LONG-TERM TRENDS IN CLIMATE AND HYDROLOGY IN AN AGRICULTURAL HEADWATER WATERSHED OF CENTRAL PENNSYLVANIA, USA

Ray B. Bryant, Haiming Lu, Kyle R. Elkin, Anthony R. Buda, Amy S. Collick, Gordon J. Folmar, and Peter J. Kleinman[1]

Abstract—Climate change has emerged as a key issue facing agriculture and water resources in the US. Long-term (1968-2012) temperature, precipitation and streamflow data from a small (7.3 km^2) watershed in east-central Pennsylvania was used to examine climatic and hydrologic trends in the context of recent climate change. Annual mean temperatures increased 0.38°C per decade, which led to an expansion of the growing season, and increased evapotranspiration (+37.1 mm per decade). Additionally, mean annual precipitation also increased while the overall change in streamflow decreased. In general, the findings suggest some challenges for producers and water resource managers with regards to increased rainfall and runoff. However, some changes such as an enhanced growing season can be viewed as a positive effect.

INTRODUCTION

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. The length of the growing season in the northeast has been increasing in response to the increase in minimum temperature throughout the northeast United States. Past climate change has also altered precipitation patterns and watershed hydrology, especially with regard to extreme events (Walsh and others 2014). On an annual basis, the total precipitation has risen at a rate of 9 mm per decade since 1900.

To date, much of the research on past climate change on agriculture and water resources has focused on a regional or national scale assessment (Horton and others 2014, Walsh and others 2014). While these assessments are important, they tend to average the effects of changing conditions over a large spatiotemporal scale and ignore specific impacts at local scales. Here, we present a holistic, long-term (1968-2012) analysis of climate and hydrologic trends (annual, seasonal, monthly and daily), in the WE-38 watershed, a long-term intensively monitored upland basin in the Appalachian mountain region of east-central Pennsylvania.

SITE

The WE-38 watershed is a 7.3 km^2 subcatchment of the Mahantango Creek watershed (420 km^2) located in the Ridge and Valley physiographic region of east-central Pennsylvania. 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 percent of total precipitation (Bryant and others 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 on shale and siltstone (125-300 m in elevation). The upland hillsides and ridges feature residual soils derived from sandstones and shales that are well drained and possess high infiltration capacities. In contrast, soils in the lower landscapes and valley bottoms are typically derived from colluvial deposits and are characterized by poor drainage, perched water tables, and frequent runoff generation by saturation excess (Buda and others 2009, Gburek and others 2006).

[1]Ray Bryant, Soil Scientist, USDA Agricultural Research Service, Pasture Systems & Watershed Management Research Unit, University Park, PA 16802
Haiming Lu, Hydrologist, Nanjing Hydraulic Research Institute, State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing 210029, China
Kyle Elkin, Research Chemist, USDA Agricultural Research Service, Pasture Systems & Watershed Management Research Unit, University Park, PA 16802
Anthony Buda, Hydrologist, USDA Agricultural Research Service, Pasture Systems & Watershed Management Research Unit, University Park, PA 16802
Amy Collick, Research Hydrologist, USDA Agricultural Research Service, Pasture Systems & Watershed Management Research Unit, University Park, PA 16802
Gordon Folmar, Hydrologist, USDA Agricultural Research Service, Pasture Systems & Watershed Management Research Unit, University Park, PA 16802
Peter Kleinman, Soil Scientist, USDA Agricultural Research Service, Pasture Systems & Watershed Management Research Unit, University Park, PA 16802

Citation for proceedings: Stringer, Christina E.; Krauss, Ken W.; Latimer, James S., eds. 2016. Headwaters to estuaries: advances in watershed science and management—Proceedings of the Fifth Interagency Conference on Research in the Watersheds. March 2-5, 2015, North Charleston, South Carolina. e-Gen. Tech. Rep. SRS-211. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 302 p.

PROCEDURES

Precipitation, temperature and streamflow data were complied using data sets that included a minimum value data point of at least once per day. In all three cases, automated data collection systems were installed between 1996 and 1997 to monitor their respective parameters at 5 minute intervals.

For portions of data that were missing, standard data augmentation techniques were used to infill occasional data gaps that resulted from site damage, equipment failure, routine maintenance or extreme events (Buda and others 2011a, Buda and others 2011b). To replace daily missing values for precipitation, simple averaging methods were used (McCuen 1998, Dingman 2002). A series of linear regressions using predictive equations related several water measuring stations were used to fill in missing streamflow data. Data gaps in temperature less than 5 hours were replaced by linear interpolation while data gaps greater than 5 hours were not replaced.

In order to relate the data from WE-38, other climatic and hydrologic records from other measurement stations in the area were examined to determine an understanding of longer-term regional trends (i.e. those that extend prior to 1968). In total, four stations were used which gave temperature, precipitation and stream-flow. Using these data, a number of different temperature, precipitation and streamflow indices were calculated in order to describe how the climate and hydrology of WE-38 changed during the 45 year study period. The indices used in the study fell into three basic categories: 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; threshold tendencies, 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 percentile-based threshold indices, which describe the excellence rates (number of days) above or below a certain threshold (consecutive days with streamflow less than the 10th percentile of the distribution).

In addition to the indices described above, we also sought to assess long-term changes in watershed evapotranspiration in WE-38 as inferred by the water balance equation. All water balance equations were done on a calendar year basis to be consistent with the assessment of trends in precipitation and temperature.

Prior to conducting formal statistical analysis of the long-term trends, all of the climate and hydrologic data, as well as the indices derived from these data were organized into four temporal scales: daily, monthly, seasonal (summer, autumn, growing, etc.) and annual. Additionally, we also assessed climatic and hydrologic trends over the fixed-length growing (15 April - 15 October) and non-growing (16 October - 14 April) seasons based on average conditions in the region.

Trends in climate and hydrology for each of the four temporal scales discussed above were evaluated using the rank-based Mann-Kendall test (Hirsch and others 1982). The rate of change for each time series was determined using the Theil-Sen slope method (Theil 1950, Sen 1968), which calculated the median slope of all possible pairs of points in the data set. For graphical representation, LOWESS regression lines were plotted, as well as an 11-yr moving average (Cleveland 1979, Matonse and Frei 2013). The Mann-Kendall tests and Theil-Sen slope calculations were completed using the water quality package in the R software environment, while Origin software was used to plot the LOWESS regression lines and moving average trends.

RESULTS AND DISCUSSION

Temperature

Temperature patterns in the WE-38 watershed were generally consistent with those observed in the northeastern US, as well as nationally. Mean temperatures in the 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 year temperature monitoring period (fig. 1a).

The mean minimum temperatures also increased throughout the WE-38 watershed from 1978-2012. On an annual basis, mean minimum temperatures showed a smooth upward trend (0.43°C per decade) during the study period (fig. 1b), increasing at a rate faster than that of the annual mean temperatures. Increases in the mean minimum temperatures were evident for all three-month seasons, both growing and non-growing seasons, and annually.

Annual mean maximum temperatures in WE-38 increased along with annual mean and annual mean minimum temperatures, albeit at generally slower rates for the time scales of the period studied. Annual mean maximum temperatures rose steadily during the study period (fig. 1c), 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 autumn seasons. All of these months and seasons also had significant increases in mean minimum temperatures as previously discussed. However, there were no increases in

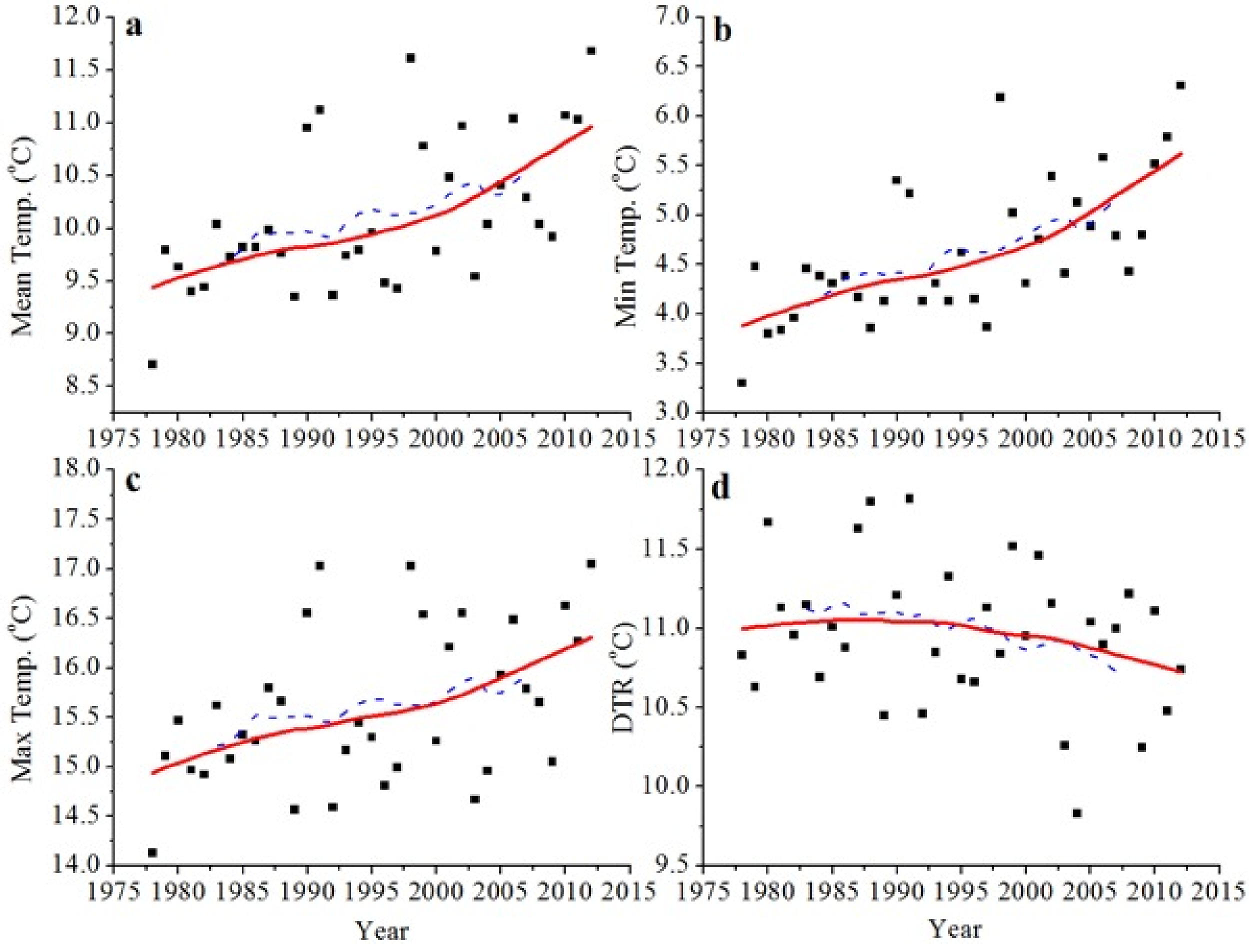

Figure 1—Long-term trends for the WE-38 watershed (1978 to 2012) in (a) annual mean temperature; (b) annual mean minimum temperature; (c) annual mean maximum temperature; and (d) diurnal temperature range (DTR). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

the mean maximum temperatures in June, July and August or in the summer season, all of which did show increases in mean minimum temperatures.

Disproportionate changes in maximum and minimum temperatures, as described above, resulted in a general declining trend in the diurnal temperature range over the extent of the watershed (fig. 1d). Diurnal temperature range decreased significantly in June and August as a result of increases in mean and 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, respectively. Notably, diurnal temperatures range increased in March and April as a result of greater increases in mean maximum temperatures relative to mean minimum temperatures.

Seasonal Changes and Core Indices

Indices of warm weather all increased in duration during the 1978 to 2012 study period. The lengths of warm season, growing season and summer season increased by 2.82, 2.83 and 4.00 days per decade, respectively, over the study period. The changes however, were not uniform over time. On average the summer season extended from early June to mid-September, but the start and end dates varied by one month. The length of the summer season (mean daily temperature over 13°C) increased continuously, but at a slightly accelerated rate after 1995 (fig. 2a). In addition, summer days (annual count of days with maximum temperature above 25°C) increased by 4.17 days per decade and tropical nights (annual count of days with minimum temperature greater than 20°C) increased 0.83 days per decade.

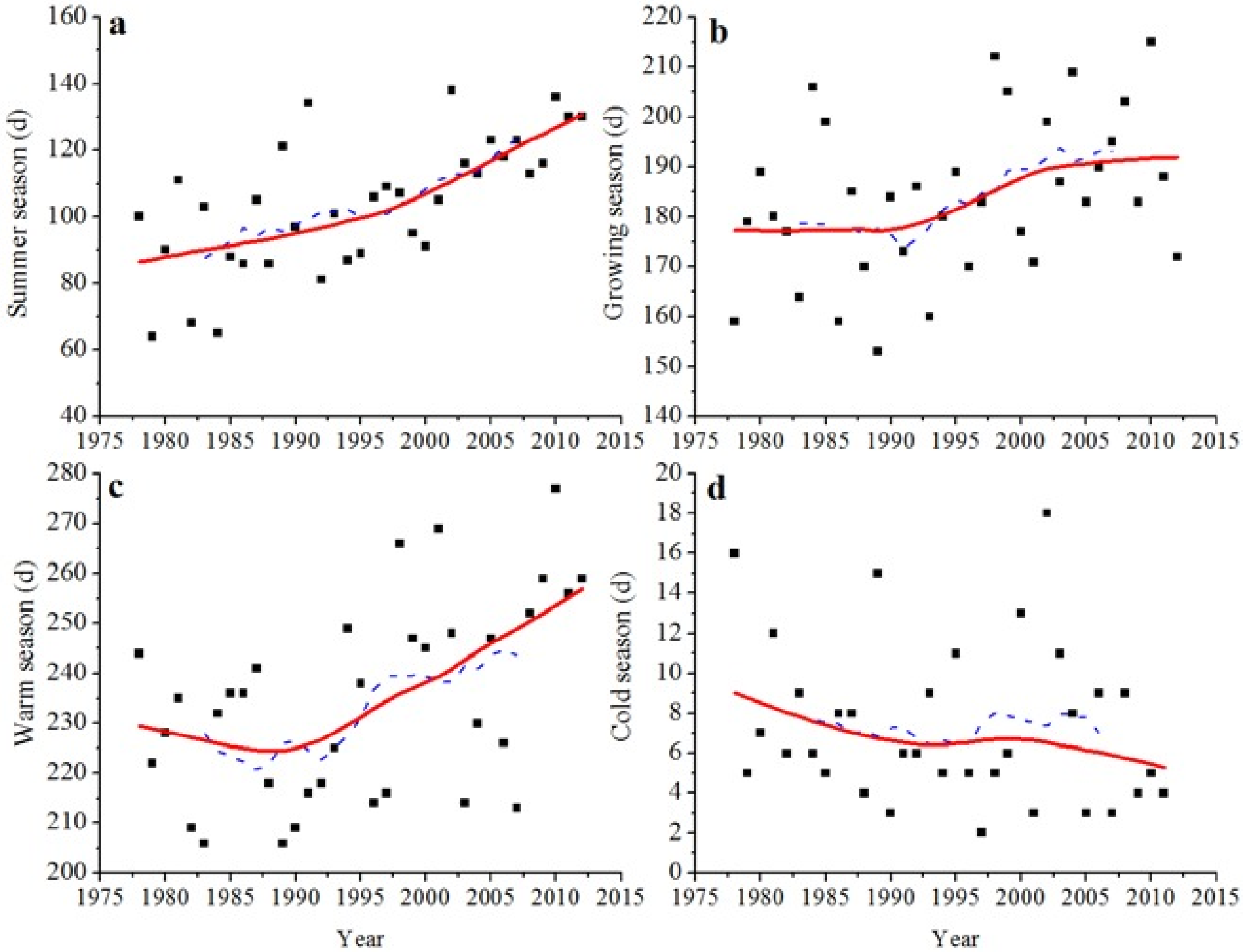

Figure 2—Long-term trends in temperature threshold indices in the WE-38 watershed (1978 to 2012) for (a) summer season; (b) growing season; (c) warm season; and (d) cold season. Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

The growing season (number of consecutive days with daily mean 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. 2b). 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. 2c). During the 1978 to 2012 period, the warm season began as early as late February and ended as late as mid-November.

In contrast, the duration of the cold weather periods in WE-38 trended shorter from 1978-2012. The average length of the cold season (consecutive days with daily temperatures below -5°C) ranged from starting as early as mid-December and ending as late as mid-February. The length of the cold season decreased at a fairly uniform rate (fig. 2d) of -0.74 days per decade, 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 -5.5 days per decade and at a uniform rate over the study period (fig. 3). Over the same period, the first freezing date in autumn occurred later at an average rate of 4.00 days per decade, and the rate of increase was greater after 1995 (fig. 3).

Precipitation

Total precipitation in WE-38 displayed inter-annual and seasonal variability over the 45 year study period. Annual total precipitation ranged from 710.3 mm to 1905.4 mm, with a mean of 1097.8 mm. Seasonally, total precipitation during the growing season (mid-April to mid-October) was 34 percent higher than during the non-growing season

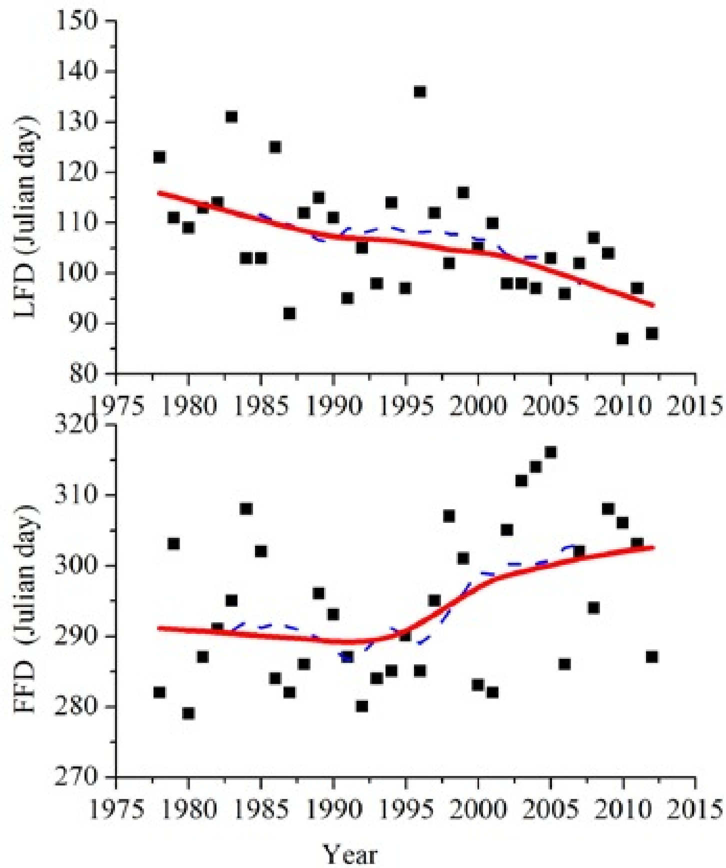

Figure 3—Long-term trends in the Julian day for last freezing date (LFD, top) and first freezing date (FFD, bottom) for the WE-38 watershed (1978 to 2012). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

with June being the wettest and February being the driest months (Table 1).

Total precipitation generally increased in the 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, however, 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. Notably, none of the four seasons showed significant changes in total precipitation.

Trends in intensity of precipitation at daily (d^{-1}) and hourly (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} per decade 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 autumn 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 in the non-growing season increased in December and January at rates of 0.61 mm h^{-1} per decade and 5.27 mm h^{-1} per decade, respectively (Table 1). Seasonal trends showed increasing hourly intensities of storm events in autumn, winter and spring, but no change in the 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, the number of days with intense rainfall remained largely unchanged during the 1968 to 2012 study period. Moderately heavy precipitation events became less frequent compared to days and event with heavier precipitation. Furthermore, days with trace and light precipitation showed opposing

Table 1—Trends in precipitation at various temporal scales in the WE-38 watershed (1968-2012). Slopes are expressed as a rate of change per decade. Slopes in red show trends with statistical significance at p<0.1.

Period		Mean precip., mm	Total precip., mm		PM1d, mm d^{-1}		PM1h, mm hr^{-1}	
			slope	p-value	slope	p-value	slope	p-value
Spring	Mar	83.13	2.3	0.27	-0.01	0.44	-0.08	0.3
	Apr	87.85	3.99	0.2	0.87	0.32	0	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	-0.3	0.41	-0.7	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	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	0.47	-0.39	0.38
Fall		297.64	7.49	0.21	**5.3**	**0.01**	**1.35**	**0.09**
Winter		208.5	4.22	0.31	0.15	0.11	**0.62**	**0.01**
Average growing season		629.11	5.2	0.4	0.7	0.37	0	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

trends during the study period with the number of days having trace precipitation increased at a rate of 0.354 days per decade. 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 precipitation that fell as light precipitation also declined. Light precipitation accounted for about 30 percent of the total.

Streamflow

Streamflow in the watershed varied seasonally and annually over the 45 year monitoring period (Table 2). Mean monthly streamflow showed strong seasonal variations typical for watersheds in the northeast US, with the lowest flows occurring in August (12.40 mm) and the highest flows occurring in March (77.83 mm). These streamflow variations 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 percent of annual precipitation) from 1968 to 2012, with inter-annual variability largely driven by annual precipitation. The lowest streamflow depth occurred in 2001 (207.4 mm), which was the drought of the study period. In contrast, 2011 saw the highest stream flow depth (1199.9 mm), which coincided with the wettest year in the study.

Total streamflow depth in WE-38 largely declined over the 45 year period (Table 2), with most of the 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. On a monthly basis, streamflow depth decreased most strongly during the month of February (-7.49 mm per decade). 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. 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.

Of the 45 year study period, 30 years had flood events with peak streamflow exceeding the 2.33 year return period. Each of these 30 flood events was either caused by a precipitation event that also exceeded the 2.33 year

Table 2—Trends in streamflow depth in the WE-38 watershed (1968 to 2012). Slopes are expressed as a rate of change per decade. Slopes in red show trends with statistical significance at p<0.1.

Period		Mean streamflow depth (mm)	Streamflow depth: Slope (mm)	Streamflow depth: 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	12.4	-0.74	0.17
Fall	Sep	28.32	-0.25	0.43
	Oct	30.84	**4.95**	**0.01**
	Nov	39.1	-0.23	0.5
Winter	Dec	56.49	1.78	0.3
	Jan	53.79	2.29	0.3
	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		509.2	-16.9	0.28

return period, or a rain-on-snow event. Notably, one of the largest floods in WE-38 occurred on January 19, 1996, and was due to rapid snowmelt induced by heavy rain. However, 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. Furthermore, the number of flood events that occur during the cold season when runoff is affected by snowmelt appears to be declining.

In WE-38, the average length of periods of low streamflow, represented by the maximum consecutive days during which mean streamflow was lower than the 10th percentile, was 16 days and ranged from 0 to 70 days (fig. 4). These low streamflow periods increased at an average rate of 1.9 days per decade over the study period. Annual evapotranspiration strongly increased in the watershed at a rate of 37 mm per decade (fig. 5).

CONCLUSIONS

The implications of climate change trends for agricultural production in WE-38 can be viewed as a net positive for the kind of row crop agriculture that is typical for 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. While warmer annual mean temperatures will result in greater evapotranspiration, monthly precipitation totals are also increasing, except for the wettest month of June.

Decreases in light precipitation events are welcome as they are less effective at supplying crop needs and with the total increase in precipitation, should be interpreted as an increase in more effective precipitation. Significantly wetter Octobers may complicate harvests, but the trend of the arrival of the first autumn freeze to occur later should mitigate this complication. The increase in intense

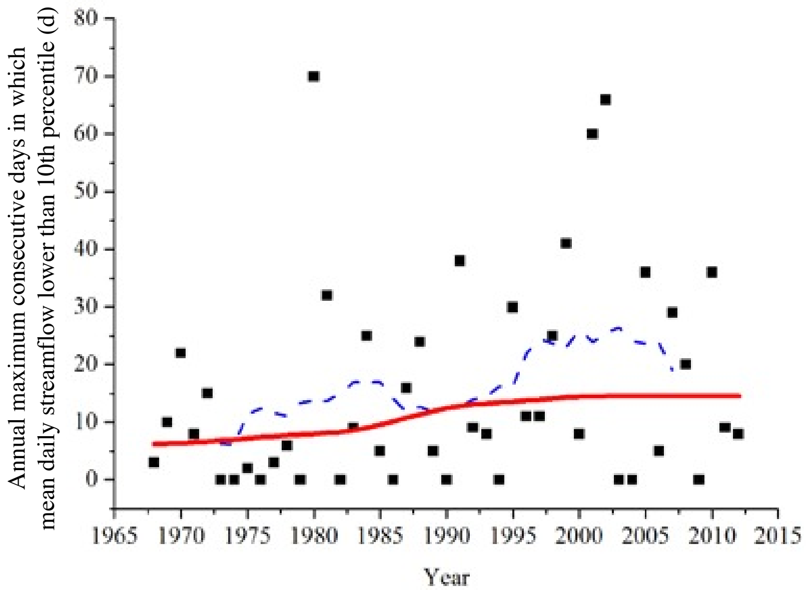

Figure 4—Long-term trends in the maximum annual consecutive number of days during which daily mean streamflow in the WE-38 watershed was lower than the 10th percentile (1968 to 2012). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

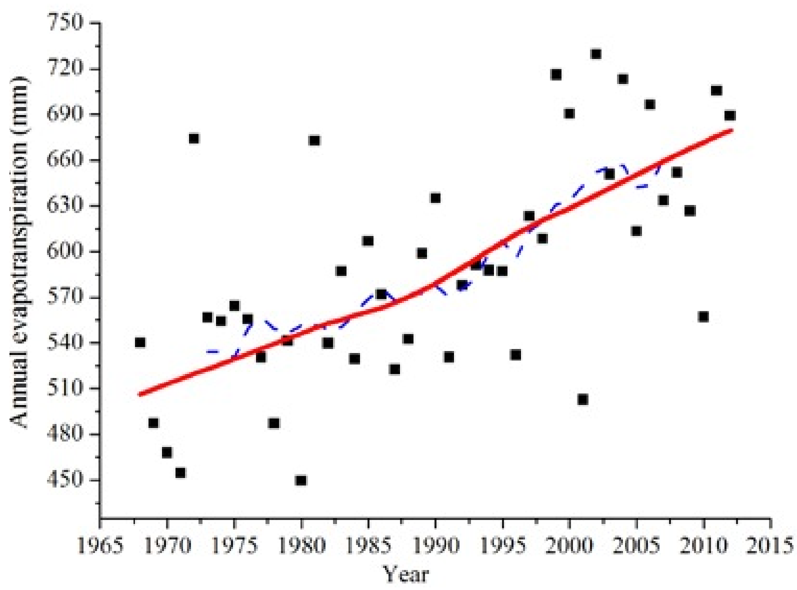

Figure 5—Long-term trends in annual actual evapotranspiration for the WE-38 watershed (1968 to 2012). Solid lines represent LOWESS regression trends and dashed lines indicate 11-year centered moving average trends.

precipitation events is indicative of a greater risk of crop damage, but is of limited geographical extent. However, the need for cost of crop insurance may become greater in response to this trend.

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 this. However, the decreasing snow accumulation that is being seen offer increased opportunities to spread manure during low runoff risk times.

In conclusion, the present and near term effects of climate change do not appear to present great challenges for agricultural production, water resources or the 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 was also granted by the China Scholarship Council, Nanjing Hydraulic Research institute (NHRI), and the China Special Fund for Water Resources Research in the Public Interest (201201026).

LITERATURE CITED

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: W08701.

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: W08702.

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: 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 hill slopes in central Pennsylvania. Hydrological Processes 23(9): 1295-1312.

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

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

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.

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.

Horton, R.; Yohe, G.; Easterling, W.; Kates, R.; Ruth, M.; Sussman, E.; Whelchel, A.; Wolfe, D.; Lipschultz, F. 2014. Chapter 16: Northeast. pp. 371-395 In: Melillo, J.M., Richmond, T.C., Yohe, G.W., eds. Climate change impacts in the United States: the third national climate assessment. U.S. Global Change Research Program.

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.

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

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.

Walsh, J.; Wuebbles, D.; Hayhoe, K.; Kossin, J.; Kunkel, K.; Stephens, G.; Thorne, P.; Vose, R.; Wehner, M.; Willis, J.; Anderson, D.; Doney, S.; Feely, R.; Hennon, P.; Kharin, V.; Knutson, T.; Landerer, F.; Lenton, T.; Kennedy, J.; Somerville, R. 2014. Chapter 2: Our Changing Climate. pp. 19-67 In: Melillo, J.M., Richmond, T.C., Yohe, G.W., eds. Climate change impacts in the United States: the third national climate assessment. U.S. Global Change Research Program.