Utilizing Long-Term ARS Data to Compare and Contrast Hydroclimatic Trends from Snow and Rainfall Dominated Watersheds

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Abstract

The U.S. Department of Agriculture–Agricultural Research Service, Northwest and Southwest Watershed Research Centers have operated the Reynolds Creek Experimental Watershed (RCEW) in southwestern Idaho and the Walnut Gulch Experimental Watershed (WGEW) in southern Arizona since the 1950s. Each watershed is densely instrumented with a variety of hydrometeorological instrumentation and has multiple gauged subwatersheds spanning a range of spatial scales. These watersheds have yielded an extensive knowledge base of watershed processes over multiple decades of use as outdoor hydrologic laboratories. Both research centers have published data reports in *Water Resources Research* describing the RCEW and WGEW and their associated characteristics and observational databases. Precipitation and runoff generation in RCEW is dominated by snow and snowmelt processes, while WGEW is dominated by thunderstorm-generated rainfall during the summer monsoon. Mean annual temperatures in the continental United States have increased from 1 to 3°C since the establishment of these experimental watersheds and this change has affected water supply, hydrology, and watershed response at both locations. This study compared and contrasted hydroclimatic variables at these experimental watersheds, including temperature, precipitation, and streamflow. Monthly, seasonal, and annual data of temperature, precipitation and runoff were tested for significant trends in these variables.

Keywords: experimental watersheds, trends, temperature, precipitation, runoff

Introduction

To understand how variations in climate, land use, and land cover will affect water supply, ecosystems, and natural resources, we must have access to long-term hydrologic and climatic databases. Data from watersheds that include significant human activities, such as grazing, farming, irrigation, and urbanization, are critical for determining the signature of human-induced changes on hydrologic processes and the water cycle. One of the primary components of effective watershed research is a sustained, long-term monitoring and measurement program. The U.S. Department of Agriculture–Agricultural Research Service (USDA–ARS) Experimental Watershed Network is one such example (Goodrich et al. 1994, Slaughter and Richardson 2000). Two of the ARS Experimental

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Watersheds in the Western United States will be featured in this study with the intent of expanding the analysis to other ARS watersheds in the future. They are the Reynolds Creek Experimental Watershed (RCEW), a 239-km^2 drainage in southwestern Idaho near Boise, and the Walnut Gulch Experimental Watershed (WGEW; 149 km^2) in southeastern Arizona near the town of Tombstone. These and the other ARS watersheds are operated as outdoor hydrologic laboratories in which watershed research is supported by long-term monitoring of basic hydroclimatic parameters.

RCEW consists of its drainage area and a third-order perennial stream draining north to the Snake River and ranges in elevation from 1,101 m above mean sea level (amsl) to 2,241 m amsl. About 77 percent of the watershed is under public ownership, with the remainder being privately owned. Primary land use of the watershed is livestock grazing with some irrigated fields along the creek at lower elevations. There is wide diversity in local climate, geology, soils, and vegetation across the Reynolds Creek landscape. Annual precipitation varies from 230 mm at the northern lower elevations to over 1,100 mm in the higher southern regions where 75 percent or more of annual precipitation occurs as snowfall. The ecology and hydroclimatology of RCEW are representative of much of the interior mountain west and Great Basin.

WGEW ranges in elevation from 1,220 to 1,950 m amsl. Its streams are ephemeral with uplands of desert shrubs dominating the lower two thirds of the watershed and desert grasses dominating the upper one third. The climate at WGEW is classified as semiarid with a mean annual temperature at Tombstone of 17.7^{o}C and mean annual precipitation of 312 mm. The precipitation regime is dominated by the North American Monsoon with about 60 percent of the annual total coming during July, August, and September. Summer events are localized short-duration, high-intensity convective thunderstorms, and winter storms are generally slower moving frontal systems. Virtually all runoff is generated by summer thunderstorm precipitation and runoff volumes, and peak flow rates vary greatly with area and on an annual basis.

More detailed descriptions of both RCEW and WGEW have been presented in special sets of papers in *Water Resources Research* (Slaughter et al. 2001, Moran et al. 2008). Research at RCEW continues to be supported by monitoring runoff at 9 weirs, 32 primary and 5 secondary meteorological stations, 26 precipitation stations, 8 snow courses and 5 snow study sites, 27 soil temperature and moisture measurement sites with 5 subsurface hill-slope hydrology sites, and 5 eddy covariance systems. WGEW contains 30 instrumented watersheds for runoff, of which 17 also monitor sediment, 88 precipitation gauges, 3 meteorological stations, 2 eddy covariance stations, and 24 soil moisture monitoring sites (5 with depth profiles). The objective of this study is to carefully examine observations common to both experimental watersheds to quantify the magnitude of climate warming and concurrent changes in precipitation and streamflow over the past 40 to 50 years.

Methods

Observations

Observations of daily maximum and minimum temperature (Tmax, Tmin), precipitation, and runoff were selected from RCEW and WGEW for slightly different time periods depending on installation of instrumentation, but most were initiated in the early to mid 1960s. For RCEW, temperature, precipitation, and runoff were analyzed for the period 1962–2006. Because of significant elevation change in RCEW and its importance to rain-snow precipitation phases, three meteorological stations and runoff weirs were selected, covering an elevation range of over 900 m. In RCEW, precipitation, Tmin, and Tmax observations were co-located. The low-elevation site (RC-Low, site 076, elevation 1,207 m) is located in a relatively broad, flat valley bottom only 108 m above, but nearly 10 km distant from, the RCEW outlet weir. Site vegetation is Wyoming big sagebrush and is typical of low elevations in RCEW. The mid-elevation site (RC-mid, site 127) is located on the eastern side of the basin near the midpoint elevation of the watershed (1,718 m). Site vegetation is dominated by low sagebrush and is typical of mid-elevation vegetation on the eastern side of RCEW. The high-elevation site (RC-high, site 176, elevation 2,093 m) is near the southern rim of the RCEW in an exposed area where a few trees and larger shrubs offer limited shelter from the wind. Site vegetation is a mix of shrubs including mountain big sagebrush, snowberry, and buckbrush. Adjacent to the site are Douglas fir and a few Aspen trees.

For WGEW, the long-term temperature observations are located adjacent to the ARS field headquarters in Tombstone. It is also adjacent to a large surface mining operation, and because of concerns about its affect on the temperature recording station, the Tombstone station was compared to 10 nearby long-term temperature records in Cochise County obtained from the National Climate Data Center. For the period 1961–2009, no significant differences between the Tombstone and adjacent records were found, but to minimize the impact of data gaps (approximately 10 percent of the data are missing) daily data were averaged for the 10 stations, not including any missing values. For precipitation and runoff, three subwatersheds were selected, spanning a range of spatial scales (Table 1). Precipitation records were analyzed for the period 1957–2010 and runoff for the period 1964–2010.

Table 1. Streamflow measurement stations.

Experimental watershed	Name	Elev. (m)	Drainage area (km^2)
RCEW	Reynolds Mtn. East	2,022	0.39
	Tollgate	1,404	55.0
	Outlet	1,099	238.0
WGEW	WG11	1,427	6.35
	WG6	1,334	81.5
	WG1	1,219	131.0

In RCEW, point measurements of precipitation were used from the same meteorological stations where temperature was recorded. For WGEW, areal average precipitation depths were computed over the three subwatersheds using the dense rain gauge network (approx. 0.570 gauges per 1 km^2) according to the procedure described in Goodrich et al. (2008).

Trend Analysis

Each daily time series was aggregated into months, seasons of a water year, and water years for trend analysis. The three-month seasons, starting from the beginning of the water year, are October, November, and December (OND); January, February, and March (JFM); April, May, and June (AMJ); and July, August, and September (JAS). Trends in air temperature, snow, and streamflow data were computed using two methods: least square (LS) linear regression and Sen's slope (SS) estimator. Although the LS method is in common use, the slope of the regression can be sensitive to autocorrelation and extreme values.

To address this problem, Hirsch et al. (1982, 1991) proposed Sen's slope estimator (Sen 1968), a nonparametric method to detect and estimate the magnitude of temporal trends in hydrologic data. This method computes slopes between all data pairs and estimates the overall representative slope as the median value among all possible slope values.

Following the analysis presented by Nayak et al. (2010), significance of these trends will be evaluated using the nonparametric Mann-Kendall statistic at α = 0.10, 0.05, 0.01, and 0.001 levels (Hirsh and Slack 1984, Yue et al. 2002 a). This statistic has the advantage of testing for consistency in the direction of change for temporally ordered data and is unbiased by the magnitude of change. Two methods will be applied to reduce the influence of autocorrelation on statistical significance of trends in time series data. First, the Mann-Kendall test with prewhitening (MK-PW), as suggested by Zhang et al. (2001), will be applied to eliminate the effects of serial correlation in the Mann-Kendall test. Second, the trend free prewhitening (MK-TFPW) approach (Yue et al. 2002 b) will be applied to minimize the effect of the MK-PW approach on the magnitude of the slope and significance of the trend present in the original data series. This approach also nonparametrically scores the significance of the trend with a sequence of symbols from weak to strong— +, *, **, *** —corresponding to the MK-TFPW test at significance levels of α = 0.10, 0.05, 0.01, 0.001, respectively.

Results

Temperature

In Figure 1, the average annual Tmin and Tmax temperatures are plotted as a function of time for the mid-elevation RCEW station (RC-mid, elevation 1,652 m) and for the average of the 10 Cochise County stations in and surrounding WGEW (WG-CC) with computed trend lines from the Sen's slope estimation method.

There was a significant increasing trend in temperature for the annual average series with a slightly stronger trend in the Tmin series (Table 2). At the seasonal level, significant increasing trends in Tmin were observed for all seasons and stations except the RCEW-Low station and the WG-CC stations during the water year season OND. Significant trends in Tmax were weaker in the case of the WG-CC data: MK-TFPW of * instead of ** or ***. In RCEW, the Tmax trends were significant in the summer (JAS) at all three elevations and in the fall (OND) and winter (JFM) at RC-High. In RCEW, the increasing temperatures had a profound effect on changing the phase of precipitation from snow to rain with the mid- and low-elevation

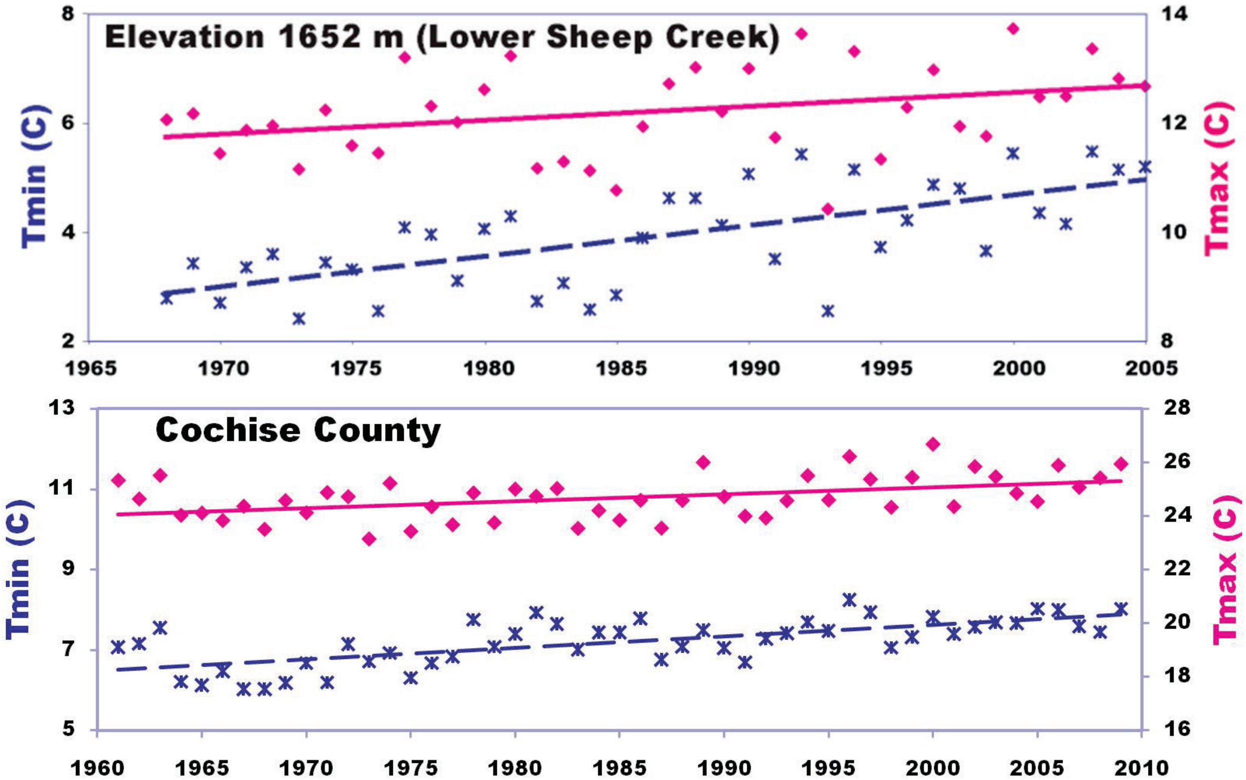

Figure 1. Average annual maximum and minimum daily temperatures for RC-Mid and WG-CC.

stations becoming dominated by rainfall in the later record. Nayak et al. (2010) discusses this result in more detail as well as its effect on snow-water equivalent trends.

Table 2. Annual average trends in Tmin and Tmax.

Station	Elev. (m)	Tmin Slope (°C/dec)	Tmin Trend sig.[a]	Tmax Slope (°C/dec)	Tmax Trend sig.[a]
RC-High	2,093	0.45	**	0.35	**
RC-Mid	1,652	0.57	**	0.29	**
RC-Low	1,200	0.36	**	0.20	*
WG-CC[b]	--	0.29	***	0.26	**

[a](MK-TFPW) test significance level: * for α = 0.05, ** for α = 0.01, and *** for α = 0.001

[b]10 Stations in and around the WGEW in Cochise Co.

Precipitation

Very few significant trends in precipitation were detected for either RCEW or WGEW. In WGEW, only a weak (+) to moderately (*) significant trend was found for February precipitation over each of the three subwatersheds. However, precipitation in February comprises just over 5 percent of the annual average and is characterized by low-intensity frontal storms that rarely generate any runoff. An increasing trend in non-summer precipitation for a group of WGEW raingages for the period from 1956 to 1996 was also found by Nichols et al. (2002). However, when an additional 10 years of data were analyzed by Goodrich et al. (2008), there was no trend, due to the influence of multiyear droughts in the more recent data.

Few statistically significant temporal trends (α = 0.10) were found in RCEW. A slight decline during the summer months of approximately 1 percent was the only significant trend. Note that summer precipitation represents a small fraction of annual precipitation, so the affect on other seasons is not significant (at the 90-percent level). The decrease in summer precipitation represents a redistribution of water year precipitation to fall and spring at mid to high elevations (Nayak et al. 2010).

Runoff

At RCEW, most of the flow during a water year occurs from March to June. During these months, nearly 90 percent of annual streamflow occurs at the high-elevation Reynolds Mountain East (RME) weir, 82 percent at the mid-elevation Tollgate (TG) weir, and 70 percent at the RCEW outlet weir. Variation of annual runoff volume is very large, with standard deviations of at least 50 percent of the annual mean at all sites. The Sen's slope values were negative over the 1962–2006 period of record for all three weirs (Table 3). However there were no significant temporal trends. At the monthly scale, streamflow has shifted toward earlier periods with a shift to late winter and early spring flows at the RME and TG weirs. Streamflow has increased in March and April and decreased in May and June. At the RCEW outlet weir, consistency in trends is less conclusive, with an increase in May flow as the only significant trend (* with $\alpha = 0.05$). It should be noted that spring and summer diversions to irrigation below the TG weir likely confounded trend analysis at the outlet weir. Examined in the context of elevation, there is a strong gradient to this shift. The high-elevation RME weir exhibits a weak but significant (+ with $\alpha = 0.10$) increase in flow in March and April, but the mid-elevation TG weir has significant (* with $\alpha = 0.05$) increase in April flow. The outlet weir exhibits a significant (*) increase in flow in May (Nayak et al. 2010).

Table 3. Water year stream discharge trends.

Watershed	Mean (10^6 m^3/WY)	Stream discharge	Sen's slope (10^6 m^3/decade)
Reynolds Mtn. East	0.21	0.10	–0.008
Tollgate	13.4	7.5	–0.75
Outlet	17.1	12.4	–1.66
WG11	0.066	0.10	–0.013
WG6	0.40	0.44	–0.040
WG1	0.37	0.38	–0.038

In WGEW, on average, there are roughly nine runoff events per year from each of the subwatersheds. Virtually all runoff occurs from the summer monsoon, and infrequent runoff occurs in the early fall as a result of tropical cyclones. While the onset of the monsoon is variable from year to year, the summer months of July, August, and September (JAS) typically contain the monsoon season and therefore almost all runoff production. Like RCEW, the Sen's slope values were negative over the 1964–2010 period of record for all three subwatersheds during this season (Table 3). The trends for WG1 and WG11 were found to be weakly (+) and moderately (**) significant, respectively, and the trend for WG6 was not significant. At the monthly level, a strongly significant (**) decreasing trend was found for all three subwatersheds for the month of September, which appears to be counterintuitive to the findings of Grantz et al. (2007). They found a significant delay in all stages of the monsoon in recent decades with a decrease in rainfall during July and an increase in rainfall during August and September. However, intrastorm precipitation intensity is the primary determinant of runoff generation.

Conclusions

RCEW and WGEW both exhibit moderate to strongly significant trends of increasing temperature that are in agreement with other studies of temperature trends in the western United States and Canada (e.g., Trenberth et al. 2007). The rate of increase in Tmin at the annual temporal scale (+0.29 to 0.57°C per decade) is greater than Tmax (+0.2 to +0.35°C per decade). In RCEW, this has resulted in the crossing of important thermal thresholds. Consequently, the snow season is at least a month shorter than it was in the mid 1960s (Nayak et al. 2010). As rain becomes a larger proportion of the total annual precipitation, runoff occurs earlier in the year.

Changes in precipitation and runoff in the WGEW were less pronounced. While there were moderately significant trends of decreasing runoff in September, it is unclear if this is related to changes in the seasonal onset of the monsoon or a change in rainfall intensity. These decreases will be investigated in more detail in future work. Sensitivity of watershed response will also be examined using runoff to rainfall ratios for each of the watersheds. This study will require improved methods to determine the spatial distribution of precipitation, which is especially challenging in the RCEW where wind-driven redistribution of snow is common. Trends in extremes will also be investigated. Extension of this work to ARS and other experimental watersheds across a wide range of hydroclimatic regions will then be undertaken.

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