***	***0.02***	***0.40***	***0.03***	***0.29***	***0.08***	-0.10	0.30
	Oct	***0.29***	***0.09***	0.39	0.11	0.21	0.19	-0.02	0.45
	Nov	0.25	0.17	0.31	0.15	0.18	0.29	0.05	0.43
Winter	Dec	0.14	0.39	0.37	0.23	0.09	0.44	-0.18	0.17
	Jan	***0.75***	***0.06***	***0.79***	***0.08***	***0.73***	***0.08***	-0.03	0.46
	Feb	0.51	0.16	0.46	0.19	0.54	0.14	-0.14	0.24
Spring		***0.47***	***0.02***	***0.33***	***0.04***	***0.52***	***0.03***	0.13	0.15
Summer		***0.29***	***0.02***	***0.45***	***0.00***	0.17	0.23	***-0.37***	***0.04***
Fall		***0.32***	***0.01***	***0.39***	***0.01***	***0.24***	***0.08***	-0.10	0.23
Winter		0.32	0.12	***0.36***	***0.09***	0.26	0.18	-0.01	0.42
Average growing season		***0.38***	***0.00***	***0.43***	***0.00***	***0.25***	***0.04***	-0.20	0.15
Average non-growing season		***0.38***	***0.03***	***0.40***	***0.02***	***0.35***	***0.06***	0.00	0.49
Annual		***0.38***	***0.00***	***0.43***	***0.00***	***0.35***	***0.01***	-0.09	0.16

[*] Here and elsewhere in the table, bolded font was intended to identify statistically significant trends. I do not see bold font used in the formatting of Table 2. Perhaps we should use italics instead?

Table 3
Trends in the duration of temperature threshold indices in the WE-38 watershed (1978 to 2012). Slopes are expressed as a rate of change per decade. Slopes in bold and italics show trends with statistical significance at p < 0.1.

Period	slope days	p-value
Summer season (Mean DT > 13°C)	***4.00***	***0.00***
Growing season (Mean DT > 5°C)	***2.83***	***0.01***
Warm season (Mean DT > 0°C)	***2.82***	***0.00***
Cold season (Mean DT < −5°C)	***-0.74***	***0.09***
Last freezing date (Julian date)	***-5.50***	***0.00***
First freezing date (Julian date)	***4.00***	***0.02***
Number of summer days (max DT >25°C)	***4.17***	***0.02***
Number of tropical nights (min DT >20°C)	***0.83***	***0.10***
Number of frost days (min DT < 0°C)	***-3.64***	***0.01***
Number of icing days (max DT <0°C)	-1.67	0.16

3.1.1. Significant trends

Mean temperatures in the WE-38 watershed exhibited significant increasing trends at annual, seasonal, and monthly time scales from 1978 to 2012. Annual mean temperatures in WE-38 showed a smooth, steadily increasing trend (0.38 °C per decade) during the 35-yr temperature monitoring period (Fig. 2a). This increasing trend is generally consistent with the recent National Climate Assessment (Kunkel et al., 2013; Horton et al., 2014), which showed that annual mean temperatures across the US northeast increased 0.09 °C per decade from 1895 to 2011. Elsewhere, Burns et al. (2007) reported a significant increase of 0.6 °C per 50 years for regional annual mean temperature (0.12 °C per decade) in the Catskill Mountain region of New York. Average 100-year temperature change from 73 climate stations in New England and New York ranged from 0.86 to 1.83 °C (0.09 to 0.18 °C per decade) over the twentieth-century (Trombulak and Wolfson, 2004). Monthly mean temperatures in WE-38 increased in six of 12 months at rates ranging from 0.29 °C per decade in October to 0.75 °C per decade in January (Table 2). Increases in seasonal mean temperatures were evident for the spring, summer and fall seasons, with the greatest rate of increase (0.47 °C per decade) occurring in spring. Seasonal mean temperatures increased at similar rates in the growing season (mid-April to mid-October) and in the non-growing season (Table 2).

Mean minimum temperatures also increased throughout the WE-38 watershed from 1978 to 2012. On an annual basis, mean minimum temperatures showed a smooth, upward trend (0.43 °C per decade) during the study period (Fig. 2b), increasing at a rate faster than that of annual mean temperatures (0.38 °C per decade). Monthly mean minimum temperatures increased in seven of 12 months at rates ranging from 0.32 °C per decade in August to 0.79 °C per decade in January. Increases in mean minimum temperatures were evident for all three-month seasons, both the growing season and the non-growing season, and annually. Burakowski et al. (2008) found that regional winter (December to March) mean and

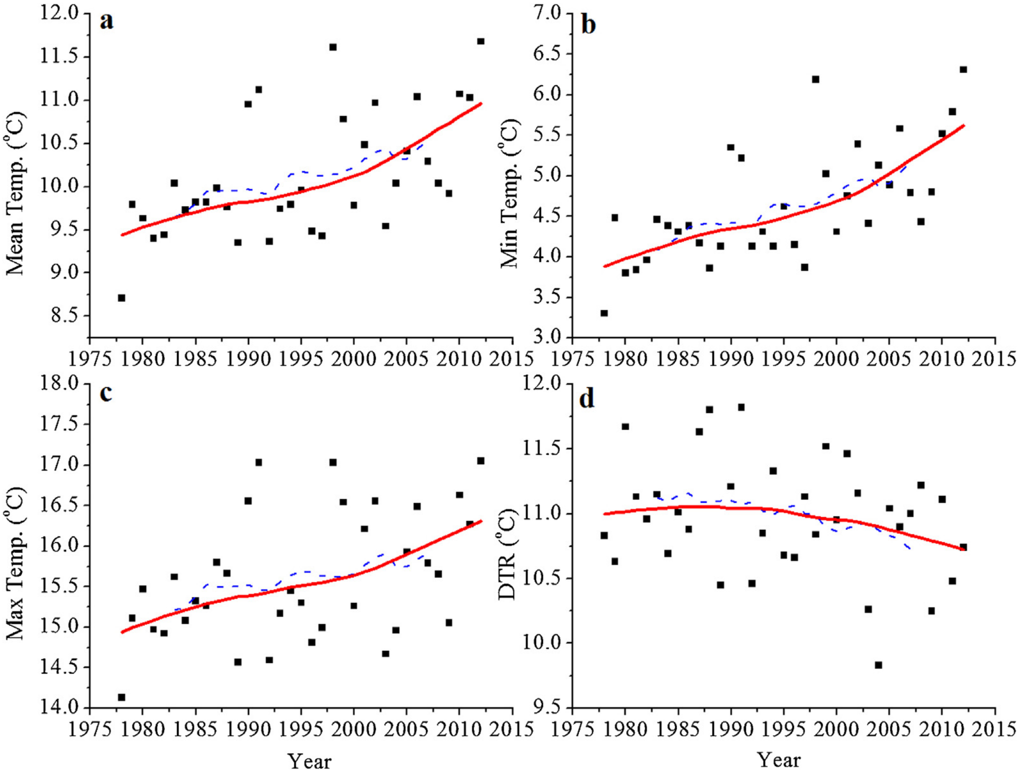


Fig. 2. Long-term trends for the WE-38 watershed (1978 to 2012) in (a) annual mean temperature; (b) annual mean minimum temperature; (c) annual mean maximum temperature; and (d) diurnal temperature range (DTR). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

minimum temperatures in the Northeast US (PA to ME) increased at rates of 0.43 and 0.42 °C per decade respectively from 1965 to 2005 with the strongest increases occurring in January and February. In comparison, winter (December to March) mean minimum temperatures in the WE-38 watershed increased at a rate of 0.36 °C per decade from 1978 to 2012 with the strongest increase occurring in January.

Mean maximum temperatures in WE-38 increased along with mean and mean minimum temperatures, albeit at generally slower rates for the time scales of investigation. Annual mean maximum temperature rose steadily during the study period (Fig. 2c), increasing at a rate of 0.35 °C per decade. Significant increases in monthly mean maximum temperatures occurred in the months of January, March, April, and September and during the spring and fall seasons. All of these months and seasons also had significant increases in mean minimum temperatures as previously discussed. However, there were no increases in mean maximum temperatures in June, July, August or the summer season, all of which did show increases in mean minimum temperatures. Asymmetrical trends in mean minimum and maximum air temperatures have been reported across various regions (Alexander et al., 2006; Burns et al., 2007; Burakowski et al., 2008; Donat et al., 2013; IPCC, 2013; Vose et al., 2005). When investigating the global trends in mean minimum and maximum temperatures, Vose et al. (2005) reported that mean minimum temperatures increased more rapidly than mean maximum temperatures (0.204 vs. 0.141 °C per decade) from 1954 to 2004.

Disproportionate changes in maximum and minimum temperatures, as described above, resulted in a general declining trend in diurnal temperature range over most time scales in the WE-38 watershed (Table 2). Diurnal temperature range decreased significantly in June and August as a result of increases in mean minimum temperatures in the absence of increases in mean maximum temperatures. There was also a significant decrease in diurnal air temperature range during the summer season and the growing season at rates of -0.37 and -0.20 °C per decade. Notably, diurnal temperature range increased in March and April as a result of greater increases in mean maximum temperatures relative to mean minimum temperatures. Vose et al. (2005) also observed a small but significant decrease in global diurnal air temperature ranges (-0.16 °C per decade) for the period 1950 to 2004, attributing it to the fact that mean minimum temperatures increased more rapidly than mean maximum temperatures. Here in the northeastern US, the observed decline in diurnal temperature range (Brown et al., 2010; Insaf et al., 2013; Qu et al., 2014) has largely been ascribed to increasing cloud cover (Lauritsen and Rogers, 2012), which can reduce diurnal temperature range by up to 50% compared with clear sky days (Dai et al., 1999). According to Lauritsen and Rogers (2012), cloud cover in in the northeastern US explains about 63% of the variability in diurnal temperature range.

Observed trends in temperature from the current study in WE-38 are in agreement with other published studies in the northeastern US (Horton et al., 2014), but the magnitude of changes observed in this study differed. The site location, period

Table 4
Trends in precipitation at various temporal scales in the WE-38 watershed (1968 to 2012). Slopes are expressed as a rate of change per decade. Slopes in bold and italics show trends with statistical significance at $p < 0.1$.

Period		Mean precip.	Total precip.		PM1d		PM1h	
		mm	slope mm	p-value	slope mm d^{-1}	p-value	slope mm hr^{-1}	p-value
Spring	Mar	83.13	2.30	0.27	-0.01	0.44	-0.08	0.30
	Apr	87.85	3.99	0.20	0.87	0.32	0.00	0.47
	May	104.46	1.48	0.33	-0.34	0.33	0.87	0.18
Summer	Jun	122.64	-9.49	0.23	-0.79	0.33	-0.34	0.37
	Jul	97.94	1.46	0.36	0.55	0.35	0.69	0.23
	Aug	98.08	5.52	0.22	-0.30	0.41	-0.70	0.17
Fall	Sep	118.83	6.35	0.19	***3.99***	***0.04***	0.83	0.19
	Oct	90.48	***8.18***[*]	***0.05***	1.35	0.19	0.00	0.38
	Nov	86.45	-4.23	0.11	-0.14	0.44	0.29	0.23
Winter	Dec	78.49	2.61	0.28	0.32	0.41	***0.61***	***0.04***
	Jan	70.91	***6.71***	***0.08***	***2.23***	***0.04***	***5.27***	***0.07***
	Feb	58.07	-0.61	0.42	-0.29	0.37	-0.06	0.26
Spring		275.45	4.31	0.31	0.21	0.36	***1.23***	***0.07***
Summer		317.68	-0.32	0.48	0.00	0.47	-0.39	0.38
Fall		297.64	7.49	0.21	***5.30***	***0.01***	***1.35***	***0.09***
Winter		208.50	4.22	0.31	0.15	0.11	***0.62***	***0.01***
Average growing season		629.11	5.20	0.40	0.70	0.37	0.00	0.48
Average non-growing season		470.51	2.52	0.42	***2.24***	***0.07***	***0.79***	***0.03***
Annual		1097.79	21.89	0.14	1.99	0.11	1.03	0.21

[*] Here and elsewhere in the table, bolded font was intended to identify statistically significant trends. I do not see bold font used in the formatting of Table 4. Perhaps we should use italics instead?

of observation, and study area provide some insight into potential causes of these differences. Our research site is located in east-central Pennsylvania, which is about two degrees of latitude less than the locations of regional studies conducted in New York and New England (Burakowski et al., 2008; Burns et al., 2007; Brown et al., 2010; Insaf et al., 2013). The recency of temperature data in our study, from 1978 to 2012, may cover a period during which the rates of temperature change are increasing compared to older studies or compared to studies that average over longer scales of space and time (e.g., Kunkel et al., 2013 for the entire US northeast). Other regional studies in the northeastern US (e.g., Burakowski et al., 2008; Burns et al., 2007) also covered much larger areas than WE-38. The reported magnitudes for different indicators of temperature change are averages across multiple locations, which could hide high values in some individual observation stations.

3.1.2. Seasonal changes and core indices

Indices of warm weather all increased in duration during the 1978 to 2012 study period in WE-38 in accordance with previous studies across the northeastern US (Brown et al., 2010; Insaf et al., 2013). The lengths of warm season, growing season and summer season, as defined by consecutive mean daily temperatures higher than 0, 5, and 13 °C, increased by 2.82, 2.83 and 4.00 days per decade respectively over the 1978 to 2012 period (Table 3), but the changes were not uniform over time. On average the summer season extended from early June to mid-September, but start and end dates varied by one month. The length of the summer season, defined as the period of time during which mean daily temperature remains above 13 °C, increased continuously, but at a slightly accelerated rate after 1995 (Fig. 3a). In addition, summer days (annual count of days with daily maximum temperatures above 25 °C) increased 4.17 days per decade and tropical nights (annual count of days with daily minimum temperatures above 20 °C) increased 0.83 days per decade, reflecting increasing trends in mean and mean minimum temperatures described previously. The growing season (the number of consecutive days with mean daily temperature above 5 °C) generally extended from mid-April to mid-October, but dates ranged by three weeks. The length of the growing season increased rapidly between 1990 and 2002, but changes prior to and after this period were minor (Fig. 3b). On average the late March to mid-November warm season (consecutive days with mean daily temperature above 0 °C) showed a flat or slightly decreasing trend prior to 1990, then increased steadily (Fig. 3c). During the 1978 to 2012 period, the warm season began as early as late February and ended as late as mid-November. Growing degree days, an agroclimatic indicator related to the growth of crops, also increased significantly from 1978 to 2012 (+62.24 growing degree days per decade; Fig. 4), which is consistent with findings by Huntington and Billmire (2014) showing generally rising trends in growing degree days (+24.4 to +53.5 growing degree days per decade) in the Gulf of Maine region.

In contrast, the duration of cold weather periods in WE-38 trended shorter from 1978 to 2012, which also agreed with recent regional assessments (Brown et al., 2010; Insaf et al., 2013). The average length of the cold season, defined as consecutive mean daily temperatures less than -5 °C, is 7 days and typically occurs in mid-January. However, the season may start as early as mid-December and may end as late as late February, and there were three years in which the season lasted longer than two weeks. The length of the cold season decreased at a fairly uniform rate (Fig. 3d) of -0.74 days per decade (Table 3),

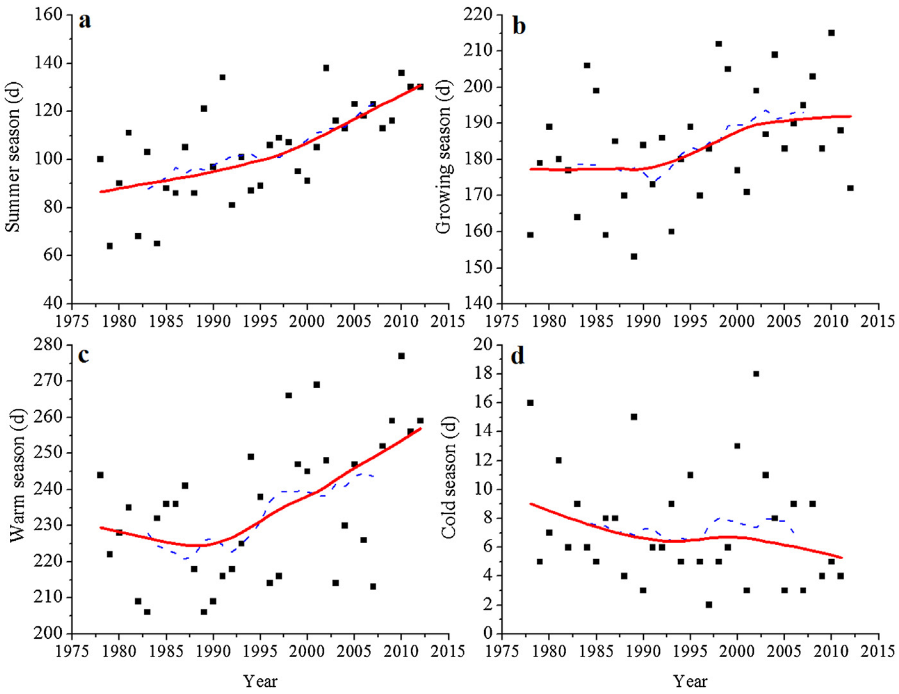


Fig. 3. Long-term trends in temperature threshold indices in the WE-38 watershed (1978 to 2012) for (a) summer season; (b) growing season; (c) warm season; and (d) cold season. Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

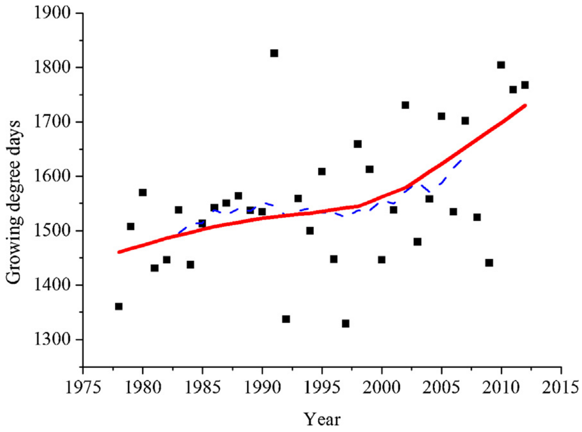


Fig. 4. Long-term trends in growing degree days (1978 to 2012) in the WE-38 watershed. Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

and the number of frost days also decreased at a rate of -3.64 days per decade. The last freezing date in spring retreated at an average rate of -5.50 days per decade (Table 3) and at a uniform rate over the period 1978 to 2012 (Fig. 5a). Over the same period, the first freezing date in fall occurred later at an average rate of 4.00 days per decade (Table 3), and the rate of increase was greater after 1995 (Fig. 5b). Collectively, the expansion of the frost-free season in WE-38 is consistent with recent research in the Catskill Mountain region of New York showing the last freezing date in spring occurring earlier by 2.6 to 4.3 days per decade and first freezing date in fall occurring later by 2.7 to 3.2 days per decade (Anandhi et al., 2013).

Despite the aforementioned trends toward an expansion of the growing season and a reduction in cold spells, the risk of frost has oddly increased over the past several decades in the northeastern US (Horton et al., 2014). Indeed, a lengthening growing season and frost-free season favor increased plant growth (Cooter and Leduc, 1995; Easterling, 2002; Frich et al., 2002; Huntington et al., 2009), a potential benefit to agriculture. However, the occurrence of extended warm periods in late winter and early spring cause plants to bloom early, rendering them susceptible to late season damaging frost events, as occurred in the eastern US in 2007 (Gu et al., 2008) and again in 2012 (Ault et al., 2013). The 2012 event, termed the "false spring of 2012", was notable because it was the earliest in the North American record and caused billions of dollars in crop damage (Ault et al., 2013). In light of these recent extreme events, recent work by Peterson and Abatzoglou (2014) shows

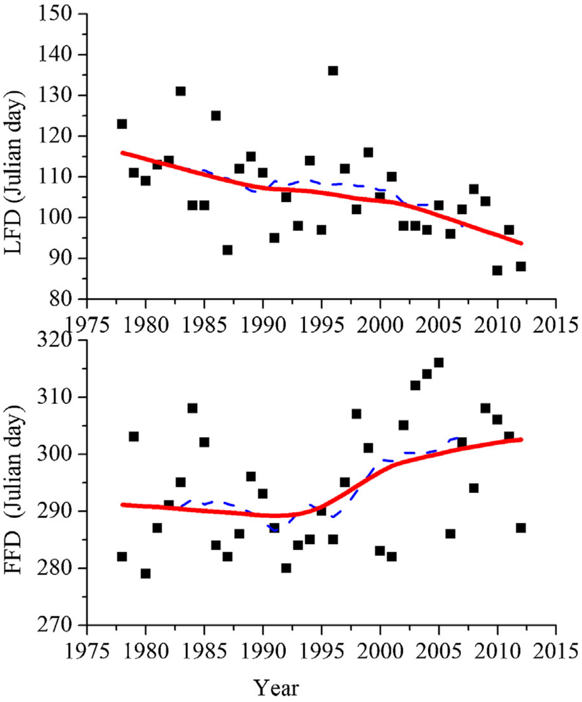


Fig.5. Long-term trends in the Julian day for last freezing date (LFD, top) and first freezing date (FFD, bottom) for the WE-38 watershed (1978 to 2012). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

Table 5

Trends in precipitation intensity categories in the WE-38 watershed (1968 to 2012). Slopes are expressed as a rate of change per year. Slopes in bold and italics show trends with statistical significance at p < 0.1.

Type	Number of days		Percentage of annual precip.	
	slope	p-value	slope	p-value
Trace precip. (<2.5 mm)	***0.354***[*]	***0.01***	***0.049***	***0.00***
Light precip. (2.5–12.7 mm)	***-0.467***	***0.00***	***-0.20***	***0.01***
Moderate precip. (12.7–25.4 mm)	0.059	0.18	0.023	0.37
Heavy precip. (25.4–76.2 mm)	0.037	0.14	0.09	0.19

[*] Here and elsewhere in the table, bolded font was intended to identify statistically significant trends. I do not see bold font used in the formatting of Table 5. Perhaps we should use italics instead?

that the incidence of false springs has actually declined across the US since 1920, and suggests that these trends would continue with further temperature increases due to climate change.

3.2. Precipitation

Total precipitation in the WE-38 watershed displayed inter-annual and seasonal variability over the 45-yr study period. Annual total precipitation in the WE-38 watershed ranged from 710.3 mm to 1905.4 mm, with a mean annual value of 1097.8 mm. Years with the least annual total precipitation included 1980 (716.3 mm) and 2001 (710.3 mm), both of which featured short-term meteorological droughts (Kunkel et al., 2013). In contrast, 2011 (1905.4 mm) and 1972 (1518.7 mm) represented record wet years in the WE-38 watershed, with enhanced precipitation largely driven by remnant tropical systems (Agnes in June of 1972; Irene in August and Lee in September of 2011). Notably, the year 2011 was also the wettest year on record across much of the northeastern US (Kunkel et al., 2013; National Climatic Data Center, 2011). Seasonally, total precipitation during the growing season (mid-April to mid-October) was 34% higher than during the non-growing season with June being the wettest month and February being the driest month (Table 4).

3.2.1. Significant trends

Precipitation generally increased in the WE-38 watershed, with the most significant trends occurring at seasonal and monthly time scales. Annual total precipitation increased at a rate of 21.89 mm per decade, consistent with regional assessments across the northeastern US (Kunkel et al., 2013), but the trend was not significant. Monthly total precipitation increased significantly in October and January at rates of 8.18 and 6.71 mm per decade respectively. The exceptionally strong increase

Table 6
Months in which daily precipitation exceeded 2-, 5- and 10-year return periods (1968 to 2012).

Year		1972	1973	1975	1976	1986	1987	1995	1998	1999	2004	2005	2006	2010	2011
Return period	2y		9		10	7	9			9		10	6	9	4,9
	5y			9		8			6		9				
	10y	6						10							9

in October rainfall in WE-38 reflects regional precipitation trends showing the greatest increases during the fall months (Kunkel et al., 2013). Notably, none of the four seasons showed significant changes in total precipitation.

Trends in the intensity of precipitation at daily (mm d^{-1}) and hourly (mm h^{-1}) time scales were variable, with significant increasing trends mostly during the non-growing season. Maximum daily precipitation increased in September and January at rates of 3.99 mm d^{-1} and 2.23 mm d^{-1} per decade, respectively. There was a significant increasing trend in maximum daily precipitation at a rate of 5.30 mm d^{-1} per decade for the fall season. Maximum daily precipitation in the non-growing season also increased at a rate of 2.24 mm d^{-1} per decade, but there was no significant change during the growing season. The hourly intensity of precipitation increased in December and January at rates of 0.61 and 5.27 mm h^{-1} per decade respectively (Table 4). Seasonal trends showed increasing hourly intensities of storm events in fall, winter and spring, but no change in summer. The hourly intensity of precipitation also increased during the non-growing season, but not during the growing season.

While the intensity of precipitation events clearly increased during the non-growing season in WE-38, the number of days with intense rainfall remained largely unchanged during the 1968 to 2012 study period. For example, there were no significant trends with respect to the number of days of moderate to heavy precipitation or the percentage of total precipitation that falls as moderate to heavy precipitation in the WE-38 watershed (Table 5). Groisman (2012) reported the occurrence of a statistically significant redistribution in the ranges of intense precipitation days/events during the past several decades over the central United States. In the current study, moderately heavy precipitation events became less frequent compared to days and events with heavier precipitation.

Days with trace precipitation and light precipitation in the WE-38 watershed showed opposing trends from 1968 to 2012. The number of days having trace precipitation in WE-38 increased at a rate of 0.354 days per decade and the percentage of total precipitation that fell in trace amounts also increased (Table 5), but trace precipitation only accounted for four or five percent of total precipitation. As observed by Groisman and Knight (2008), the increasing trend in trace precipitation should be interpreted with caution, as changes in measurement precision (i.e., increasing the precision from 2.5 mm to 0.254 mm) may have induced an artificial trend in the data set. In contrast to trace precipitation, the number of days having light precipitation (2.5 to 12.7 mm) decreased at a rate of -0.467 days per decade and the percentage of total precipitation that fell as light precipitation also declined. Light precipitation accounted for about 30 percent of total precipitation.

4.2.2. Extreme events

Very heavy precipitation, that which falls in amounts greater than 76.2 mm per 24-hour period, did not occur in all years and only accounted for two or three percent of the total precipitation over the 1968 to 2012 period. According to Bonnin et al. (2006), the two-, five-, and 10-yr return periods for daily total precipitation in the WE-38 watershed were 76, 94, and 110 mm per 24 h period. There were 19 events that exceeded the two-year return period during the 45-yr record, but 15 of those events occurred after 1978 (Table 6). In the 1979 to 2010 period, compared to the preceding 30-yr period, Groisman (2012) observed significant increases in the frequency of very heavy and extreme (>155 mm) precipitation events over the central United States. In WE-38, both days that exceeded the 10-yr return period in 1972 were a single event in June associated with the remnants of Hurricane Agnes (June 21-22, 1972). More recently, Tropical Storm Lee delivered 130 mm precipitation over a 24-hour period (September 7, 2011). Over the 1968 to 2012 monitoring period, only one of these very heavy precipitation events occurred in April, while the rest occurred in the summer-fall months of June through October.

Recent studies suggest that the frequency of extreme precipitation events is increasing across the northeastern US. In a study of extreme hydrological events in the Catskill Mountains and Hudson River Valley in southern New York State, Matonse and Frei (2013) found a marked increase in the frequency of extreme events in the warm season (June-October) during the last two decades, with an accelerated rate of increase since the mid-1990s. From the global perspective, a recent study used the latest gridded land-based precipitation dataset (HadEX2) to show there are more areas with significant increasing trends in extreme precipitation amounts, intensity and frequency than there are areas with decreasing trends (Donat et al., 2013). In addition, DeGaetano (2013) showed that recurrence intervals for 100-yr rainfall events in the northeastern US have decreased by 40%, meaning that what was once a 100-yr storm (based on data from 1950 to 1970) is now considered a 60-yr storm (based on more recent data from 1978 to 2007).

3.3. Streamflow

Streamflow in the WE-38 watershed varied seasonally and annually over the 45-yr monitoring period (Table 7). Mean monthly streamflow depth showed strong seasonal variations typical of watersheds in the humid northeastern US, with the lowest flows occurring in August (12.40 mm) and the highest flows in March (77.83 mm). These streamflow variations

Table 7
Trends in streamflow depth in the WE-38 watershed (1968 to 2012). Slopes are expressed as a rate of change per decade. Slopes in bold and italics show trends with statistical significance at $p < 0.1$.

Period		Mean streamflow depth	Streamflow depth	
		mm	Slope mm	p-value
Spring	Mar	77.83	-0.45	0.48
	Apr	62.69	-1.94	0.34
	May	47.26	-3.68	0.11
Summer	Jun	34.92	-1.86	0.16
	Jul	14.19	***-1.24***[*]	***0.06***
	Aug	0.43	-0.74	0.17
Fall	Sep	28.32	-0.25	0.43
	Oct	30.84	***4.95***	***0.01***
	Nov	39.10	-0.23	0.50
Winter	Dec	56.49	1.78	0.30
	Jan	53.79	2.29	0.30
	Feb	52.34	***-7.49***	***0.02***
Spring		187.78	-8.24	0.21
Summer		61.49	***-5.12***	***0.08***
Fall		97.56	3.44	0.28
Winter		163.44	-8.01	0.24
Average growing season		178.38	***-11.19***	***0.08***
Average non-growing season		332.54	-5.54	0.22
Annual		509.20	-16.90	0.28

[*] Here and elsewhere in the table, bolded font was intended to identify statistically significant trends. I do not see bold font used in the formatting of Table 7. Perhaps we should use italics instead?

reflected seasonal patterns in temperature and evapotranspiration, which were highest in summer and lowest in winter. On an annual basis, streamflow depth averaged 509.2 mm (46% of annual precipitation) from 1968 to 2012, with inter-annual variability largely driven by annual precipitation. The lowest streamflow depth in WE-38 occurred in 2001 (207.4 mm), which was the drought of record during the 45-yr study period. In contrast, the year 2011 saw the highest streamflow depth (1199.9 mm) in WE-38, which coincided with the wettest year on record in the watershed, as well as across the northeastern US (Kunkel et al., 2013).

3.3.1. Significant trends

Total streamflow depth in the WE-38 watershed largely declined over the 45-yr study period (Table 7), with the most significant reductions occurring at monthly and seasonal time scales. Annual total streamflow depth decreased by -16.9 mm per decade, although the trend was not statistically significant. While this trend runs contrary to recent studies of large river basins showing increases in streamflow over the past century (Sagarika et al., 2014; Yang et al., 2014b), it is supported by a local study of small basins across Pennsylvania showing decreasing streamflows statewide (Zhu and Day, 2005). On a monthly basis, streamflow depth decreased most strongly during the month of February at a rate of -7.49 mm per decade. This change may be due to less snowmelt in February as a result of increasing mean and minimum temperatures in January that result in less snow accumulation. Significant decreases in streamflow depth also occurred in July and during the summer season at rates of -1.24 mm and -5.12 mm per decade, respectively, as well as during the average growing season (-11.19 mm per decade). Notably, streamflow depth increased markedly in October at a rate of 4.95 mm per decade, reflecting the strong increase in monthly total precipitation observed in WE-38, as well as elsewhere across the northeastern US (Kunkel et al., 2013).

3.3.2. Extreme events

There were 30 years having flood events with peak streamflow exceeding the 2.33-year return period during the 45-year study period. The months in which these events occurred are shown in Table 8. Fourteen of the 17 precipitation events that exceeded the two-year return period (Table 6) produced peak streamflows that exceeded the 2.33-year return period. The three precipitation events that did not produce such high peak streamflow occurred during September and October when streamflow is typically low, as has been observed elsewhere (Small et al., 2006).

Rain-on-snow events have also produced large floods in the WE-38 watershed, as well as across the greater northeastern US (Pradhanang et al., 2013a). Notably, one of the largest floods in the WE-38 watershed occurred on January 19, 1996, and was due to rapid snowmelt induced by heavy rain across the region (Leathers et al., 1998). Although snow accumulation data were not collected in the WE-38 watershed, the date of the runoff event and temperature and precipitation records leading up to the event were examined to determine whether snowmelt contributed to runoff generation. By decade, the ‘70s, ‘80s, ‘90s and 2000s had numbers of flood events (those exceeding the 2.33-year return period) that were not affected

Table 8
Months in which peak daily streamflow exceeded 2.33-, 10-, 25- and 100-year return periods (1968 to 2012). Numbers followed by an asterisk indicate events where snowmelt played a role in runoff generation.

Year	Q2.33	Q10	Q25	Q100
1970	4			
1971	2*			
1972				6
1973	9, 12[a]	2*,[a]		
1975			9	
1976	6,1*		10	
1977	7,2*			
1978	2*			
1979	3,2*	1*		
1981	2*			
1982	3*,[a]			
1983	12*			
1984	6			
1985	2*			
1986	3*			7,8
1987	9			
1989	6		6	
1992		11[a],11[a]		
1993	5,11			
1995	10,11			
1996	10			1*
1998		6, [a]		
2000	6			
2002	11[a]	12*,[a]		
2003	9			
2004	5	9		
2006		6		
2008	3			
2010	1*			
2011	3,4,4		9[a]	9
sum	33	8	4	5

[a] Estimated from daily mean streamflow.

by snowmelt of 9, 6, 8, and 7 respectively. Numbers of flood events that were affected by snowmelt for those decades are 7, 5, 1 and 1 respectively. There does not appear to be any trend associated with the number of flood events that occur in the warm season and are not affected by snowmelt, but the number of flood events that occur during the cold season when runoff is affected by snowmelt appears to be declining. A recent study by Pradhanang et al. (2013a) reports that decreasing trends in rain-on-snow events is expected across the region as minimum temperatures increase in the winter, which is consistent with observations of fewer floods generated by snowmelt runoff in the WE-38 watershed.

In contrast to floods, which develop rapidly in response to precipitation inputs, low streamflows are a symptom of extended rain-free periods that can adversely affect stream ecology (Pradhanang et al., 2013b). In WE-38, the average length of periods of low streamflow, represented by the maximum consecutive days during which mean daily streamflow is lower than the 10th percentile, was 16 days, but ranged from 0 days during wet years to 70 days in dry years (Fig. 6). These low streamflow periods typically occurred in July or August. The length of low streamflow periods increased at an average rate of 1.9 days per decade over the 1968 to 2012 period. This trend is broadly consistent with work by Groisman and Knight (2008), which showed that the percent of dry-day episodes lasting one month or longer increased over the eastern US from 1967 to 2006.

. *Actual and potential evapotranspiration*

Actual evapotranspiration, defined as annual total precipitation minus annual total streamflow depth (Huntington and Billmire, 2014), strongly increased in the WE-38 watershed at a rate of 37.10 mm per decade from 1968 to 2012 (Fig. 7). These trends largely agreed with recent global (Ukkola and Prentice, 2013) and national (Walter et al., 2004; Szilagyi et al., 2001) scale assessments showing that actual evapotranspiration, as determined by catchment water balance methods, increased by 10 to 20 mm per decade. Studies in the US northeast suggest that actual evapotranspiration is increasing at rates ranging from 2.3 mm per decade (Yang et al., 2014a) to 19 mm per decade (Huntington and Billmire, 2014). More recently, a study by Kramer et al. (2015) showed that actual evapotranspiration increased by 2.2 to 12.3 mm per decade in seven out of eight hydrological units east of the Mississippi River. Notably, actual evapotranspiration appears to be increasing faster in WE-38 than in other regions in the eastern US.

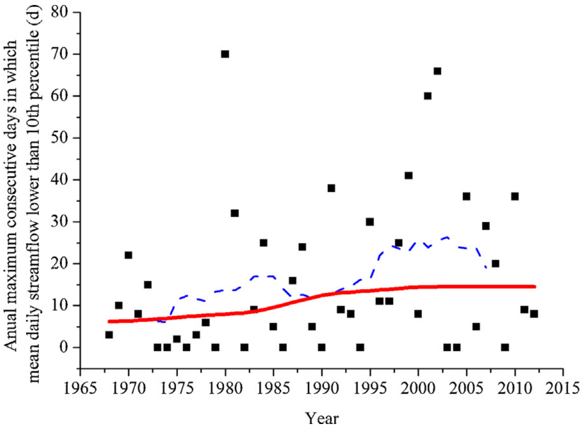


Fig. 6. Long-term trends in the maximum annual consecutive number of days during which daily mean streamflow in the WE-38 watershed was lower than the 10th percentile (1968 to 2012). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

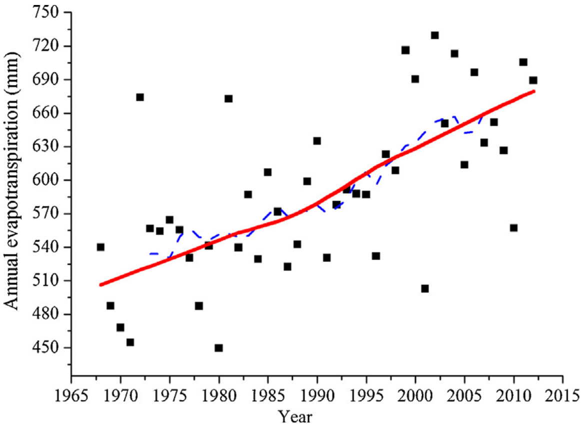


Fig. 7. Long-term trends in annual actual evapotranspiration for the WE-38 watershed (1968 to 2012). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

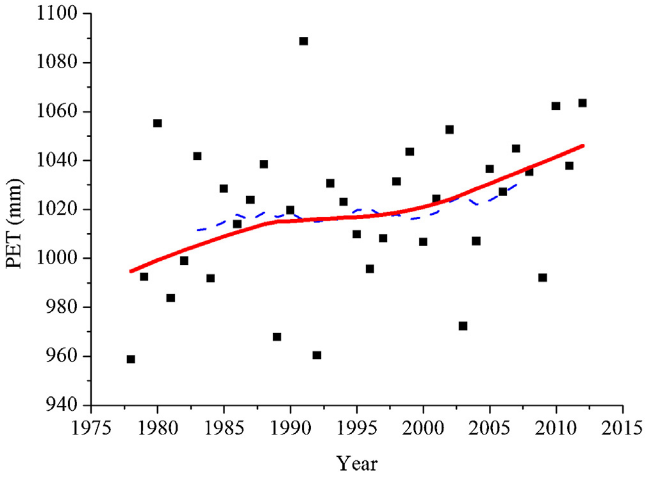


Fig.8. Long-term trends in annual potential evapotranspiration for the WE-38 watershed (1968 to 2012). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

Potential evapotranspiration, calculated by the Priestly-Taylor model, also increased by 11.29 mm per decade from 1978 to 2012 (Fig 8), the period during which daily temperature data were available in WE-38. Over the same time frame, actual evapotranspiration increased by 42.26 mm per decade, which was slightly greater than the aforementioned trend (+37.10 mm per decade) encompassing the full hydrologic record. Trends in potential and actual evapotranspiration were both positive in WE-38, indicating that changes in the energy balance could have accounted for some of the increase in actual evapotranspiration. Perhaps more important was the difference in magnitude between the trend slopes, with actual evapotranspiration increasing 3.7 times faster than potential evapotranspiration. Greater increases in actual relative to potential evapotranspiration suggest that the process is becoming more efficient (i.e., a greater proportion of potential evapotranspiration in WE-38 is being realized). One possible explanation for increased evapotranspiration efficiency is a rise in groundwater storage (Tuttle and Salvucci, 2012), which would be expected with increased precipitation and groundwater recharge.

A complete temporal accounting of groundwater storage changes in WE-38 was beyond the scope of this study. However, we provide some initial insight into this possibility using 18 years (1995 to 2012) of groundwater level data from a USGS monitoring well in WE-38 that is part of the Climate Response Network (http://groundwaterwatch.usgs.gov/net/ogwnetwork.asp?ncd=crn; Site #: 404,239,076,362,001). By applying the annual water table fluctuation method of Kramer et al. (2015) and assuming a specific yield of 0.01 for the fractured aquifers in WE-38 (Heppner et al., 2007), we observed an increasing but insignificant trend in groundwater storage (+9.37 mm per decade) over the 18-year time frame. Indeed, Sharma and Walter (2014) reported a slight increase in groundwater storage (+6.4 mm per decade) that may have contributed to rising actual evapotranspiration levels in the Missouri River Basin. Here in the eastern US, however, studies maintain that changes in groundwater storage have contributed little to actual evapotranspiration trends (Huntington and Billmire, 2014; Kramer et al., 2015). Certainly, additional well data and a longer inference period would be needed to fully ascertain the influence of groundwater storage on actual evapotranspiration trends in WE-38.

Lacking sufficient evidence for a groundwater storage effect on evapotranspiration, it appears most likely that enhanced evapotranspiration efficiencies in WE-38 are being driven by changes in seasons and augmented rainfall amounts that affect the growth of plants. Indeed, simultaneously increasing trends in growing season length (+2.83 days per decade) and growing degree days (+62.24 growing degree days per decade) in WE-38 would stimulate earlier leaf-out by plants and later senescence (Huntington and Billmire, 2014), and therefore provide an extended time period during which transpiration could take place. In addition, Kramer et al. (2015) offer evidence that trends in the Normalized Difference Vegetation Index (NDVI), a measure of vegetation greenness, are highly correlated with trends in actual evapotranspiration throughout the eastern US, suggesting that increased precipitation amounts are stimulating plant growth and increasing the density of vegetation, and thereby augmenting evapotranspiration rates during the growing season. Moreover, recent worldwide declines in pan evaporation (Roderick et al., 2009) coupled with the fact that transpiration by plants accounts for over two-thirds of evapotranspiration (Jasechko et al., 2013) also point to plant transpiration as a primary factor driving the observed increases in actual evapotranspiration in WE-38.

4. Implications

The implications of climate change trends for agricultural production in the WE-38 watershed can be viewed as a net positive for the kind of row crop agriculture that is typical of the study area, at least in the near term. Warmer temperatures, driven primarily by increasing minimum temperatures, lead to longer growing seasons and more growing degree days. However, the variability associated with the occurrence of the last freezing temperature in spring appears to be increasing, and the risk of a late freeze remains in spite of the trend toward an earlier average last spring freeze date. Whereas warmer temperatures will result in greater evapotranspiration, monthly precipitation totals are trending upward except for the wettest month of June. The decrease in light precipitation is welcome as these events are less effective at supplying crop needs and, with the overall increase in total precipitation, should be interpreted as an increase in more effective precipitation. A significantly wetter October may complicate harvests, but the trend for the arrival of the first freeze of fall to occur toward the end of October mitigates that complication. Very heavy precipitation events that exceed the two year return period are increasingly common and occur primarily during the growing season. These events are frequently associated with strong thunderstorms and are indicative of a greater risk of crop damage, but are of limited geographical extent. The need for and cost of crop insurance may become greater in response to this trend.

Recent climatic changes are also influencing the natural flow regime in WE-38, which has important implications for aquatic life (Poff et al., 1997). For instance, the Mahantango Creek and its tributaries, one of which drains the WE-38 watershed, are trout streams. Whereas the stream is not used for irrigation, swimming, boating or as a source of drinking water, its use for recreational fishing is probably the most sensitive indicator of the impacts of climate change trends on water resources. Spring (February to April) streamflow depth is decreasing, most significantly in February. Winter flood events affected by snowmelt are declining. While the frequency of summer-fall flood events remains unchanged, low flow periods in July, August, and September are trending longer by 1.9 days per decade. Extended low streamflow periods in the late summer and early fall could increase stream water temperatures above thresholds that are tolerable to cold water fish species like trout. Taken together, these trends suggest that the natural flow regime in WE-38 is shifting to a new phase that features fewer wintertime floods and longer periods of low flow in the summer.

With respect to the conservation of the Chesapeake Bay, nutrients and sediment are the major pollutants that derive from agricultural watersheds in the Susquehanna River Watershed. Under current Pennsylvania regulations winter spreading of manure is allowed, but producers are discouraged against spreading on snow or frozen ground. Increasing mean and minimum temperatures that are resulting in less snow, accumulation, shorter periods of snow cover, and fewer flood events affected by snowmelt offer increased opportunities to spread manure during times when risk of runoff is relatively low, with the possible exception of January when total precipitation is increasing. With respect to April and May when most nutrients are being applied, there don't appear to be any trends that would increase the risk of nutrient loss in runoff. In fact, streamflow depth is decreasing in the spring. However, the apparent increasing frequency and severity of flood events that exceed the 2.33 year return period is cause for concern for both nutrient and sediment delivery to the Chesapeake Bay, as well as stream bank destabilization and erosion that would exacerbate efforts to control sediment delivery.

In conclusion, the present and near term effects of climate change do not appear to present great challenges for agricultural production, water resources or Chesapeake Bay conservation efforts, but that does not mean that the effects of these changes will not worsen in the future. Additionally, the rate of change generally appears to be much greater than what has been observed in other studies of other geographical areas, and it appears to be increasing. Whereas that rate of change is not expected to reverse itself, the potentially negative, longer term effects of climate change will be realized sooner.

Acknowledgments

This study is a contribution from the USDA–ARS Pasture Systems and Watershed Management Research Unit with collaboration and financial support from the USDA–NRCS. Financial support for the lead author was provided by the China Scholarship Council, Nanjing Hydraulic Research Institute (NHRI), and the China Special Fund for Water Resources Research in the Public Interest (201201026). We are very grateful to the reviewers for their constructive comments that helped to improve the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.10.004.

References

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein-Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, R., Tagipour, A., Kumar, K.R., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M., Vazquez-Aguirre, J.L., 2006. Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research-Atmospheres 111, http://dx.doi.org/10.1029/2005jd006290.

Anandhi, A., Zion, M.S., Gowda, P.H., Pierson, D.C., Lounsbury, D., Frei, A., 2013. Past and future changes in frost day indices in Catskill Mountain region of New York. Hydrological Processes 27, 3094–3104.

Archibald, J.A., and M.T. Walter. 2014. Do energy-based PET models require more input data than temperature-based models? –an evaluation at four humid fluxnet sites. *Journal of the American Water Resources Association* 50(2): 497-508.

Ault, T.R., Henebry, G.M., de Beurs, K.M., Schwartz, M.D., Betancourt, J.L., Moore, D., 2013. The False Spring of 2012: earliest in North American Record. EOS Transactions 94, 181–182.

Bonnin, G.M., Martin, D., Lin, B., Parzybok, T., Yekta, M., Riley, D., 2006. NOAA Atlas 14 Precipitation-Frequency Atlas of the United States Volume 2 Version 3.0: Delaware, District of Columbia, Illinois, Indiana, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring. Maryland.

Brown, P.J., Bradley, R.S., Keimig, F.T., 2010. Changes in extreme climate indices for the northeastern United States, 1870-2005. Journal of Climate 23, 6555–6572.

Bryant, R.B., Veith, T.L., Feyereisen, G.W., Buda, A.R., Church, C.D., Folmar, G.J., Schmidt, J.P., Dell, C.J., Kleinman, P.J.A., 2011. US Department of Agriculture Agricultural Research Service Mahantango Creek Watershed, Pennsylvania, United States: Physiography and history. Water Resources Research 47, http://dx.doi.org/10.1029/2010wr010056.

Bryant, R.B., K. Havstad, P., Heilman, P.J., Kleinman, T.B., Moorma, M.S., Moran, J.L. Steiner, and T. Strickland, 2012. Long Term Agroecological Research Network –Shared Research Strategy. Available online: http://www.ars.usda.gov/SP2UserFiles/Program/211/LTAR%20SRS%20-%20Final%20Version%20-%20130905 pdf (verified September 12, 2014).

Buda, A.R., Veith, T.L., Folmar, G.J., Feyereisen, G.W., Bryant, R.B., Church, C.D., Schmidt, J.P., Dell, C.J., Kleinman, P.J.A., 2011a. U.S. Department of Agriculture Agricultural Research Service Mahantango Creek Watershed, Pennsylvania, United States: Long-term precipitation database. Water Resources Research 47, http://dx.doi.org/10.1029/2010wr010058.

Buda, A.R., Feyereisen, G.W., Veith, T.L., Folmar, G.J., Bryant, R.B., Church, C.D., Schmidt, J.P., Dell, C.J., Kleinman, P.J.A., 2011b. U.S. Department of Agriculture Agricultural Research Service Mahantango Creek Watershed, Pennsylvania, United States: Long-term stream discharge database. Water Resources Research 47, http://dx.doi.org/10.1029/2010wr010059, W08703.

Buda, A.R., Kleinman, P.J.A., Srinivasan, M.S., Bryant, R.B., Feyereisen, G.W., 2009. Factors influencing surface runoff generation from two agricultural hillslopes in central Pennsylvania. Hydrological Processes 23 (9), 1295–1312.

Burakowski, E.A., Wake, C.P., Braswell, B., Brown, D.P., 2008. Trends in wintertime climate in the northeastern United States: 1965–2005. Journal of Geophysical Research-Atmospheres 113, http://dx.doi.org/10.1029/2008JD009870.

Burns, D.A., Klaus, J., McHale, M.R., 2007. Recent climate change trends and implications for water resources in the Catskill Mountain region, New York. Journal of Hydrology 336 (1-2), 155–170, http://dx.doi.org/10.1016/j.jhydrol.2006.12.019.

Campbell, J.L., Driscoll, C.T., Pourmokhtarian, A., Hayhoe, K., 2011. Streamflow responses to past and projected future changes in climate at the Hubbard Brook Experimental Forest, New Hampshire, United States. Water Resources Research 47, http://dx.doi.org/10.1029/2010wr009438.

Cleveland, W.S., 1979. Robust Locally Weighted Regression and Smoothing Scatterplots. Journal of the American Statistical Association 74 (368), 829–836.

Cooter, E.J., Leduc, S.K., 1995. Recent Frost Date Trends in the North-Eastern USA. Int. Journal of Climatology 15 (1), 65–75.

Dai, A., K.E. Trenberth, T.R. Karl, 1999. Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. Journal of Climate 12, 2451–2473.

DeGaetano, A.T., 2013. Time-dependent changes in extreme-precipitation return-period amounts in the continental United States. Journal of Applied Meteorology and Climatology 48, 2086–2099.

Dingman, S.L., 2002. Physical Hydrology, 2nd ed. Prentice Hall, Upper Saddle River, N.J. 646 pp.

Donat, M.G., L.V. Alexander, H., Yang, I., Durre, R., Vose, R.J.H., Dunn, K.M., Willett, E., Aguilar, M., Brunet, J., Caesar, B., Hewitson, C., Jack, A.M.G. Klein-Tank, Kruger, A.C., Marengo, J., Peterson, T.C., Renom, M., Rojas, C.O., Rusticucci, M., Salinger, J., Elrayah, A.S., Sekele, S.S., Srivistava, A.K., Trewin, B., Villarroel, C., Vincent, L.A., Zhai, P., X. Zhang, S. Kitching, 2013. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. Journal of Geophysical Research-Atmospheres 118 (5), 2098–2118, http://dx.doi.org/10.1002/jgrd.50150.

Douglas, E., Whelchel, A., Yarnal, B., 2013. Climate change and regional and local identities: New England, Mid-Atlantic and Urban Northeast Corridor, and Central Appalachia. In: Climate Change in the Northeast: A Sourcebook. In: Horton, R., Solecki, W., Rosenzweig, C. (Eds.), Draft Technical Input Report prepared for the U.S. National Climate Assessment, Available online at: http://downloads.usgcrp.gov/NCA/Activities/nca_ne_full_report_v2 pdf. verified October 3 2014) 2013.

Durbin, J., Watson, G.S., 1950. Testing for Serial Correlation in Least Squares Regression. I. Biometrika 37 (3–4), 409–428.

Durbin, J., Watson, G.S., 1951. Testing for Serial Correlation in Least Squares Regression. II. Biometrika 38 (1–2), 159–179.

Easterling, D.R., 2002. Recent changes in frost days and the frost-free season in the United States. Bulletin of the American Meteorological Society 83 (9), 1327–1332.

Engman, E.T., Parmele, L.H., Gburek, W.J., 1974. Hydrologic impact of tropical storm Agnes. Journal of Hydrology 22 (1-2), 179–193.

Flippo Jr., H.N., 1977. Bulletin No. 13. Floods in Pennsylvania. Pennsylvania Department of Environmental Resource. Harrisburg. PA. 59 p.

Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Klein-Tank, A.M.G., Peterson, T., 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. Climate Research 19 (3), 193–212.

Fuka, D., M.T. Walter, J.A., Archibald, T.S. Steenhuis, and Z.M. Easton, 2013. A community modeling foundation for Eco-Hydrology. R package version 0.4.12. http://cran.r-project.org/web/packages/EcoHydRology/index.html (verified May 14, 2015).

Gburek, W.J., Needelman, B.A., Srinivasan, M.S., 2006. Fragipan controls on runoff generation: Hydropedological implications at landscape and watershed scales. Geoderma 131 (3-4), 330–344.

Groisman, P.Y., and R.W. Knight, 2008. Prolonged dry periods over the conterminous United States: new tendencies emerging during the last 40 years. *Journal of Climate* 21: 1850-1862.

Groisman, P.Y., Knight, R.W., Karl, T.R., 2012. Changes in Intense Precipitation over the Central United States. Journal of Hydrometeorology 13 (1), 47–66.

Groisman, P.Y., Knight, R.W., Zolina, O.G., 2013. Recent trends in regional and global intense precipitation patterns. In: Pielke Sr., R.A. (Ed.), Climate Vulnerability: Understanding and Addressing Threats to Essential Resources. Academic Press, Burlington, MA, pp. 25–55.

Gu, L., P.J. Hanson, W.M., Post, D.P., Kaiser, B., Yang, R., Nemani, S.P. Pallardy, 2008. The 2007 eastern US spring freeze: increased cold damage in a warming world? BioScience 58 (3), 253–262.

Hamburg, S.P., Vadeboncoeur, M.A., Richardson, A.D., Bailey, A.S.A.S., 2013. Climate change at the ecosystem scale: a 50-year record in New Hampshire. Climatic Change 116, 457–477.

Hatfield, J., G. Takle, R., Grotjahn, P., Holden, R.C., Izaurralde, T., Mader, E. Marshall, and D. Liverman, 2014. Ch. 6: Agriculture. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M., Melillo, Terese (T.C.) Richmond, and G.W. Yohe (Editors). U.S. Global Change Research Program. pp. 150-174. http://dx.doi.org/10.7930/J02Z13FR.

Helsel, D.R., and R.M. Hirsch, 2002. Statistical Methods in Water Resources Techniques of Water Resources Investigations Book 4, Chapter A3. U.S. Geological Survey. 522 pp.

Heppner, C.S., Nimmo, J.R., Folmar, G.J., Gburek, W.J.D., Risser, W., 2007. Multiple-methods investigation of recharge at a humid-region fractured rock site, Pennsylvania, USA. Hydrogeology Journal 15, 915–927.

Hirsch, R.M., 1979. An evaluation of some record reconstruction techniques. Water Resources Research 15 (6), 1781–1790.

Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of Trend Analysis for Monthly Water-Quality Data. Water Resources Research 18 (1), 107–121.

Hirsch, R.M., Ryberg, K.R., 2012. Has the magnitude of floods across the USA changed with global CO_2 levels? Hydrological Sciences Journal 57 (1), 1–9.

Hodgkins, G.A., Dudley, R.W., Huntington, T.G., 2003. Changes in the timing of high river flows in New England over the 20th Century. Journal of Hydrology 278 (1-4), 244–252.

Horton, R., G. Yohe, W., Easterling, R., Kates, M., Ruth, E., Sussman, A., Whelchel, D. Wolfe, and F. Lipschultz, 2014. Ch. 16: Northeast. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M., Melillo, T.C., Richmond, G.W. Yohe (Editors). U.S. Global Change Research Program. pp. 371-395. http://dx.doi.org/10.7930/J0SF2T3P.

Huntington, T.G., 2003. Climate warming could reduce runoff significantly in New England, USA. Agricultural and Forest Meteorology 117, 193–201.

Huntington, T.G., 2009. Climate warming-induced intensification of the hydrologic cycle: an assessment of the published record and potential impacts on agriculture. Advances in Agronomy 109, 1–53.

Huntington, T.G., Richardson, A.D., McGuire, K.J., Hayhoe, K., 2009. Climate and hydrological changes in the northeastern United States: recent trends and implications for forested and aquatic ecosystems. Canadian Journal of Forest Research 39 (2), 199–212.

Huntington, T.G., Billmire, M., 2014. Trends in precipitation, runoff, and evapotranspiration for rivers draining to the Gulf of Maine in the United States. Journal of Hydrometeorology 15 (2), 726–743.

Insaf, T.Z., Lin, S., Sheridan, S.C., 2013. Climate rends in indices for temperature and precipitation across New York State, 1948-2008. Air Quality, Atmosphere, and Health 6, 247–257.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jasechko, S., Sharp, Z.D., Gibson, J.J., Birks, S.J., Yi, Y., Fawcett, P.J., 2013. Terrestrial water fluxes dominated by transpiration. Nature 496, 347–350.

Jassby, A.D., and J.E. Cloern, 2010. wq: Exploring water quality monitoring data. R package. Version 0. 2-8. http://cran.r-project.org/web/packages/wq/index.html (verified October 3, 2014).

Jiménez Cisneros, B.E., T. Oki, N.W., Arnell, G., Benito, J.G., Cogley, P. Döll, T. Jiang, and S.S. Mwakalila, 2014. Freshwater resources. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, C.B., Field, V.R., Barros, D.J., Dokken, K.J., Mach, M.D., Mastrandrea, T.E., Bilir, M., Chatterjee, K.L., Ebi, Y.O., Estrada, R.C., Genova, B., Girma, E.S., Kissel, A.N., Levy, S., MacCracken, P.R. Mastrandrea, and L.L. White (Editors). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K.P., Lindseay, J., Charlson, R.J., Peterson, T.C., 1993. A New Perspective on Recent Global Warming - Asymmetric Trends of Daily Maximum and Minimum Temperature. Bulletin of the American Meteorological Society 74 (6), 1007–1023.

Kramer, R.J., Bounoua, L., Zhang, P., Wolfe, R.E., Huntington, T.G., Imhoff, M.L., Thome, K., Noyce, G.L., 2015. Evapotranspiration trends over the eastern United States during the 20th century. Hydrology 2, 93–111.

Kunkel, K.E., Stevens, L.E., Stevens, S.E., Sun, L., Janssen, E., Wuebbles, D., Rennells, J., DeGaetano, A., Dobson, J.G., 2013. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 1. Climate of the Northeast U.S. NOAA Technical Report NESDIS 142-1. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C. 87 pp.

Lauritsen, R.G., Rogers, J.C., 2012. U.S. diurnal temperature range variability and regional causal mechanisms, 1901-2002. Journal of Climate 25, 7216–7231.

Leathers, D.J., Kluck, D.R., Kroczynski, S., 1998. The severe flooding event of January 1996 across north-central Pennsylvania. Bulletin of the American Meteorological Society 79 (5), 785–797.

Matonse, A.H., Frei, A., 2013. A Seasonal Shift in the Frequency of Extreme Hydrological Events in Southern New York State. Journal of Climate 26 (23), 9577–9593.

McCuen, R.H., 1998. Hydrologic Analysis and Design, 2nd ed. Prentice Hall, Upper Saddle River, N.J.

McMaster, G.S., Wilhelm, W.W., 1997. Growing-degree days: one equation, two interpretations. Agricultural and Forest Meteorology 87, 291–300.

McGuiness, J.L., Mills, W.C., Nixon, P.R., 1979. Chapter 3: Climate. In: *Field Manual for Research in Agricultural Hydrology*. D.L. Brakensiek. H.B. Osborn, and W.J. Rawls (Editors). USDA Agriculture Handbook No. 224, 215–237.

Najjar, R.G., Pyke, C.R., Adams, M.B., Breitburg, D., Hershner, C., Kemp, M., Howarth, R., Mulholland, M.R., Paolisso, M., Secor, D., Sellner, K., Wardrop, D., Wood, R., 2010. Potential climate-change impacts on the Chesapeake Bay. Estuarine Coastal and Shelf Science 86 (1), 1–20.

National Climatic Data Center, 2011. State of the Climate. Available at: http://www.ncdc.noaa.gov/sotc/national/2011/13 (verified September 25, 2014).

National Weather Service, 1989. Cooperative Station Observations. National Weather Service Observing Handbook No. 2. US GPO, Washington, D.C, pp. 83.

Peterson, T.C., Heim Jr, R.R., Hirsch, R., Kaiser, D.P., Brooks, H., Diffenbaugh, N.S., Dole, R.M., Giovannettone, J.P., Guirguis, K., Karl, T.R., Katz, R.W., Kunkel, K., Lettenmaier, D., McCabe, G.J., Paciorek, C.J., Ryberg, K.R., Schubert, S., Silva, V.B.S., Stewart, B.C., Vecchia, A.V., Villarini, G., Vose, R.S., Walsh, J., Wehner, M., Wolock, D., Wolter, K., Woodhouse, C.A., Wuebbles, D., 2013. Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States. Bulletin of the American Meteorological Society 94 (6), 821–834.

Peterson, A.G., Abatzoglou, J.T., 2014. Observed changes in false springs over the contiguous United States. Geophysical Research Letters 41, 2156–2162.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47 (11), 769–784.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food security and food production systems. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Pradhanang, S.M., Frei, A., Zion, M., Schneiderman, E.M., Steenhuis, T.S., Pierson, D., 2013a. Rain-on-snow runoff events in New York. Hydrological Processes 27, 3035–3049.

Pradhanang, S.M., Mukundan, R., Schneiderman, E.M., Zion, M.S., Anandhi, A., Pierson, D.C., Frei, A., Easton, Z.M., Fuka, D., Steenhuis, T.S., 2013b. Streamflow Responses to Climate Change: Analysis of Hydrologic Indicators in a New York City Water Supply Watershed. Journal of the American Water Resources Association 49 (6), 1308–1326.

Priestly, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100, 81–92.

Qu, M., Wan, J., Hao, X., 2014. Analysis of diurnal temperature range change in the continental United States. Weather and Climate Extremes 4, 86–95.

R Development Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria. ISBN 3-900051-07-0. Available from: http://www.R-project.org/ (verified October 3, 2014).

Ries III, K.G., 2007. The national streamflow statistics program: A computer program for estimating streamflow statistics for ungaged sites. U.S. Geological Survey Techniques and Methods 4-A6. 37 pp.

Roderick, M.L., Hobbins, M.T., Farquhar, G.D., 2009. Pan evaporation trends and the terrestrial water balance. II. Energy balance and interpretation. Geography Compass3 /2, 761–780.

Schwartz, M.D., Ahas, R., Aasa, A., 2006. Onset of spring starting earlier across the Northern Hemisphere. Global Change Biology 12 (2), 343–351.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association 63, 1379–1389.

Shaw, S.B., Riha, S.J., 2011. Assessing temperature-based PET equations under a changing climate in temperate, decidiuous forests. Hydrological Processes 25, 1466–1478.

Small, D., Islam, S., Vogel, R.M., 2006. Trends in precipitation and streamflow in the eastern U.S.: paradox or perception? Geophysical Research Letters 33, http://dx.doi.org/10.1029/2005gl024995.

Szilagyi, J., Katul, G.G., Parlange, M.B., 2001. Evapotranspiration intensifies over the conterminous United States. Journal of Water Resources Planning and Management 127, 354–362.

Theil, H., 1950. A rank-invariant method of linear and polynomial regression analysis. I, II, III. *Nederl. Akad. Wetensch* Proc. 53: 386–392, 521–525, 1397–1412.

Trombulak, S.C., Wolfson, R., 2004. Twentieth-century climate change in New England and New York, USA. Geophysical Research Letters 31, http://dx.doi.org/10.1029/2004gl020574.

Tuttle, S.E., Salvucci, G.D., 2012. A new method for calibrating a simple, watershed-scale model of evapotranspiration: maximizing the correlation between observed streamflow and model-inferred storage. Water Resources Research 48, W05556.

Ukkola, A.M., Prentice, I.C., 2013. A worldwide analysis of trends in water-balance evapotranspiration. Hydrology and Earth System Sciences 17, 4177–4187.

Vose, R.S., Easterling, D.R., Gleason, B., 2005. Maximum and minimum temperature trends for the globe: An update through 2004. Geophysical Research Letters 32, http://dx.doi.org/10.1029/2005gl024379.

Walbridge, M.R., Shafer, S.R., 2011. A long-term agro-ecosystem research (LTAR) network for agriculture. Fourth Interagency Conference on Research in the Watersheds, 26-30 September, 2011, Fairbanks, AK. Available online: http://www.ars.usda.gov/SP2UserFiles/Program/211/LTAR%20Walbridge%20and%20Shafer%202011%20Paper.pdf (verified September 12, 2014).

Walsh, J., D. Wuebbles, K., Hayhoe, J., Kossin, K., Kunkel, G., Stephens, P., Thorne, R., Vose, M., Wehner, J., Willis, D., Anderson, S., Doney, R., Feely, P., Hennon, V., Kharin, T., Knutson, F., Landerer, T., Lenton, J. Kennedy, and R. Somerville, 2014. Ch. 2: Our Changing Climate. In: *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M., Melillo, T.C., Richmond, G.W. Yohe (Editors). U.S. Global Change Research Program. pp. 19-67. http://dx.doi.org/10.7930/J0KW5CXT.

Walter, M.T., Wilks, D.S., J-YP, arlange, R.L.S., chneider, 2004. Increasing evapotranspiration from the conterminous United States. Journal of Hydrometeorology 5, 405–408.

Walter, M.T., Brooks, E.S., McCool, D.K., King, L.G., Molnau, M., Boll, J., 2005. Process-based snowmelt modeling: does it require more input data than temperature-index modeling? Journal of Hydrology 300, 65–75.

Yang, Q., H. Tian, X., Li, B., Tao, W., Ren, G., Chen, C., Lu, J., Yang, S., Pan, K. Banger, 2014a. Spatiotemporal patterns of evapotranspiration along the North American east coast as influenced by multiple environmental changes. Ecohydrology, http://dx.doi.org/10.1002/eco.1538.

Yang, Q., H. Tian, M.A.M., Friedrichs, M., Liu, X. Li, 2014b. Hydrological responses to climate and land-use changes along the North American East Coast: a 110-year historical reconstruction. Journal of the American Water Resources Association, http://dx.doi.org/10.1111/jawr.12232.

Zhang, X.B., L. Alexander, G.C., Hegerl, P., Jones, A.K., Tank, T.C., Peterson, B. Trewin, 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdisciplinary Reviews-Climate Change 2 (6), 851–870.

Zhang, Q., Brady, D.C., Ball, W.P., 2013. Long-term seasonal trends of nitrogen, phosphorus, and suspended sediment load from the non-tidal Susquehanna River Basin to Chesapeake Bay. Science of the Total Environment 452, 208–221.

Zhu, Y., Day, R.L., 2005. Analysis of streamflow trends and the effects of climate in Pennsylvania, 1971 to 2001. Journal of the American Water Resources Association 41 (6), 1393–1405.