

Long-term Forest Management and Climate Effects on Streamflow

Shelby G. Laird, C.R. Ford, S.H. Laseter, J.M. Vose

Abstract

Long-term watershed studies are a powerful tool for examining interactions among management activities, streamflow, and climatic variability. Understanding these interactions is critical for exploring the potential of forest management to adapt to or mitigate against the effects of climate change. The Coweeta Hydrologic Laboratory, located in North Carolina, USA, is a 2,185-ha basin wherein forest climate monitoring and watershed experimentation began in the early 1930s. Extensive climate and hydrologic networks have facilitated research in the basin and region for over 75 years. Our purpose was (1) to examine long-term trends in climate and streamflow in reference watersheds, and (2) to synthesize recent work that shows that managed watersheds respond differently to variation in extreme precipitation years than reference watersheds. In the basin and in the region, air temperatures have been increasing since the late 1970s. Drought severity and frequency have also increased over time, and the precipitation distribution has become more variable. Reference watersheds indicate that streamflow is more variable, reflecting precipitation variability. Streamflow of extreme wet and dry years show that watershed responses to management differ significantly in all but a forest with coppice management. Converting deciduous hardwood stands to pine altered the streamflow response to extreme precipitation years the most. High evapotranspiration rate and increased soil water storage in the pine stands may be beneficial to reduce flood risk in wet years, but they create conditions that could exacerbate drought. Our results suggest that forest management can mitigate extreme

precipitation years associated with climate change; however, offsetting effects suggest the need for spatially-explicit analyses of risk and vulnerability.

Keywords: climate, long-term monitoring, streamflow, forest management, watershed

Introduction

Climate change projections suggest significant changes in temperature (e.g., 2–9°F, or 1–5°C) and precipitation over the next several decades (U.S. Global Change Research Program 2009). Land managers and policy makers are challenged to develop adaptation and mitigation strategies to protect and ensure long-term forest health and sustained ecosystem services. Changing climate is one among many current and potential future threats to the sustainability of forest water resources. Population growth has increased demand for clean water, and pressures from sprawling metropolitan areas, interbasin transfers, and wastewater discharge are all threats to water quality and quantity (Sun et al. 2008). Other threats and stressors include changes in land use, invasive species, and fire. Often these stressors occur simultaneously, making it difficult to distinguish the effects of one single threat on streamflow (Vose et al. 2011). Long-term watershed research can offer valuable insights into the interactions among forest stressors and streamflow, as well as management options that might help forests adapt to or mitigate the effects climate change on water supplies.

Detecting climate change effects in streamflow data is complex, since simultaneous changes in land use (e.g., urbanization and development) can occur, and the signal of the latter can be greater in magnitude than the climate change signal. Long-term data from forested watershed that have undergone little to no change in land use can provide a robust way to detect the climate change signal in streamflow. Paired watershed studies that implement forest management regimes while accounting for climate variation are also a powerful means to investigate the effect of both management prescriptions and climate change on streamflow. Both

Laird is a postdoctoral research fellow with Auburn University stationed at Coweeta Hydrologic Lab. Email: sgl0001@auburn.edu. Ford is a scientist, Laseter is a hydrologist, and Vose is a research scientist and project leader, all with the U.S. Department of Agriculture, Forest Service, Southern Research Station, Coweeta Hydrologic Lab, 3160 Coweeta Lab Road, Otto, NC 28763.

approaches require sufficient length of records to allow effects to be detected. Without long-term data from research watersheds where land use is either constant or well documented, climate and management trends on streamflow may be difficult to identify (Burt 1994).

Streamflow responses to climate change are strongly related to changes in local precipitation, but are less so for temperature; however, the magnitude and timing of response may differ with different forest structure and species. Regions of the United States have shown both increasing precipitation and streamflow (Genta et al. 1998, Kiley 1999, Groisman et al. 2004) and decreasing water yield (National Research Council of the National Academies 2008), requiring further investigation and data collection to confirm regional effects. These large differences may be due to the highly variable precipitation changes. A larger portion of the available research attempts to predict streamflow, water supply, or water resources in relation to precipitation changes from various climate change scenarios (Milly et al. 2005, Moreau 2007, Seager et al. 2009). These models also show variable response to climate change due to a broad range of predictions for future precipitation.

Our objectives for this paper are (1) to present long-term climate trends from the Coweeta Hydrologic Laboratory, (2) to examine streamflow patterns in two control watersheds, varying in elevation, and (3) to discuss management strategies to adapt to or mitigate the effects of climate change on forested watersheds.

Methods

Site Description

Coweeta Hydrologic Laboratory is a U.S. Forest Service Southern Research Station Experimental Forest located in the Nantahala Mountain Range of western North Carolina, USA (Figure 1). Coweeta has been the focus of watershed experimentation since 1934. The Coweeta basin is 1,626 ha; elevations range from 675 to 1,592 m. Historic vegetation patterns have been influenced by human activity, primarily through both clearcut and selective logging, the introduction invasive species (Elliott and Hewitt 1997, Nuckolls et al. 2009), and fire (Hertzler 1936, Douglass and Hoover 1988). Forests on reference watersheds are relatively mature (approx. 85 years old) oak-hickory (at lower elevations) and northern hardwood species (at higher elevations) (Elliott and Swank 2008).

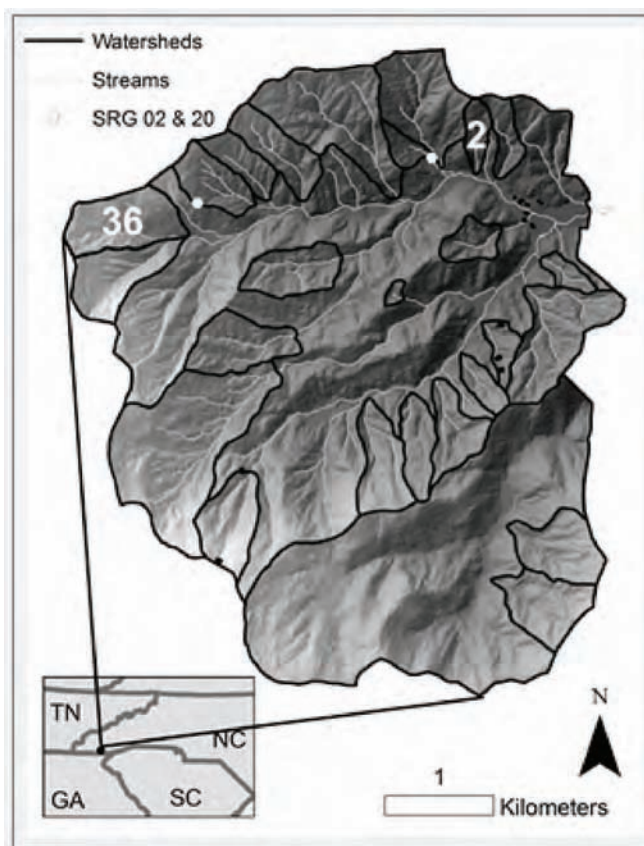


Figure 1. Map of the Coweeta Hydrologic Laboratory showing elevation gradients and main and subwatersheds. Watersheds 2 and 36 are labeled. (SRG, standard rain gauge)

Climate

Daily air temperature and precipitation have been recorded at the Coweeta main climate station (CS01) continuously since 1934. Temperature is recorded daily at 8 a.m. Eastern Standard Time using a National Weather Service (NWS) maximum, minimum, and standard thermometer. Total daily precipitation is collected in an 8-inch standard rain gauge (NWS). Recently, Laseter et al. (in review) presented the long-term trends in climate. We present a subset of those trends herein for comparison purposes.

Streamflow

To assess long-term trends in streamflow related to climate, we analyzed streamflow data from two control watersheds at Coweeta, watersheds 36 and 2 (Figure 1). The watersheds have similar aspects but varying elevations (Table 1). Streamflow data have been collected every 5 min since January 1936 for watershed 2 (WS2) and since May 1943 for watershed 36

(WS36). Both watersheds have remained undisturbed since the late 1920s, with the minor exception of a partial defoliation of WS36 by cankerworm from 1972 to 1979. Both watersheds consist of mixed hardwood forest, though the higher elevation watershed (WS36) contains northern hardwood community species.

Table 1. Characteristics of two control watersheds.

	WS 2	WS 36
Max elevation (m)	1,004	1,542
Elevation at weir (m)	709	1,021
Area (ha)	12	49
Aspect	SSE	SSE
Closest standard rain gauge (SRG)	20	02

Data from the closest standard rain gauge near each watershed were assumed to be representative of rainfall across the watershed. Standard rain gauge (SRG) 02 was used for watershed 36 and SRG 20 was used for watershed 02 (Figure 1).

We analyzed time trends in two ways. First, precipitation was regressed directly against streamflow using simple linear regression. The fit of the relationship was analyzed by looking at residuals and other possible variables of influence, including temperature (not discussed). Secondly, we calculated a runoff coefficient (RO/P) index for the two control watersheds by dividing annual streamflow (RO) by annual precipitation (P). From a simple mass hydrologic balance, streamflow output is the balance of

precipitation inputs minus evapotranspiration (ET) losses: $RO = P - ET$. The ratio of RO to P is thus the fraction of rainfall that appears as streamflow. We used a penalized B-spline curve to analyze any possible trends in the runoff coefficient over time. Spline fit used default and custom settings for SAS 9.2, including 3 degrees, 10 control points (knots), and weight of 0 to characterize the spline curves.

Management

The interaction of management and climate was determined recently by Ford et al. (in press); they analyzed data from six paired treatment and reference watersheds throughout the Coweeta basin. They modeled the responses of streamflow to vegetation and climate. Management included species conversion, clearcuts on high and low elevation, coppice, and old field succession. We present some of the results of that study herein for comparison purposes.

Results and Discussion

Long-Term Climate

Climate data from Coweeta shows that average maximum, annual, and minimum air temperatures have increased significantly relative to the long-term mean, appearing to begin in the late 1970s (Figure 2). The rate of increase is about 0.5°C per decade beginning in the mid 1970s.

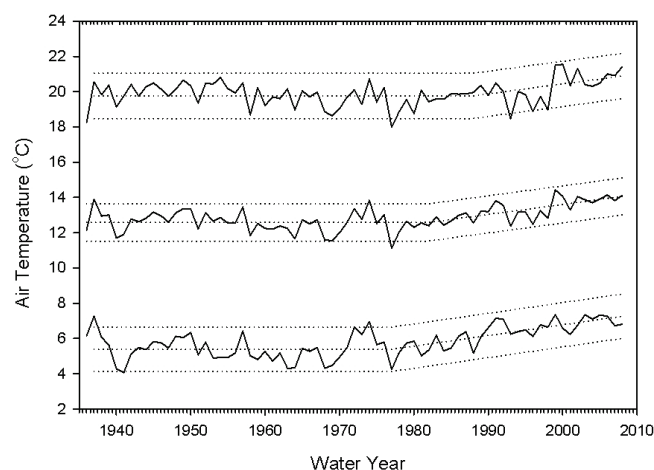


Figure 2. Long-term average maximum (top), annual (middle), and minimum (bottom) air temperatures at Coweeta Hydrologic Laboratory climate station CS01 in Laseter et al. (in review).

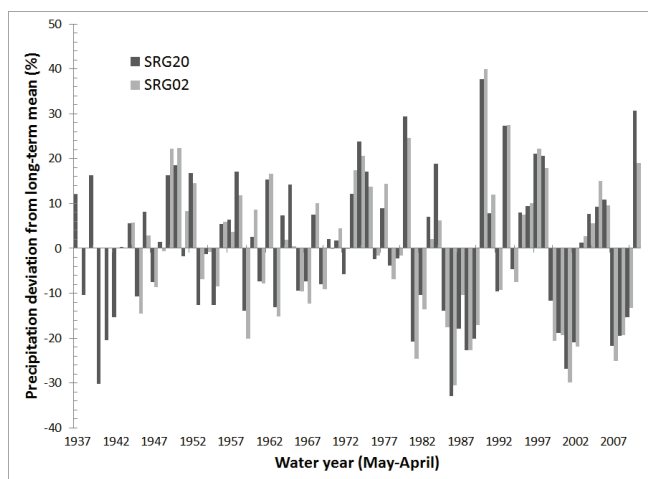


Figure 3. Deviation of annual precipitation totals from the long-term mean recorded at Coweeta Hydrologic Laboratory standard rain gauges 02 and 20.

Coweeta has some of the highest annual precipitation amounts in the eastern United States, averaging 1,794 mm/yr. Analyses of long-term precipitation suggest no significant change in mean precipitation at Coweeta (Ford et al., in press; Laseter et al., in review); however, the variability of precipitation is changing over time. For example, extreme annual precipitation (i.e., low and high rainfall) event years are occurring more frequently with time (Figure 3), which has resulted in increased recent drought severity and frequency (Laseter et al., in review).

Long-Term Streamflow

Streamflow data indicate similar trends to those found in precipitation data, including increased variability since the 1970s, largely due to the strong linear relationships between precipitation and streamflow for the two control watersheds (Figure 4). The higher elevation watershed 36 predicted streamflow or runoff is $RO'_{36} = 0.92P - 204.77$ ($R^2=0.68$, $p<0.01$), and the lower elevation watershed 02 predicted streamflow is $RO'_{02} = 0.71P - 626.87$ ($R^2=0.78$, $p<0.01$).

For any given amount of precipitation, annual streamflow on the higher elevation watershed (WS36) is at least 500 mm greater than that for the lower elevation watershed (WS2), and differences become even greater at higher amounts of precipitation. Greater streamflow per unit precipitation at the higher elevation WS36 is related to a combination of factors that reduce

ET, including a shorter growing season, differences in species composition, and indirectly steep slopes and shallow soils.

Runoff coefficient analysis shows a clear upward then downward trend over time (Figure 5), which is most well defined in WS02. Simple spline curves were used for graphical display of the trends in data, which will be more completely analyzed in further study. Trend lines for both watersheds suggest decreases in the fraction of precipitation that ends up as streamflow, and hence increases in ET, over time. Our data show an increase up to the mid 1970s, followed by a leveling off or slight decrease thereafter. Decline in the runoff coefficient for WS02 is greater than that for WS36. The declining trend seems to begin in both watersheds around 1980 and may coincide with a drought that occurred at that time. More research is needed to determine the causes of this declining ratio.

Temporal variation in RO/P suggests that either biological or physical factors are changing the rainfall-runoff relationship in both WS2 and WS36. We suggest that most of this variation is due to changes in climatic driving variables and (or) structural and functional attributes that determine ET. For example, data from long-term vegetation plots indicate changes in species composition (Elliott and Vose 2011), with subsequent effects in transpiration (Ford et al., in press). Due to the nature of reference watersheds, the runoff coefficient

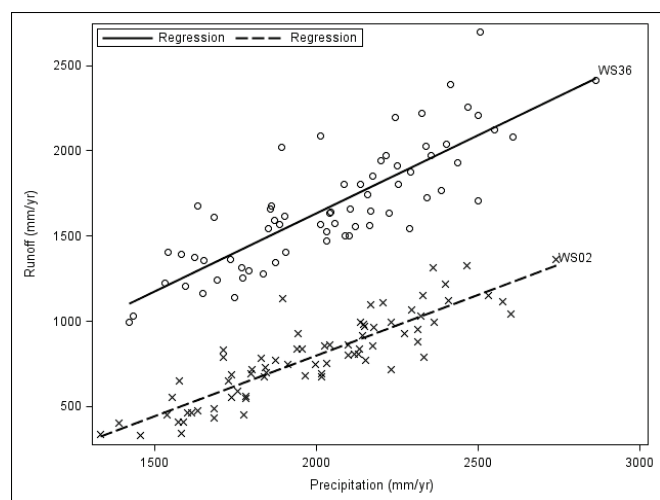


Figure 4. Precipitation versus streamflow for watersheds 36 and 2.

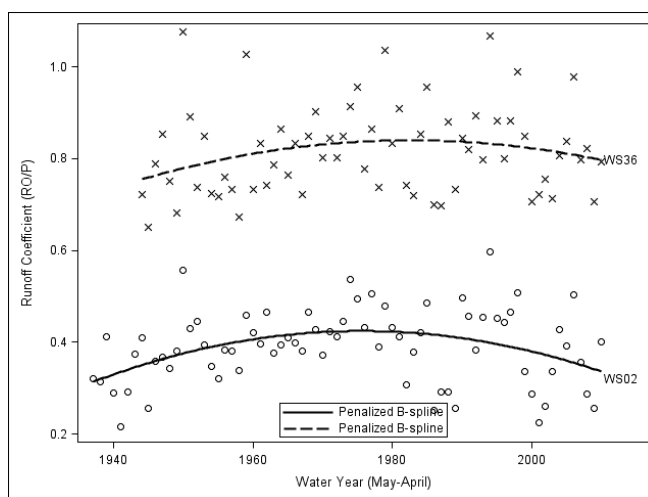


Figure 5. Runoff coefficient (RO/P) over time with penalized B-spline curves to show trends over time. RO/P increases through the first part of the period of record until about 1980, when a decrease is shown for both watersheds.

is a variation of ET adjusted for P. In an altered watershed where roads, compaction, altered flow paths and other interference factor in, the runoff coefficient then represents much more than ET.

Management Implications

In each of the management scenarios, management significantly altered the expected level of streamflow (Figure 6). All watersheds showed significant declines in streamflow excesses over time compared to what would have been expected, with most managed watersheds returning to near expected levels of streamflow within a decade.

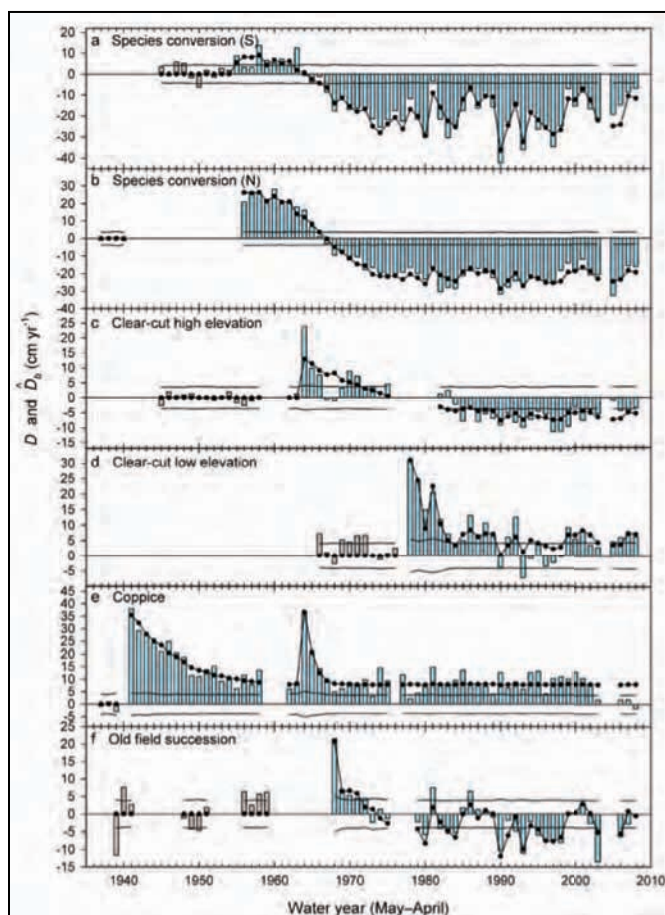


Figure 6. Streamflow response to six management treatments. Bars show observed streamflow excesses (D) during pretreatment (grey) and posttreatment (cyan) years. Solid lines show bounds of prediction interval. Filled symbols and lines show modeled streamflow responses ($\hat{D}_b$). From Ford et al. (in press).

Some management options, such as species conversion to pine, created persistently lower levels of streamflow than expected following canopy closure until the end of

the record. A coppice forest management strategy allowed for a long-term higher streamflow than the expected levels. Other management strategies eventually returned streamflow to near those expected.

Conclusions

Long-term climatic records indicate warming and increased variability in annual precipitation over the past three decades. The combination of reference and managed watersheds provided a unique opportunity to examine streamflow responses to this variation and examine interactions between management activities and climate.

Precipitation explained a significant portion of the variation in streamflow response for the control watersheds. Runoff coefficients initially increased then declined over time, suggesting corresponding changes in ET over time. The change from an increasing trend to a decreasing trend with time coincided with drought increases in the 1980s and increasing temperature in the late 1970s.

Different forest management strategies could potentially mitigate or exacerbate effects associated with climate change. Forest management affects the vegetation structure and function of the watershed. Streamflow responses depended on the management treatment, and they could be used to mitigate climate change effects. Looking purely at water quantity shows forest management can mitigate for extreme precipitation events in a changing climate. However, these changes should be taken in context with other factors such as carbon sequestration, local climate, and water quality.

Long-term data such as those recorded at Coweeta Hydrologic Laboratory show the trends over time that can sometimes be difficult to resolve in shorter temporal datasets. When managing a forest over the long term, corresponding data collected over the time period of management is key to understanding the full scope of forest development on water resources.

Acknowledgments

This research was supported by the U.S. Department of Agriculture Forest Service, Southern Research Station and by National Science Foundation grant DEB0218001 to the Coweeta Long-Term Ecological Research program at the University of Georgia. We thank Ge Sun and Tony Crump for helpful review/comments.

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Proceedings of the Fourth Interagency Conference on Research in the Watersheds

Observing, Studying, and Managing for Change

Edited by C. Nicolas Medley, Glenn Patterson, and Melanie J. Parker

Scientific Investigations Report 2011–5169

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Suggested citation:
Medley, C.N., Patterson, Glenn, and Parker, M.J., eds., 2011, Observing, studying, and managing for
change—Proceedings of the Fourth Interagency Conference on Research in the Watersheds: U.S. Geological
Survey Scientific Investigations Report 2011–5169, 202 p.

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