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Impact of weather and climate scenarios on conservation assessment outcomes

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Abstract: Selected watershed studies of the Conservation Effects Assessment Project (CEAP) are reviewed and findings are interpreted from the perspective of potential conservation outcomes due to climate change scenarios. Primary foci are runoff, soil erosion, sediment transport, and watershed sediment yield. Highlights, successes, and challenges with regards to climate change impacts on soil erosion, runoff, and watershed sediment yield are presented. The covered information adds to the existing knowledge base of climate change impacts and provides another piece of information that may be useful in the planning and management of agricultural watersheds; assessment of conservation needs; and development, funding, and implementation of conservation programs. The selected conservation assessment studies include, among others, a thought experiment on the sensitivity of soil erosion, runoff, and sediment yield to changes in rainfall; a computer-based investigation of potential climate change effects on runoff and soil erosion in a southeastern Arizona rangeland; the complex response of northern Mississippi watersheds to runoff variations and channel stabilization measures; the impact of conservation practices and a persistent pluvial period on watershed runoff and sediment yield in Oklahoma; and stream bank erosion during major flooding in Iowa and river corridor management. A study of rainfall-runoff in a north-central Missouri watershed and a curve number analysis in a northern Appalachian experimental watershed are included herein. Findings showed that climate change scenarios of increased precipitation intensity lead to an exponential increase in soil erosion, runoff, and watershed sediment yield, thereby stressing current conservation practices or future practices designed with present day practice standards. This diminishes conservation practice effectiveness and increases sediment supply to the stream network. The sensitive response of the watershed hydrologic system may lead to renewed soil erosion that is large enough to offset the reduction in soil loss achieved by current conservation practices. However, in alluvial-floodplain environments with non-cohesive bed and bank material, watershed sediment yield is controlled by channel discharge and energy slope, neither of which is influenced by traditional in-field conservation practices or channel bank stabilization structures. Thus, control of sediment yield will gradually shift in the downstream direction from sediment supply to sediment transport capacity and blur any existing relation between a climate change signal, in-field conservation outcomes, and sediment yield at watershed outlets. Targeting conservation practices to erosion prone areas, expanding conservation coverage, and adapting agronomic practices may be necessary to prevent excessive soil erosion and downstream sedimentation under climate change scenarios that include intensified precipitation.

Key words: conservation effectiveness—Conservation Effects Assessment Program—climate impacts—runoff—sediment yield—soil erosion

Conservation Effects Assessment Project (CEAP) watershed studies address impacts of climate scenarios on environmental benefits, effectiveness of conservation practices, and soil assessment outcomes on agricultural landscapes. In the early 1900s, mechanization opened the door

to large-scale intensive agriculture in the United States. Within a few years, accelerated soil erosion became a major problem that culminated with the Dust Bowl (Phillips and Harrison 2004). Soil conservation and flood prevention programs were developed and gradually implemented over the next six

decades, changing much of the rural landscape. By the time of the 1996 Farm Bill, annual funding of conservation title programs was large enough to trigger mandates for cost-benefit analyses of conservation programs. In response, the CEAP was initiated in 2003 to provide an accounting of environmental benefits and effectiveness of conservation practices on agricultural landscapes (Mausbach and Dedrick 2004; Duriancik et al. 2008).

The distinct possibility that climate change may already be occurring (Karl and Knight 1998; Groisman et al. 2005) introduced another dimension and challenge to the assessment and interpretation of the effectiveness of conservation programs (Delgado et al. 2011). The Intergovernmental Panel on Climate Change (IPCC) reported that global climate change was intensifying the hydrologic cycle (IPCC 2007) with projected precipitation and frequency of extremely wet seasons to increase over much of the United States (Christensen et al. 2007). Temperatures will continue to rise in the near future (Dore 2005; Tebaldi et al. 2006), and precipitation trends are uncertain and may increase or decrease for various locations and seasons (Hayhoe et al. 2007; Diodato and Bellocchi 2009; Campbell et al. 2011; Garbrecht et al. 2014). Intensified precipitation and increased frequency of extreme events would likely result in more runoff, higher soil erosion rates, potentially severe gullying, and related off-site sedimentation problems (SWCS 2007; Zhang et al. 2010; Zhang et al. 2012; Dabney et al. 2012a).

The potential impacts of climate change on the effectiveness of field-scale conservation practices are complex and involve a great number of drivers, many physiographic variables, interdependencies, and feedback

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mechanisms (Delgado et al. 2011; Nearing et al. 2004, 2005). In addition to annual climate trends, seasonal changes in climate are of particular relevance for crop production systems (Hatfield et al. 2013) where agricultural producers themselves become drivers in the rainfall-runoff-erosion system as they adjust crop types, planting dates, and management in response to their perception of climate change (O'Neal et al. 2005).

At the watershed scale, climate change impacts on sediment yield are even more complex to predict. Mixing of sediments from different sources, fine sediment enrichment, preferential transport, sediment sorting, deposition, remobilization, periodic flushing, and sediment transport limited by capacity add to the difficulty in identifying and interpreting observed changes in watershed sediment yield (Pelletier 2012). Response of natural vegetative cover to seasonal shifts in temperatures, precipitation patterns, and frost events is difficult to predict. Detecting a climate change signal and conservation outcomes is made even more difficult by legacy geomorphologic channel instabilities that persist long after shifts in cultural and conservation practices occur. Together, all these runoff, erosion, and drainage processes contribute to obfuscate any existing relation between a climate change signal and watershed sediment yield. This makes it extremely difficult to attribute observed changes in watershed sediment yield to specific impacts of climate change on conservation outcomes.

Conservation Assessment Overview

In this investigation, selected CEAP watershed assessment studies that identify and interpret potential impacts of climate scenarios on conservation outcomes are discussed. Watershed assessment approaches, type of climate and hydrologic data used, complexity of various runoff-erosion-sediment transport processes involved, and extent of assessment findings are reviewed. Diversity and success of approaches used to infer impacts of climate scenarios on conservation outcomes are highlighted. The insights gained by this investigation can assist others in the selection of an appropriate climate impact assessment approach that matches the scope and objective of a particular conservation application. Examples of applications include development of alternative land management options for different climate

scenarios, assessment of effectiveness of current conservation practices under assumed future climate conditions, and estimation of funding and implementation needs for conservation programs that provide adequate protection under a changed climate.

The focus of this investigation is on the impact of climate scenarios on soil conservation outcomes. Hence, the primary watershed processes of interest are runoff, soil erosion, sediment transport, and sediment yield. Soil erosion is assumed to occur as a result of rainfall impact and surface runoff. Soil erosion in snow dominated environments and/or under frozen or freeze/thaw ground conditions are beyond the scope of this study. Direct climate change variables that impact runoff and soil erosion are rainfall intensity and frequency. Large rainfall events are of particular relevance as they produce the highest soil erosion and are often the design target for conservation practices. Temperature is considered an indirect climate change variable with regard to soil erosion as it affects ground cover which in turn protects the soil from rainfall detachment and slows surface runoff. Adjustments of crop types, planting dates, agronomic management, and other anthropogenic activities in response to climate change are considered. Complex, long-term biome responses associated with temperature change (e.g., plant community adaptation to a changed temperature or precipitation regime) and long-term geomorphic evolution of the watershed drainage system associated with runoff change are beyond the scope of this effort.

Within this general framework, six selected CEAP watershed studies that address impacts of climate scenarios on soil conservation are reviewed. First, a simple thought experiment is conducted to estimate the sensitivity of hillside and channel erosion, runoff, and sediment yield to changes in rainfall intensity and frequency under highly simplified boundary conditions. Sensitivity estimates help identify erosion and drainage processes, and, by association, conservation outcomes, that are most susceptible to climatic change. This empirical-conceptual analysis is followed by a computer-based investigation of possible climate change effects on runoff and soil erosion in a southeastern Arizona rangeland. The study highlights the need for effective rangeland management to prevent acceleration of soil loss not only due

to the direct driver of climate change, but also to reduce the rate of transition from grass to shrub-dominated vegetation ecosystems. Next, implications of runoff variations, channel bank protection, and grade control measures in northern Mississippi watersheds are reviewed with regard to watershed sediment yield, and off-site effects of climate change and conservation practices are discussed. This is followed by a study of the combined impact of conservation practices and a persistent pluvial period on watershed runoff and reservoir sedimentation in a large agricultural watershed in south-central Oklahoma. Thereafter, stream bank erosion during major flooding in Iowa during the summer of 2008 and river corridor management alternatives are examined to infer mitigating conservation practices to control the anticipated increase in sediment movement under an intensified climate regime. In a review of runoff records of a north-central Missouri watershed, the cause of trends in observed maximum flow and number of flooded days are discussed in terms of changes in precipitation patterns and intensity, as well as in terms of anthropogenic activities in the watershed, some with origins in the very conservation programs that were implemented to protect soil and water resources. Lastly, 72 years of rainfall and runoff data on the Agricultural Research Service (ARS) North Appalachian Experimental Watershed in Coshocton, Ohio, are used to calculate the curve number (CN) and to establish if a relationship exists between climate change and CN variations.

A Simple Thought Experiment: Sensitivity of Watershed Response to Climate Change

There are no simple relationships between climate, soil erosion, runoff, and sediment yield from which watershed response can be readily calculated (Klemes 1981). Nevertheless, a thought experiment involving a simplified conceptual representation of the watershed drainage system under assumed uniform rainfall, soil, and cover conditions can provide qualitative insights as to which component of the rainfall-erosion-runoff-sediment transport system is most sensitive to climatic change and most relevant for conservation outcomes. In this section, the word "rainfall" implies runoff-producing rainfall. Also, the watershed drainage system was assumed to consist of

two functionally distinct components: the hillside and the channel network.

The hillside was modeled as a sloping rectangular plane (figure 1) (Wooding 1965). Boundary conditions for rainfall-runoff considerations were assumed to be wet antecedent soil moisture conditions, saturated soil hydraulic conductivity, uniform rainfall rate of duration less than time of concentration, and kinematic-wave flow conditions. The need to consider other site-specific boundary conditions (hillside slope, width, surface roughness, etc.) was largely eliminated by expressing change in rainfall, runoff, soil erosion, and sediment transport capacity as a ratio of their respective value. For example, a change in rainfall due to climate change leads to a corresponding change Δq from the reference runoff q (the runoff before the change). Hillside slope and surface roughness are boundary conditions that remain unchanged. Expressing the change in runoff Δq as a fraction of the reference runoff (q) allows cancellation of hillside slope and surface roughness and leads to an expression for change in runoff that is only a function of rainfall. This approach is used here to relate a change in rainfall to a corresponding change in runoff.

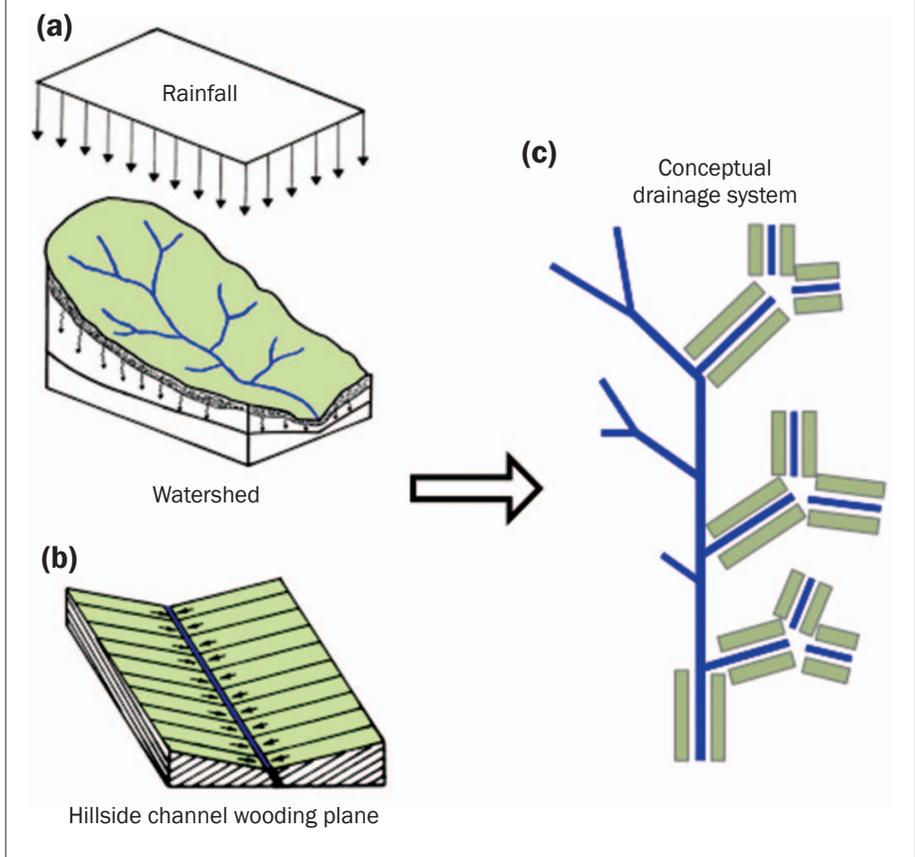
Hillside Rainfall, Runoff, Erosion, and Sediment Transport Relationships. The relationship linking relative change in hillside runoff and relative change in rainfall was derived from Manning's flow resistance equation (Chow 1964) with hillside runoff depth expressed in terms of rainfall and duration of rainfall:

$$\frac{\Delta q}{q} = \left(1 + \frac{r}{(r-i)} \frac{\Delta r}{r}\right)^a - 1, \quad (1)$$

where variable q is runoff per unit width, r is rainfall rate, i is saturated infiltration capacity, and exponent a is a constant and has a value of 5/3 (Chow 1959).

Exponent a and coefficient $r/(r-i)$ in equation 1 are both larger than 1, resulting in an exponentially amplified runoff response ($\Delta q/q$) to a change in rainfall ($\Delta r/r$). For example, with an assumed uniform rainfall rate of 75 mm h⁻¹ (2.95 in hr⁻¹) and a saturated infiltration rate of 25 mm h⁻¹ (0.934 in hr⁻¹), a potential 10% increase in rainfall ($\Delta r/r$) would result in a corresponding 26% increase in runoff ($\Delta q/q$). This exponential signal-response amplification suggests that a climate change scenario containing an increase in rainfall intensity should be of concern for hill-

Figure 1
The conceptual watershed model (a) showing the uniform rainfall, soil, and cover conditions; (b) the hillside component, and (c) the channel network component.



side conservation practices that are based on a design flow or storm. The disproportionate increase in runoff with rainfall may diminish the intended erosion control effectiveness of a conservation practice and/or potentially damage conservation structures (terraces, vegetated waterways, etc.).

An increase in the frequency of rainfall events (due to climate change) does not affect the erosion-control effectiveness of a conservation practice on a storm-by-storm basis, but does contribute to the annual runoff volume (and annual soil erosion and sediment yield). The relative change in runoff volume ($\Delta v_y/v_y$) is equal to the relative change in number of rainfall events ($\Delta n/n$):

$$\frac{\Delta v_y}{v_y} = \frac{\Delta n}{n}, \quad (2)$$

where v_y is annual runoff volume, n is number of rainfall events per year, and Δn is the increase in number of rainy days with average rainfall.

The relationship between rainfall and hillside soil erosion was based on the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). The soil erosion factor R was

modeled as a power function of daily rainfall (Petkovsek and Mikos 2004), and sediment transport capacity was modeled as a power function of hillside runoff and slope (Prosser and Rustomji 2000; Govers 1990):

$$\frac{\Delta R_y}{R_y} = \left(1 + \frac{\Delta r}{r}\right)^g - 1, \quad (3)$$

where R_y is annual soil erosion factor and g is the exponent with value $g = 2$ (Petkovsek and Mikos 2004). It is noted that soil erosion is proportional to R_y (all other terms in the USLE are held constant) and $\Delta R_y/R_y$ is equivalent to $\Delta e_y/e_y$ where e_y is annual soil erosion. Also, in the derivation of equation 3, rainfall was the independent variable and the number of rainfall events was held constant. Thus, the change in annual soil erosion is only the result of changes in daily rainfall:

$$\frac{\Delta q_s}{q_s} = \left(1 + \frac{r}{(r-i)} \frac{\Delta r}{r}\right)^{ak} - 1, \quad (4)$$

where variable q_s is transport capacity by weight and by unit hillside width, k is an exponent with recommended value of 1.4 (Prosser and Rustomji 2000; Govers 1990),

and exponent a was previously determined to have value of 5/3. The value of exponent ak is 2.3.

Both relative change in soil erosion and sediment transport capacity are exponentially related to a relative change in rainfall and imply an exponential signal-response amplification. It is noted that the exponents of the hillside runoff (equation 1), soil erosion (equation 3), and transport capacity (equation 4) relationships are in increasing order (1.7, 2, and 2.3, respectively). This suggests that soil transport capacity is more sensitive to changes in rainfall than soil erosion, which in turn is more sensitive to rainfall than hillside runoff. Thus, a climate change scenario that includes an increase in rainfall intensity will lead to a larger relative increase in soil erosion and sediment yield than it would increase runoff.

Watershed Rainfall, Runoff, and Sediment Transport Relationships. The thought experiment previously applied to assess the sensitivity of hillside response to climatic change was expanded to include the watershed channel network. The channel network was modeled as channel segments connected by junction nodes that integrate the runoff from all hillsides into a single watershed response (figure 1). Channel transmission losses and base flow were assumed negligible, interflow from hillsides was assumed to be a constant fraction of hillside saturated infiltration rate, and soil properties and rainfall characteristics were assumed to be spatially uniform. The principles of linearity and superposition were adopted to account for the different arrival times and summation of individual hillside runoff hydrographs at the watershed outlet.

With these simplifying assumptions, channel flow Q was modeled as the summation of all upstream hillside runoff with appropriate reduction to account for the shape of the hillside hydrographs, the spatial distribution of the hillsides within the watershed, and the lag in arrival time of individual hillside hydrographs at the watershed outlet (Leopold 1974):

$$\frac{\Delta Q}{Q} = \left(1 + \frac{r}{(r-i)} \frac{\Delta r}{r}\right)^a - 1. \quad (5)$$

A relative change in channel flow ($\Delta Q/Q$) was found to be exponentially related to the relative change in rainfall rate ($\Delta r/r$). The interflow contribution and the hydrograph lag-reduction did not appear explicitly in

the relation because they were implicitly contained in the reference flow value (Q). Also, the relationship was similar to the relationship for hillside runoff (equation 1) and displayed the same climate signal amplification characteristics as previously discussed for the hillside runoff.

The volume of channel flow leaving the watershed per rainfall event was modeled as the summation of upstream hillside surface runoff and interflow. A linear relationship was found between change in rainfall rate $\Delta r/r$ and change in channel flow volume leaving the watershed $\Delta V_i/V_i$ (equation 6). While the amount of change in rainfall and runoff was the same (preservation of mass), the relative change is different. Referring to the previous example ($r = 75 \text{ mm h}^{-1}$ [2.953 in hr^{-1}], $i = 25 \text{ mm h}^{-1}$ [0.984 in hr^{-1}], and $u = 5 \text{ mm h}^{-1}$ [0.197 in hr^{-1}]), a 20% change in rainfall r would result in a 28% change in runoff volume.

$$\frac{\Delta V_i}{V_i} = \frac{r}{r-i+u} \frac{\Delta r}{r} \text{ with } r > i > u, \quad (6)$$

where V_i is total runoff volume per rainfall event and u is interflow or quick return flow.

The relationship between relative change in channel sediment transport capacity and relative change in rainfall rate was analyzed for channel flow (Q) using the Du Boys (Brown 1950) and the Shields (Shields 1936) sediment discharge formulae. Adopting the same assumptions as were adopted for channel flow, the relationship between channel sediment transport capacity (Q) and rainfall was found to be exponential. With the exception of the exponent, both relationships are the same. The value of the exponent was 2 or 2.7 depending if Du Boys or the Shields' sediment discharge equation was used. The value of the exponent was in line with the average value of 2.5 for streams in the midwestern United States, reported by Leopold and Maddock (1953) (cited in Leopold et al. 1964):

$$\frac{\Delta Q_s}{Q_s} = \left(1 + \frac{\Delta r}{r} \frac{r}{(r-i)}\right)^2 - 1, \quad (7)$$

and

$$\frac{\Delta Q_s}{Q_s} = \left(1 + \frac{\Delta r}{r} \frac{r}{(r-i)}\right)^{2.7} - 1, \quad (8)$$

The sediment transport capacity relationship given in equation 8 is the most sensitive relation of the eight relationships presented. Based on the previous example, ($r = 75 \text{ mm h}^{-1}$ [2.953

in hr^{-1}], $i = 25 \text{ mm h}^{-1}$ [0.984 in hr^{-1}]) a 10% change in rainfall rate would result in a 45% change in sediment transport capacity.

The sediment transport capacity relationships do not provide information on actual amount of sediment transported which is a function of sediment availability and supply. They only reflect changes in hydraulic flow and sediment transport conditions due to a change in rainfall. Also, the source of eroded and transported sediments is not addressed. While it is clear that sediment yield at the hillside scale is from the hillside, the source of the transported sediment in the channel network is ill defined due to sediment mixing, multiple sources of sediment (i.e., hillsides, channel bed and banks, farm roads, gullies, etc.), wash load, and channel hydraulic controls, which make it difficult to attribute a change in watershed sediment yield to climate change and to any one upstream conservation practice.

Overall, the thought experiment identified changes in hillside runoff, soil erosion, and sediment yield to be exponentially related to changes in rainfall rate (intensity) and linearly related to changes in number of rainfall-runoff events (frequency). Changes in sediment yield were most sensitive to changes in rainfall intensity. The exponential character of the hillside runoff, erosion, and sediment yield response to changes in rainfall intensity was also found at the watershed scale for channel flow and sediment transport. Thus, climate change scenarios that include an increase in rainfall will have a greater impact on conservation outcomes if the rainfall increase is in the form of higher rainfall intensity as compared to rainfall frequency. This is particularly relevant because rainfall intensity and frequency observations in the United States suggest that extreme precipitation events appear to be increasing in intensity and frequency (Easterling et al. 2000; Groisman et al. 2005; Christensen et al. 2007; Karl et al. 2009).

Climate Change Effects on Runoff and Soil Erosion in Southeastern Arizona Rangelands

In the southwestern United States, rangelands have experienced more than a century of transition from grasslands to shrublands due to complex interactions among overgrazing, climate change, and fire control (Platt 1959; Cable and Martin 1973; McClaran 2003). Soil erosion is a primary driver of

soil degradation on most semiarid rangelands. The transition from dominance of grasses to shrubs is thought to have increased both runoff and soil loss by water erosion over wide regions of rangelands (Martin and Morton 1993).

Climate change in the southwestern United States already appears to be occurring. Trends to warmer temperatures and decreased annual precipitation have been observed (IPCC 2007; Karl et al. 2009). Other studies suggest that periods of severe drought have also increased in frequency and duration in this region (Groisman et al. 2004; Ellis et al. 2010) resulting in significant impacts to vegetation and ground cover (Hamerlynck and Huxman 2009; McAuliffe and Hamerlynck 2010). Projections of future climate suggest that the trend in this region is expected to be toward more aridity and significant drying during the twenty-first century (Seager et al. 2007, 2010). Also, the frequency of extreme precipitation events, as indicated by the amount of precipitation falling in the upper percentiles of rainfall amounts, has been increasing in the southwestern United States since the 1930s (Easterling et al. 2000). Intense precipitation is expected to continue to increase in this region, especially during periods of El Niño (IPCC 2007).

The study area used here was Major Land Resources Area (MLRA) 41, located in southeastern Arizona (89%) and southwestern New Mexico (11%), covering in total an area of 40,765 km² (15,746 mi²) (USDA NRCS 2006). Major Land Resource Area 41 is located in the transition zone between the Sonoran and Chihuahuan deserts, with a pattern of topography, soil, climate, water resources, and land use dominated by a series of mountain chains and arid, usually ephemeral, river basins. Elevation ranges from 800 to 1,400 m (2,625 to 4,593 ft) in most of the area, and up to 1,800 m (5,906 ft) in the mountains. The average annual precipitation is 230 to 510 mm (9.06 to 20.08 in) across most of this area, of which more than half occurs with high intensity thunderstorms during the summer monsoon between July and early September.

Data from the IPCC AR4 coupled ocean-atmosphere Global Circulation Models (GCM) simulations (IPCC 2007) were used to estimate the potential future climate. The monthly precipitation projections were derived from seven GCMs.

Three nonmitigated IPCC Special Report on Emissions Scenarios (SRES) (A2, A1B, and B1) were selected to represent different greenhouse gas emissions scenarios of high, medium, and low, respectively (IPCC 2007). The scenarios were implemented for all seven models for the time period of 30 years from 2030 through 2059. To calibrate the GCM results, we also collected data from the “Climate of the 20th Century” experiment (20C3M), which simulates climate conditions during 1850 to 2000 that was driven by the preindustrial greenhouse gas emissions. The 20C3M run during 1970 to 1999 was used as the baseline period. A spatiotemporal downscaling process (Zhang 2005, 2007) was used to downscale monthly precipitation of GCM projections at scale of GCM grid boxes to scale of specific weather stations.

Ground-based field measurements were made of vegetation cover, soil, and topography at 151 randomly distributed sites in MLRA 41 between 2003 and 2006. These data were used to build input files for the runoff and erosion modeling. The Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al. 2011) was used to calculate runoff and soil loss at the hillslope scale for each sample point.

Our results suggested no significant changes in annual precipitation across the region under the three scenarios, which is not necessarily consistent with the expectation of change for the southwest United States as a whole (Seager et al. 2007, 2010). However, projected mean annual runoff and soil loss increased significantly, ranging from 79% to 92% and from 127% to 157%, respectively, relative to 1970 to 1999 (figure 2). This is due to a projected increase of summer precipitation and a reduction of winter precipitation. The dramatic increases in runoff and soil loss were attributed to the increase in the frequency and intensity of extreme events in the study area, with an even greater increase for 99th percentile compared to the 95th percentile (figure 3).

Other studies have also illustrated the importance of rainfall intensity to soil erosion, as well as the possibility of increased erosion with no trends or decreasing trends in total rainfall. Nearing et al. (2005) used a suite of seven erosion models to look at potential impacts of rainfall and cover changes on soil erosion, and indicated that increases and decreases in rainfall intensity even without changes in overall rainfall amounts or num-

ber of days of rainfall caused significant soil erosion increases and decreases, respectively. This basic result is confirmed by empirical results, as implied in the formulation of the rainfall erosion index in the USLE with the use of the maximum 30 minute rainfall value (I_{30}) (Wischmeier 1959). Pruski and Nearing (2002) used projected rainfall from GCMs to look at eight locations across the United States, with several different cropping systems and soils types, and showed model results of several instances where rainfall decreased yet soil erosion increased. These results were due to several reasons, including those associated with vegetation changes, but a contributing factor was that part of the expected change in rainfall would come in the form of larger rainfall events with higher intensities.

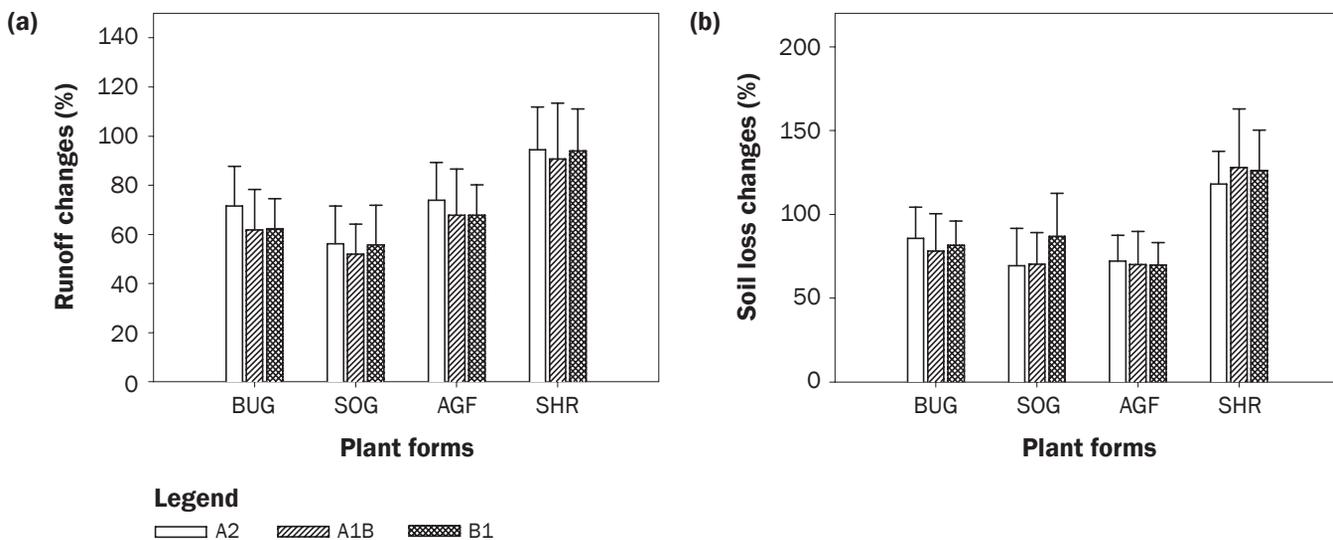
The likelihood of increases in heavy storms and soil erosion rates may be expected to accelerate the transition of grasslands to the degraded shrub states (Schlesinger et al. 1990). Modeling results suggested a greater projected increase in annual runoff and soil loss from shrub communities than other plant communities. Thus, our study highlights the need for effective rangeland management to prevent acceleration of soil loss not only due to the direct driver of climate change, but also to reduce the rate of transition from grass to shrub-dominated vegetation ecosystems. The results show that climate change as a driver can increase soil erosion on rangelands, but also can have important ecological and environmental consequences that should be explicitly considered in the context of management. For example, conservation management should be targeted to currently uninvaded grasslands to prevent the transition mechanisms that result in the degraded, shrub-dominated state.

Complex Response in Northern Mississippi

North-central Mississippi, like much of the Southeast and Midwest, has watershed systems that display impacts of previous mismanagement. European settlement in the nineteenth century was followed by rapid deforestation and increased runoff and erosion. Plugging of stream channels and valley sedimentation (up to 2 m [6.5 ft]) was followed by channel straightening, leading to rapid incision and downstream sedimentation (Shields et al. 1995; Dabney et al. 2012b). Presently many channels are unstable, with sediment yields ~1,000 t km⁻² yr⁻¹ (4,047 tn ac⁻¹ yr⁻¹), or about twice the national average. Sediment sources

Figure 2

Changes in (a) mean annual runoff and (b) soil loss across the four primary plant community groupings (bunch grass [BUG], sod grass [SOC], annual grass and forbs [AGF], and shrub [SHR]) during the time period of 2030 to 2059 relative to the period of 1970 to 1999. Each value represents the mean of seven Global Circulation Models (\pm se).



are primarily channel banks which are mostly comprised of cohesive materials (Simon and Rinaldi 2006; Kuhnle et al. 2008; Wilson et al. 2008). Watershed sediment yields currently reflect effects of land use conversion (e.g., Conservation Reserve Program [CRP], urbanization), in-channel structural measures, and perhaps climatic trends.

Under legislation passed in 1984, three federal agencies constructed more than US\$300 million worth of channel erosion control measures in 16 watersheds in northern Mississippi between 1985 and 2003. This effort was named the Demonstration Erosion Control Project (DEC). Typical measures are listed in table 1. Most work was completed between 1985 and 1995 and was located in 7 larger watersheds. Limited amounts of land treatment were also included in the DEC, and other conservation programs such as Environmental Quality Incentives Program (EQIP) and CRP came on line during this period. Flows of water and suspended sediment emanating from these watersheds were measured for 11 to 17 years over the period of most intense construction and for several years thereafter. The resultant data set allows examination of offsite impacts of runoff variation and in-stream conservation measures on watershed suspended sediment yield.

The DEC data set was examined using seasonal Kendall tests (Hirsch et al. 1982) to examine the presence of trends in the discharges, sediment concentrations, and

flow-adjusted sediment concentrations (Smith et al. 1982; Schertz et al. 1991) using software implemented as described by Slack et al. (2003) and Helsel et al. (2005). Details of analysis are provided by Shields (2008a, 2008b, and 2009). It should be noted that the trend detection procedure (seasonal Kendall test) was nonparametric and thus insensitive to the absolute magnitude of extreme values (peak flows). Results of trend detection analysis are provided in table 2. Positive trends were detected for water discharge for two of the seven gage records. Surprisingly, suspended sediment load remained free from trends at six of the seven gages and displayed a slight positive trend at the seventh. The gage with the positive sediment load trend had no trend in water discharge. No trend was detected for flow-adjusted instantaneous measured suspended sediment concentration at six of the seven gages. The only trend that was detected for the flow adjusted concentrations was a slight downward trend for a watershed in which eight small reservoirs were constructed (table 1). However, the statistical analysis for this trend may not be valid, because water discharge in this watershed exhibited a significant upward trend ($p = 0.05$). The statistical analysis of trend in flow-adjusted concentrations was based on the assumption that the time series of flows is stationary (i.e., has undergone no change with time such as that produced by reservoir closure) (Schertz et al. 1991).

Studies by others using indirect approaches and focused on individual watersheds have indicated that sediment yields from watersheds in this region should have declined over the period of observation (Simon and Darby 2002; Kuhnle et al. 1996, 2008). The lack of statistically significant temporal trends in the DEC suspended sediment data may be due to temporal lags in watershed response (Trimble 1974). Channel systems store sediments, and plugs of sediment may continue to move through channel networks even after source yields are reduced. The strong random component in the time series of suspended sediment concentration may have obscured trends. Clearly, the large variance present in real sediment transport data tends to obscure effects of control measures and climatic variations. Such effects must be large to produce statistically significant differences.

On the other hand, it may be possible that the DEC did not significantly reduce sediment yields. Channel bank erosion via mass wasting and related processes, which dominate sediment sources in these watersheds, has been described in detail by Thorne (1999). Mass wasting occurs during prolonged rainy periods, when bank soils are weak and saturated and toe scour removes material from banks, steepening them, and setting up episodic failures. Greatest rates of bank retreat may not coincide with highest streamflow peaks. However, bank sloughing can stockpile fine-grained sediments at bank

Figure 3

Mean annual frequency of and fraction of total annual precipitation coming from extreme events defined as the 95th percentile for (a) frequency of extreme events and (c) fraction of extreme events, and the 99th percentile for (b) frequency of extreme events and (d) fraction of extreme events of daily rainfall amount for the time period of 1970 to 1999 and the projected period of 2030 to 2059. Each value is the mean of seven models (\pm se) for the future periods.

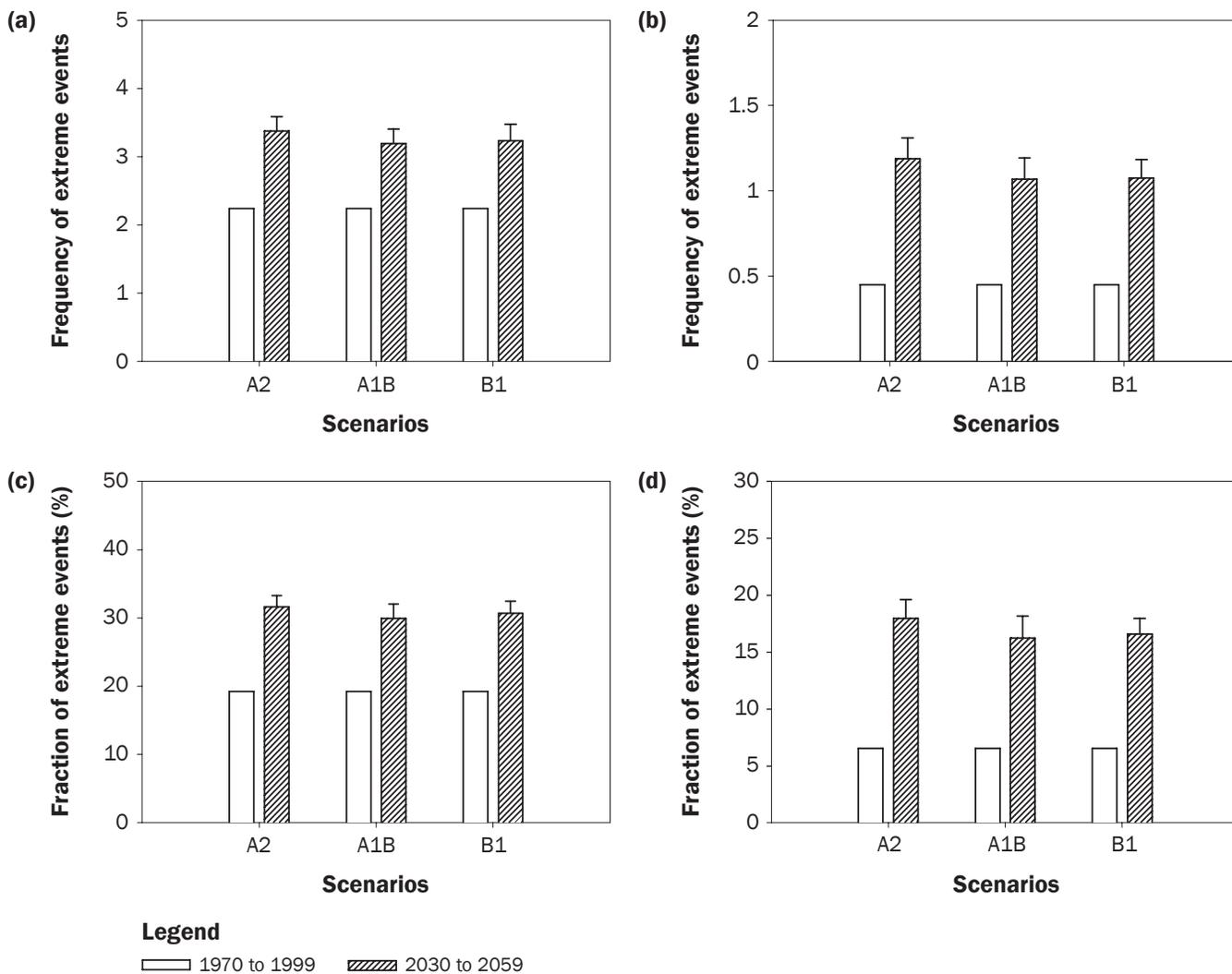


Table 1

Major channel erosion control construction in Demonstration Erosion Control Project (DEC) watersheds.

Watershed	US Geological Survey station	Contributing area (km ²)	DEC project structures completed as of 1996*			
			Number of grade control structures	Bank protection (km)	Number of riser pipes	Small reservoirs
Hotopha Creek	07273100	90	15	9.8	46	0
Peters Creek	07275530	205	15	20	56	0
Hickahala Creek	07277700	313	34	10	119	0
Otocalofa Creek	07274252	251	3	12	48	8
Batupan Bogue	07285400	622	32	27	76	0
Harland Creek†	07287404	161	3	45	95	0
Abiaca Creek	07287160	202	3	0	9	0

*From USACE (1996)

†Construction data is for the Black Creek Watershed. Sediment records are for station 07287404 (Harland Creek), a subwatershed comprising about 13% of Black Creek Watershed.

Table 2

Results of seasonal Kendall tests for presence of monotonic trend over approximately 11-year period. Test results include Kendall's τ (rank correlation coefficient) and the p -value for significance of τ , adjusted for serial correlations.

Watershed	Period used for this analysis	Water discharge		Suspended sediment load		Flow-adjusted suspended sediment concentration	
		τ	p	τ	p	τ	p
Hotopha Creek	1986 to 1997	0.03	0.89	0.05	0.54	0.11	0.23
Peters Creek	1986 to 1997	0.13*	0.07*	0.02	0.89	-0.04	0.69
Hickahala Creek	1987 to 2003	0.11	0.33	0.04	0.69	-0.08	0.18
Otocalofa Creek	1986 to 1997	0.26*	0.05*	0.13	0.28	-0.13*	0.08*
Batupan Bogue	1985 to 1996	0.004	0.98	0.06	0.55	0.08	0.31
Harland Creek	1986 to 2000	0.05	0.44	0.11*	0.06*	0.09	0.37
Abiaca Creek	1991 to 2003	-0.15	0.14	0.00	1.00	0.11	0.37

* $p < 0.10$

toes and channel margins that are removed during higher flows, further complicating linkage between climate (precipitation) and sediment yield. Although many reaches of DEC watershed channels have been stabilized by bank protection, grade controls, or both, long reaches (particularly in low-order channels and gullies) were not treated and remain in early stages of channel evolution (Harvey and Watson 1986; Simon 1989a), thus elevating sediment yield (Simon 1989b). Ultimately, sediment transport is linked to the product of discharge and energy slope, and neither of these variables were impacted by the measures constructed under DEC, with the possible exception of the aforementioned small reservoirs emplaced in Otocalofa Creek Watershed (table 1). The Demonstration Erosion Control Project work included more than 29.4 km (18.3 mi) of channelization, usually in reaches near watershed mouths, which increased channel energy slope upstream. Effects of other treatments on energy slope were limited to reaches immediately upstream from grade control structures. Furthermore, grade controls were sized and located to reduce energy slopes to stable values, but stable values were determined based on empirical relationships between slope and contributing drainage area using reaches visually characterized as stable for references (Shields et al. 1995). Even these apparently stable reaches may still convey elevated loads of sediment from upstream reaches, gullies, rills, and sheet erosion.

These results indicate that watershed-level effects of even large-scale erosion control measures are difficult to detect more than 5 to 15 years. Fluvial systems may respond in complex ways to widespread application of channel erosion controls. Real reductions in sediment concentrations in alluvial envi-

ronments with fine bed and bank material may be hard to achieve if channel peak discharge and energy slopes are not reduced through re-meandering or other measures. By implication, increases in peak discharge and frequency due to climate change may override effects of channel erosion control on watershed sediment yield. Excess sediment supply from upland sources and untreated channels and gullies will deposit in the downstream drainage system before it reaches the watershed outlet, whereas reduction in upland sediment supply will remobilize previously stored excess sediments or access bed and bank sources. Either way, the sediment transport, deposition, and remobilization dynamics buffer the effect of upland soil conservation and channel stabilization measures on downstream sediment yield, with or without climate change. The science of predicting the response of unstable channel networks to shifts in discharge regime and erosion controls and the attendant impact on watershed sediment yield is currently inadequate for quantitative analysis.

Effects of Climate Variations and Soil Conservation on Sedimentation of a West-Central Oklahoma Reservoir

Soil conservation practices on agricultural land reduce soil erosion and sediment delivery to receiving creeks and streams (Berg et al. 1988; McGregor et al. 1990; Trimble 2008). However, upstream conservation practices do not necessarily lead to an immediate and proportional reduction in observed watershed sediment yield (Santhi et al. 2005; Shields 2008a; Trimble 1999). In a large watershed it may take several decades to implement soil conservation practices over a large enough area to realize an observable response at the watershed outlet. Garbrecht

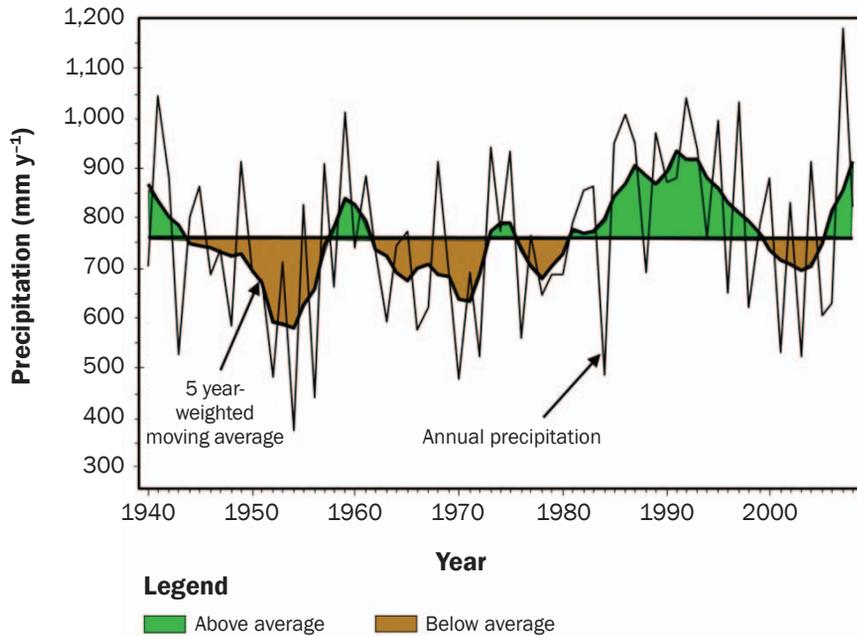
and Starks (2009) investigated the integrated effects of land use conversion, soil conservation practices, and a climate shift on the sedimentation of the Fort Cobb Reservoir in central Oklahoma. Precipitation, watershed runoff, and suspended sediment data that reached back to the 1940s provided a unique opportunity to assess watershed sediment yield before and after implementation of conservation practices, as well as before and after a mid-1980 climate shift towards a sustained pluvial time period (figure 4).

Sediment discharge rating curves derived from data representing agronomic practices of the 1940s (called preconservation period; 1940 to 1964) and rating curves derived from data representing current conservation conditions (called postconservation period; 1984 to 2008) were used to partition and attribute changes in watershed sediment yield to upstream conservation efforts and climate shift. The individual and combined impacts of conservation practices and climate shift on reservoir sedimentation were analyzed, and estimates of reservoir lifespan were computed based on conservation practices and climatic conditions (Garbrecht and Starks 2009).

Conservation Practices and Sediment Yield. Watershed sediment yield (same as reservoir sedimentation rate) was estimated to be 221,700 m³ y⁻¹ (6.278 Mft³ y⁻¹) and 215,300 m³ y⁻¹ (6.097 Mft³ y⁻¹) for pre and postconservation conditions, respectively. The difference between the two sediment yield estimates was only 3%. This gave the impression that conservation practices were ineffective at reducing sediment yield and reservoir sedimentation rates. However, this interpretation is incomplete because it did not account for the effects of the wetter climate that started in the mid-1980s. The

Figure 4

Annual precipitation and persistent variations (heavy line; 5-yr weighted moving average; weights: 0.134; 0.232; 0.268; 0.232; 0.134) in the Fort Cobb Reservoir Watershed 1940 to 2008 based on NWS Cooperative Observer Network climate stations at Weatherford, Lookeba, Carnegie, and Fort Cobb (NCDC 2009). Green and brown colored areas represent time periods of predominantly above or below average annual precipitation, respectively.



shift to wetter conditions increased runoff, soil erosion, channel transport, and sediment yield, and veiled effects of implemented conservation practices.

The effects of the climate shift on watershed sediment yield were removed by assuming the climate shift in the 1980s did not occur and the climatic characteristics of 1940 to 1964 prevailed through 2008. The evaluation concluded that watershed sediment yield was reduced by 60% to 65% in response to implementation of soil conservation practices. Thus, in the absence of confounding climatic factors, soil conservation practices implemented on the Fort Cobb Reservoir Watershed over the last 50 years would have resulted in a sizable reduction in reservoir sedimentation rate. However, the increased runoff, soil erosion, sediment yield, and sedimentation rate due to the wetter climate starting in 1984 offset the reduction in sedimentation rate due to conservation practices, leading to the erroneous appearance that conservation practices were ineffective.

Climate Shift and Reservoir Sedimentation: Sedimentation through 2008. Effectiveness of soil conservation practices at reducing reservoir sedimentation rate was evaluated by

considering what the reservoir sedimentation would have been if conservation measures had not been implemented. The resulting sedimentation volume would have exceeded the design sedimentation storage capacity by the year 2008 leading to an encroachment on reservoir functionality. However, with conservation practices in place, the estimated total sedimentation volume was 64% of the design sedimentation storage capacity. As expected, conservation practices slowed reservoir sedimentation, but additional erosion and sediment yield due to the wetter climate offset most of the sediment yield reductions achieved by conservation practices.

Climate Shift and Reservoir Sedimentation: Sedimentation beyond 2008. Reservoir sedimentation in the coming decades depended very much on assumptions made about the future climate. If wetter climatic conditions were to persist, full reservoir functionality would be expected to last for about 31 years after 2008. If climatic conditions were to return to average conditions, then the design sediment storage capacity would be filled by the design target date of 2060. If dry climatic conditions were to reestablish, then the reservoir would remain fully functional for another 88 years after 2008. The sensitivity

of sediment yield to a climate shift is further illustrated by comparing the hydrology of 1984 to 2008 period to that of the 1940 to 1964 period; an increase in annual precipitation of 11% led to an increase in mean annual discharge of 80%, which led, in turn, to a 185% increase in sediment yield. This sensitivity and the wide range of reservoir longevity reflects the influential role changing or varying climatic conditions may have on watershed sediment yield and reservoir sedimentation, and the need for long-term conservation plans to slow reservoir sedimentation and postpone costly reservoir rehabilitation work.

Bank Movement Resulting from a Channel-Forming Flood on the South Fork Iowa River

Increases in stream discharge have occurred in the midwestern United States during the past 70 years due to changes in both land use and climate. Since the 1970s, climate change, in the form of increased precipitation and greater humidity, has been shown to be the larger of the two drivers (Nangia et al. 2010; Tomer and Schilling 2009). These trends have increased baseflow in midwestern streams (Schilling and Libra 2003). However, the frequency of intense storms delivering large amounts of rain in short time periods is also expected to increase in much of the United States under a warmer climate (Nearing et al. 2004). Several analyses have confirmed this, and Bukovsky and Karoly (2011) suggested that the total number of rainfall events may decrease while the frequency of high-intensity events increases, meaning that both flood and drought may increase in frequency in central North America as global temperatures increase. More intense rainfall events lead to higher runoff and increased risk of flooding. Unfortunately, human activity has accelerated sedimentation of rivers and river valleys, leaving riparian corridors vulnerable to impacts from flooding. Historical (i.e., post-European settlement) sedimentation of river valleys has been recognized as a pervasive issue impacting management of river corridors across North America (Simon and Rinaldi 2006; Trimble 1999; Walter and Merritts 2008).

In the South Fork of the Iowa River (SFIR), Iowa, the extent of historical sedimentation and its impact on floodwater storage capacity of the floodplain of this 60,000 ha (148,000 ac) watershed was eval-

uated by Yan et al. (2010). They estimated floodwater storage capacity of the SFIR's floodplain was reduced by $5.1 \times 10^6 \text{ m}^3$ (4,100 ac ft). Accumulation of recent sediment along alluvial valleys increases stream bank heights, making the banks more susceptible to erosion because greater discharge volumes remain confined to the channel before it is possible for floodwater to spread onto the floodplain. This increases the channel velocity and erosive force at bank-full discharge. In addition, higher banks may limit the availability of phreatic water, affecting the growth, rooting, and types of bank vegetation, and leading to greater bank erosion (Micheli and Kirchner 2002). Channel straightening was a common response to sedimentation problems especially in the mid-1900s (Simon and Rinaldi 2006). Yan et al. (2010) were able to document how the SFIR and its tributaries, Tipton Creek (TC) and Beaver Creek (BC), had been straightened since 1939. Beaver Creek had seen significantly more straightening than TC or SFIR. This setting provided an opportunity to identify difference in channel responses to a major flood event, which occurred in 2008. This flood is viewed as a test case for channel response to the types of flood events that we might see more frequently in the future due to climate change. Results would indicate how the susceptibility of midwest streams to more frequent floods under a changing climate might be mitigated by riparian-zone conservation efforts.

Note the focus in this case is on channel widening rather than incision. Streams in much of the upper Midwest do not become incised in response to increases in discharge and confinement of discharge to the channel by accreted sediment. This is because many midwest river valleys were carved by glacial meltwaters, which left behind coarse outwash deposits that effectively resist erosion/incision under today's hydrologic regime. The coarseness of the streambed forces the streams to adjust to increased discharge by widening. Simon and Klimetz (2008) conducted a geomorphic assessment of the SFIR streambanks and confirmed the SFIR channels were undergoing processes of channel widening.

This case study followed up on the described results above, with the objective to map the widening of SFIR stream channels resulting from a major flooding event during June of 2008, to test hypotheses about how stream straightening and vege-

tative cover impact bank movement from extreme events. One problem with a trend of increased flooding frequency is that estimating the average return period of a given-size event becomes impossible, because the basic assumption of stationarity, which permits estimation of flood frequency distribution, is violated by a changing climate (Milly et al. 2008). Under these circumstances it becomes more imperative to apply best management practices along river corridors, and undertake studies to understand the effectiveness of these practices.

To conduct the study, positions of stream banks observed in 2002 aerial photography were digitized for the SFIR and its tributaries. The bank positions were then digitized again, using imagery from a light detection and ranging (LiDAR) survey conducted in early 2009. The difference in bank positions was determined, and overlap polygons were classified as either erosional or depositional, and their areas were summed. Narrow polygons, defined as having an area to perimeter ratio less than 2, were neglected.

Bank movement was assumed to result from a flood event in 2008. Daily discharge at the lower SFIR gage (Tomer and Schilling 2009) exceeded bankfull discharge for approximately 10 days beginning June 6, 2008, and peaked at approximately four times bankfull discharge on June 9, 2008. During this time period, more than 175 mm (7 in) of rain fell on soils that were already saturated by rainfall in late May, leading to nearly 150 mm (5.9 in) discharge; the peak discharge on June 9, 2008, delivered 25 mm (nearly 1 in) in that single day. The largest events from 2002 to 2007 were 2 events in 2007 that each resulted in peak discharge that was about half the peak daily discharge in the June of 2008 event.

A comparison of results among the three streams (table 3) indicate that differences in net bank erosion and stream widening were related to the degree of channel straightening, expressed as stream sinuosity (table 3). Beaver Creek, which had been subject to the greatest channel straightening, was widened by 6.5 m (21.3 ft), and had nearly 13 times as much area of eroded as accreted banks. In contrast, the SFIR, subject to the least straightening (Yan et al. 2010), was widened by 2.5 m (8.2 ft), and the area of erosional bank polygons exceeded that of depositional polygons by a factor of <3 (table 3).

There was also evidence that vegetation has an important role in determining susceptibility of stream banks to erosion. Riparian areas that were in some form of conservation cover and exhibited full grass canopies showed little bank movement (figure 5). This figure provides a single example, but multiple sites with full grass cover and little evidence of bank movement were observed during aerial surveys. These bank areas contrasted with areas where continuous grazing resulted in poor pasture conditions and relatively little vegetative cover, where evidence of unstable banks was dominant (figure 5). Data from Bear Creek, Iowa (Zaimes et al. 2004), indicate that bank erosion from unstable banks in continuously grazed pastures was on average 84% of the erosion rate observed where row crops were planted up to the stream, and that the average proportion of total bank length that was unstable was similar (to within 1%) in these two settings. Minimal (or controlled) grazing pressure should encourage greater root-length density of grasses, which improves soil strength as discussed by Simon and Collison (2002).

These results of this study are preliminary, but suggest that two factors determine a stream's susceptibility to bank erosion in this upper midwestern setting. First, healthy riparian ecosystem with stable stream banks should be encouraged by riparian management practices that keep streambank areas in permanent conservation cover. We found clear evidence that riparian buffers can attenuate bank movement and are effective to manage river corridors being subjected to a greater frequency of extreme events. Second, straightened channels are more susceptible to bank erosion. Where possible, reestablishing the meandering pattern of straightened streams can also reduce the severity of impacts from large flood events. Other practices that help streams become reconnected with their floodplains, such as oxbow restoration, should also be helpful.

Under current trends of changing climate, we do not know at what frequency to expect extreme flood events like the one observed in this watershed in 2008. However, the frequency of extreme precipitation events has increased and may continue to increase. We also know that conservation practices applied to agricultural fields in upland areas can mitigate runoff volumes, and that both upland and riparian management are critical to good watershed management.

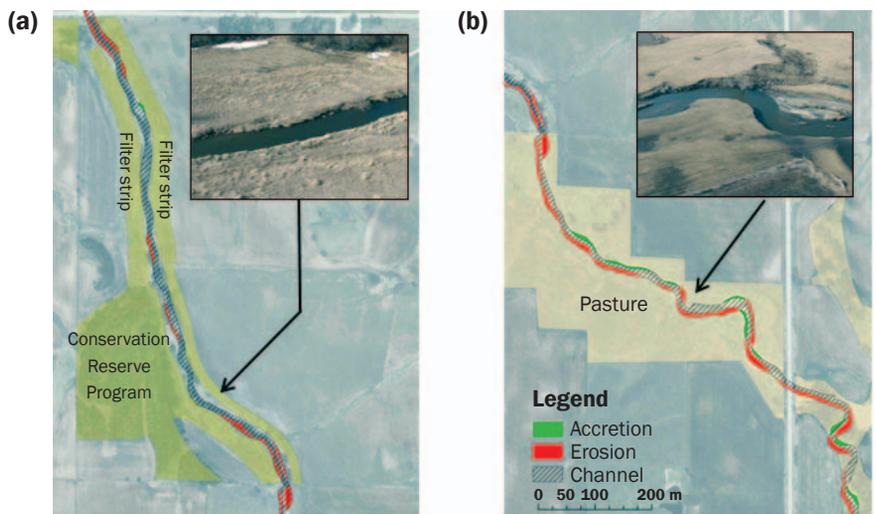
Table 3

Comparison of channel sinuosity, extent of accreted and eroded banks, net channel widening, and ratios of eroded:accreted areas of bank movement between 2002 and 2008. Sinuosity and channel length were reported by Yan et al. (2010).

Stream	Sinuosity (m m ⁻¹)	Area of accreted banks (m ²)	Area of eroded banks (m ²)	Net channel widening (m)	Ratio eroded: accreted bank area
South Fork	2.20	96,531	246,125	2.48	2.55
Tipton Creek	2.02	27,066	100,558	2.63	3.72
Beaver Creek	1.47	12,502	167,330	6.52	12.82

Figure 5

Little stream bank movement was observed after a severe flood in 2008 where (a) full grass canopies were established and (b) closely grazed pasture showed clear susceptibility to bank movement. Inset photos are video frames captured near indicated location during helicopter survey in March of 2009. The two sites shown are along adjacent sections of Tipton Creek.



Tomer et al. (2005) showed that conservation tillage practices reduced runoff volumes and increased baseflow in a small watershed experiment. Average discharge increased under conservation practices, but the variability in streamflow was decreased at the same time. This result suggests conservation practices can mitigate flood and drought impacts. In order to reduce impacts of extreme rainfall events, maintaining and, where possible, increasing soil organic matter (SOM) is critical; a 1% increase in SOM can improve water holding capacity by up to 4.7%, depending on soil texture (Hudson 1994). This means that in a 30 cm (11.8 in) thick surface horizon, increasing the SOM by 1% potentially decreases the magnitude of a runoff event by 14 mm (0.5 in). The volume of historical sediment accreted in the SFIR river valleys has the potential to exacerbate the magnitude of every flood event

by 11 mm (0.4 in) (Yan et al. 2010). If heavy rainfall onto saturated soil occurs more frequently in the future, large runoff volumes will be inevitable. Good soil conservation that maintains SOM and high infiltration capacities will be particularly important in watersheds where long term impacts of poor soil management during the early decades of agricultural settlement have decreased floodwater storage capacities in local river valleys. The lingering impacts from poor soil management in the past, which exacerbate the severity of present and future floods underscores the importance of soil conservation, especially as extreme events appear to be increasing in frequency. As soil conservation practices reduce the variability of streamflow, it is clear that one other benefit of good soil management is more stable hydrologic conditions in riparian and aquatic ecosystems. Because conservation cover along riparian

corridors helps stabilize streambanks, this complements the effects of well managed upland soils, providing a complete and integrated management system to help mitigate effects of climate change including impacts from flooding.

Changes in Watershed Runoff/Sediment Regime Due to Weather and Climate

This study area is the Goodwater Creek Experimental Watershed, a 7,250 ha (17,920 ac) agricultural area in north-central Missouri which was established in 1967. Most of the watershed is characterized by soils having a restrictive layer of smectitic clays with very low permeability, which impede infiltration through the soil profile. This claypan layer can be found from 10 cm (4 in) to 100 cm (40 in) deep in the soil profile. It controls the hydrology by restricting soil water storage to that which is above the claypan. During droughts, available water is limited and drought stress appears more quickly than on other soils. During wet periods, the limited water storage capacity is quickly filled, after which the soil becomes saturated above the claypan and additional rain results in increased surface runoff (Kitchen et al. 1999; Jung et al. 2005). If slope is sufficient, lateral subsurface flow occurs along the claypan.

The 40-year increasing trends that are observed in maximum flow and number of flooded days could be the result of changes in precipitation patterns and intensity. However, they could also be linked to anthropogenic activities in the watershed, some caused by economic factors beyond reach of watershed planners, and some with origins in the very programs that were implemented to protect soil and water resources. We review the nature of these trends and how some of the anthropogenic activities could lead to a similar signal as we observe in the data.

Daily flow volumes and rates were available from 1972 to present. Linear regression analysis was performed to detect temporal trends in yearly average and peak rain, average and peak flow, number of out-of-bank days, and number of no flow days with time, in years, as the independent variable. Years were defined as the hydrologic year from October 1 to September 31. An *a priori* level of significance of 5% was selected, with results of the regression slope also being presented for an *a priori* level of significance of 10%. First-order positive and negative autocorrelation were assessed with the Durbin-Watson statistical

test using a 5% *a priori* level of significance. If the Durbin-Watson statistic was significant, autoregression analysis was performed using the maximum likelihood estimate of the first order autoregressive model, and these regression statistics were then reported.

Results. As expected, there was no significant autocorrelation for any of these variables. There was also no detected trend in either annual total rain or annual peak daily rain (table 4). Trends in annual flow and number of no-flow days are not fully conclusive, being significant only at a 10% level. However, there was a significant increase of annual peak daily flow and number of out-of-bank days. During the first decade of this period, out-of-banks conditions happened only during 8 events, but occurred 13, 22, and 31 times in the second, third, and fourth decades, respectively. This increase of the frequency at which the stream exceeds its channel was accompanied by an increase in peak flow itself, indicating not just an increase in frequency of the floods but also of their severity.

In the absence of a clear trend signal for annual rain or annual peak rain, it is not certain that the observed increase in annual peak flow and frequency of floods can be attributed to climate change. It is certainly possible that small and nondetected changes in precipitation patterns, intensity, or total volume may have had larger effects on peak flow through the interactive processes of infiltration, plant growth, water storage, and groundwater flow. It is also possible that the changes in precipitation patterns occurred at the seasonal level rather than annually. However, other changes in the watershed, which occurred in response to climate change or other factors, would alter aspects of the hydrologic cycle in a similar direction. We review here some of these factors.

Land Use. Detailed land use in the watershed is not available for the whole study period. Therefore, Boone and Audrain county data, obtained from the National Agricultural Statistics Survey, were used as a proxy. The total area of row crops planted in Boone and Audrain counties increased from 1972 to 1984, then decreased to 1975 acreage and stabilized around that value in 1987, with 20% more area planted with row crops in 1987 than in 1972. In a watershed where 70% of the watershed is in row crops, this represents 14% of the watershed. The magnitude of that increase was quite significant as there

Table 4
Existence and significance of trends in yearly rain and flow characteristics with time for over 40 years in the Goodwater Creek Experimental Watershed.

Variable	Regression slope	p statistic
Yearly rain (mm)	Not relevant	0.1115
Yearly peak daily rain (mm)	Not relevant	0.1569
Yearly flow (mm)	4.419	0.0772
Yearly peak daily flow (mm)	0.830	0.0014
Number of out-of-banks days	0.215	0.0018
Number of zero flow days	-0.872	0.0781

was 25% more area planted in 1984 than the long-term average since 1987, or 18% of the watershed. One could assume those were acres of highly erodible land enrolled in the CRP established in the 1985 Farm Bill. The increase and further decrease in cropped acreage was balanced by a corresponding decrease and then increase of grass land, i.e., pasture and hay fields. More cropped area at the expense of grass land would reduce the overall evaporation out of the watershed and result in higher flows. This is especially true during the spring rains, when grass is growing fast but corn (*Zea mays* L.) and soybean (*Glycine max* L.) crops are just being planted. In addition, field operations in row crop fields tend to increase bulk density and decrease soil hydraulic conductivity (Jiang et al. 2007, Jung et al. 2005; Mudgal et al. 2010) and Manning coefficients, which result in a greater runoff potential and higher peak runoff than from hay fields or pastures.

Crop Distribution. While planted area has been relatively constant since 1987, crop distribution among the four major crops (i.e., corn, soybean, wheat [*Triticum aestivum* L.], and sorghum [*Sorghum bicolor* L.]) have fluctuated following trends in commodity prices, weather constraints, and the various agricultural programs during these 40 years. Audrain County, for example, has seen the planted corn area first decrease by 50% from 1972 to 1981, then return to their 1972 level by 1997, and finally increase by another 50% by 2007. On the other hand, soybean area first increased until 1987, then decreased until 1993, and increased again to slightly under their late 1980s level. Shifts of this nature can alter the water demand, residue cover, evaporation, and alter the hydrologic cycle. However, differences in runoff, erosion, and sediment yields associated with different crops are lower than between row crops and pastures.

Soil Profile. Claypan soils are inherently fragile and subject to high runoff and erosion. A study by Lerch et al. (2005) estimated that in a field that had been either cropped

or pastured for the last 150 years, the depth of soil above the claypan decreased by 13 cm (5.12 in) on average over that period. If we extend this average soil loss rate over the land in row crops (75% of the watershed) and assume it is still valid today, this would represent a loss of 3.5 cm (1.38 in) in 40 years, or 14% of a top soil layer that is on average 20 to 25 cm (7.87 to 9.84 in) deep. The lost storage capacity, i.e., 5 mm (0.197 in), thus represents an equivalent 14% loss of the average 36 mm (1.42 in) in the row crop fields, which contributes to higher runoff, peak flows, and soil erosion. While the eroded soil may be deposited and contribute to increase storage capacity elsewhere in the watershed, the runoff from the fields is likely to concentrate and the increased storage capacity is not necessarily usable.

Urbanization. The upstream town of Centralia, located on the watershed divide at the upstream end of the watershed, initially declined in population by 6% between 1970 and 1990 but then increased by 17% to attain a level that is 11% higher than in 1970. The number of houses built in Centralia may better represent the hydrologic impact of this growth. Based on the number of houses from each decade relative to the number of existing houses in 1970, we estimate a 71% increase in houses from 1970 to 2010. These statistics necessarily imply an increase in impervious area, not just of rooftops, but also driveways, sidewalks, and streets. The commercial properties to service the larger population would have their own impervious area. Along with the construction of new houses, improvements have been made to the drainage system, which are of benefit to the inhabitants but contribute to higher peak flows.

Conservation Practices. On the other hand, some long-term anthropogenic activities in the watershed have the potential to confound detection of a climate change signal. Construction of ponds fall in that category, causing retention of flow, decreasing

the peak flow and increasing evaporation. There is no inventory of ponds in the watershed, but satellite images provide enough resolution to see there are many of them. Parallel terraces with an underground outlet also would contribute to short term water retention and peak flow reduction. Some have been built in the watershed in the last 15 years. Prior to that, preference was given to constant-grade terraces discharging in a grassed waterway. Both types would slow the delivery of surface runoff from the fields to the streams.

In summary, a significant increase in annual flow, annual peak flow, and number out-of-bank flow events was detected in this watershed over a period of 40 years. Given that these trends were not detected in the precipitation record, it is difficult to discern whether these trends were due to climate (rainfall intensities for example as seen in the previous study), anthropogenic changes, or a combination of both. Several changes have taken place over the last 40 years in the watershed that could have contributed to an increase in flow and peak flow rates, including land use changes, loss of soil storage capacity, and increases in impervious areas at the upstream end of the watershed. On the other hand, some conservation practices implemented in these 40 years also contribute to a decrease in peak flow rates.

The study illustrates that trends in runoff are not necessarily related to climate change. Land use and land management have been shown to affect flow and water balance (Glavan et al. 2012). Similarly, soil erosion has been shown to affect soil water storage and water balance (van Wesemael et al. 2006). If changes in precipitation patterns were present, it would be difficult to distinguish how much of the trend in runoff was due to these changes and how much was due to other anthropologic causes. The impacts from the different factors were described here in qualitative terms. Absolute and relative quantification of these impacts would require the use of hydrologic models, which is beyond the scope of this article. Whatever the cause for increased magnitude and frequency of peak flows, conservation efforts to reduce these floods are necessary to reduce stream bank erosion and minimize negative impacts on receiving streams and other water bodies. Retention structures, crops that modify the water balance in a positive direction, land cover that may improve soil

quality, and tillage systems that conserve soil on the landscape all have potential to directly or indirectly lower peak flows.

Variation in Curve Number over Time on a Coshocton, Ohio, Watershed

Changing climate is generally manifested through gradually increasing air temperatures and changing precipitation amounts over several decades. Changing precipitation and increasing air temperature, in turn, can affect other parts of the hydrological cycle such as soil-moisture-depletion rates between rainfall events through changing evapotranspiration rates. A question arises whether these changes are affecting watershed runoff generation potential, an important component for evaluating the effectiveness of conservation practices on landscapes.

Weather data at the USDA ARS, North Appalachian Experimental Watershed (NAEW) near Coshocton, Ohio, collected from about 1940 through 2006, show no trend for annual precipitation totals at the 0.59 level (figure 6a) using the nonparametric rank-correlation test for trend. Further examination of trends in *monthly* total precipitation yielded no trends for any month at less than the 0.06 level. Considering a level of 0.05 as being statistically significant, the 0.06 level can be classified as not significant to borderline significant. However, when average annual air temperature is plotted against year for the entire period of record, a statistically significant rank correlation was found (<0.0001 level) (figure 6), with a rate increase in temperature of 0.024°C yr⁻¹ (0.043°F yr⁻¹). The temperature trend may affect evapotranspiration of the NAEW area, but precipitation appears stationary. Bonta and Barker (2010) also showed that NAEW air temperature data (in terms of degree days) began a more rapid increase since about 1979.

The NRCS Curve Number method (Hawkins et al. 2009) is likely the most widely used model worldwide for estimating runoff from watersheds, and is often mandated by statute for soil and water conservation designs. The CN equation accounts for an initial abstraction (I_a) of precipitation prior to runoff generation. Classically, I_a has been assumed to be 0.2 times the potential watershed storage (S). However, recent analyses of measured runoff and precipitation data suggest a coefficient of 0.05 instead (Hawkins et al. 2009). The CN is computed through an equation that forces a range from

0 to 100. The CN typically ranges from approximately 50 to 100, with larger values representing higher runoff-producing watersheds. Variables S and CN represent the effects of land management and soil characteristics on runoff production.

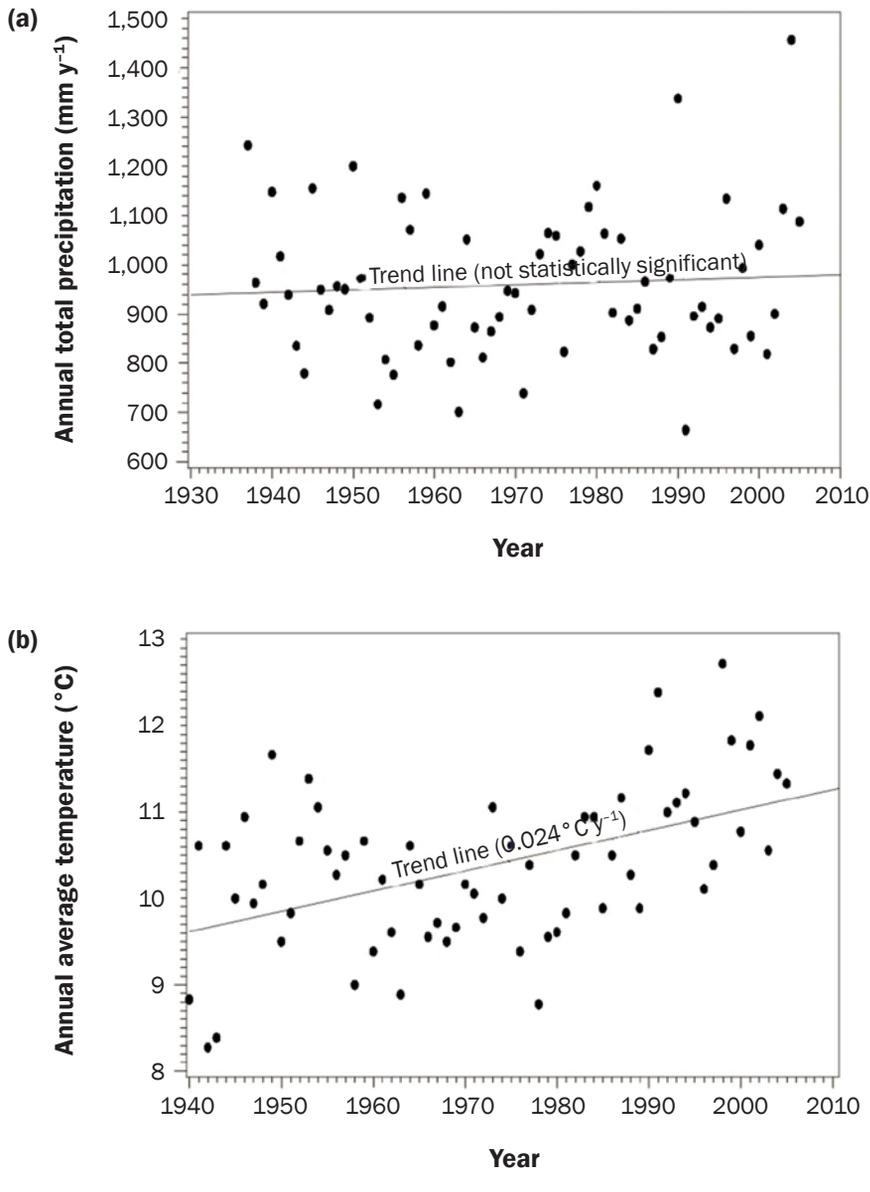
Under an increasing temperature regime, evapotranspiration may increase I_a by increasing available soil-water storage. Consequently, more rainfall may be abstracted during the beginning of a rainfall-runoff event. However, because I_a is fixed at 0.2 in the classical CN method, the effect of changes in measured I_a may be subtle because changes in CN will result only if there are changes in field-measured event precipitation (P) and discharge (Q) used to compute CN. Consequently, an investigation of the effects of climate change on CN, the objective of this case study, is a first step toward a more comprehensive investigation of climate change on components of the hydrological cycle using unique NAEW data. This investigation is exploratory and lays the groundwork for more detailed investigations into impacts of climate change on runoff and water-quality in general. A study of measured I_a variation is beyond the scope of the present investigation.

Few small experimental watershed data exist with long records of precipitation (P) and runoff (Q), and during which land management was constant. One such small watershed, 0.66 ha (1.63 ac) in size with an average slope of 21.7% is found within the NAEW. The watershed has been used for hay production since about 1938, and has been monitored for runoff for most months during the time periods from 1938 through 1972 and 1979 through 2010, an approximate 68-year record of P and Q . Soils on the watershed are loamy, and there is no textural buildup in the profile (Kelley et al. 1975). Consequently, the soils have high permeability and overlie fractured bedrock. Precipitation and Q data have been tabulated in breakpoint form during the periods of record. Growing-season watershed P - Q data were used, defined as the inclusive months March through October.

Rainfall-runoff events were identified using the GETPQ96 program (Dripchack and Hawkins 1996) using the P and Q data. The runoff and causal precipitation data identified were subjected to the asymptotic method for estimating CN (Hawkins 1993). In this method, the total runoff and causal

Figure 6

Annual trends for (a) precipitation and (b) temperature (Bonta 2006).



precipitation were separately ordered and CN computed using the ordered data. CN_{∞} is the asymptote at large P , and it is used in the nonlinear curve fitting of the CN and P data. According to the following equation suggested by Hawkins (1993),

$$CN = CN_{\infty} + (100 - CN_{\infty}) e^{-KP}, \quad (9)$$

where CN_{∞} is the asymptotic watershed CN and K is a fitting parameter.

For climate change investigation, the data were grouped into periods of time that could be used to examine trends. Exploratory calculations of CN revealed that four-year

periods provided an adequate set for this trend analysis. For each four-year period, CN was computed using the asymptotic method resulting in approximately 18 groups of CN during the period of record. Curve number was examined for trend using the nonparametric rank correlation test. This test was used because an underlying equation and distribution are not required and the test is not sensitive to extremes. Curve number assumes fixed $I_a = 0.2$ seconds, so changes in measured I_a are not reflected in possible CN changes except indirectly through changes in magnitudes of event P for a given Q in field data.

Figure 7 illustrates the good fit of equation 9 to all of the CN- P data for the entire period of record ($CN_{\infty} = 76$, $K = 2.22$, sample size = 406 events). The CN data remain relatively constant starting at about $P = 25$ mm (0.98 in). The CN enveloping line plots the CN at which direct runoff begins for a given P .

CN_{∞} for four-year periods ranged from 61.6 to 87, with an average of 73.3, median of 73.8, and coefficient of variation of 9.6%. Sample sizes for the four-year periods ranged from 3 to 64, with a median of 19.5 events. The parameter differences between this CN_{∞} for individual groups of data and for the one for all data are due to the larger variability and smaller sample sizes for the four-year periods compared with using all data ($n = 406$). Figure 8 is an example of CN- P plot for a four year period having $CN_{\infty} = 69.3$ and $K = 1.43$. The fitted curve for this group of data (16) remains relatively constant at approximately $P > 50$ mm (2 in).

The variation of CN with time (figure 9) does not show an overall trend. However, the most recent CN groups are steadily increasing. The rank correlation probability is 0.15 for the entire data set, suggesting no trend in CN. Considering the grouped data since approximately 1979, the rank correlation is 0.52, suggesting no trend in CN with time for recent data as well.

The data allow an exploratory examination of possible effects of climate change on runoff and subsequently water quality. The following conclusions can be made:

- Curve number has not changed significantly (statistically) over 72 years. This is more indicative of no change in precipitation because the coefficient used to compute I_a is assumed to be constant in the method (0.20).
- There is no significant change in CN since 1979, a year of observed change in air temperature at the NAEW. However, later years suggest an increasing CN trend.

This exploratory and preliminary study of the Coshocton runoff data suggests that runoff estimation in conservation practice planning that depends on the CN method is not likely affected by climate change. Furthermore, changes in runoff due to precipitation affected by climate change can be estimated directly. However, the effects of air temperature on other CN component variables such as I_a need further investigation. The wealth of other unique NAEW data will be

useful to understand the effects of changes in climate on these components and on different parts of the hydrological cycle.

Summary and Concluding Remarks

Seven case studies that address climate change and soil erosion, watershed sediment yield, and conservation outcomes were reviewed. Climate change conservation issues were presented and discussed in respective sections. The scope and intent of the study are described in the introductory sections. Here relevant insights are summarized and conclusions are presented.

Several of the studies showed that climate change scenarios exhibiting an increase in rainfall intensity were associated with a disproportionate (exponential) increase in runoff and soil erosion. This differs from the expected response to increases in rainfall frequency, which generally leads to a comparatively smaller (proportional) increase, on a storm-by-storm basis, in soil erosion, runoff, and sediment yield. Sediment transport capacity was found to be more sensitive to changes in rainfall than runoff and/or soil erosion. In general, an increase in rainfall intensity and frequency will stress upland conservation practices, diminish their effectiveness, and increase the sediment supply to the stream network. The above considerations and the projected intensification of extreme rainfall events reemphasize the need to continue, if not expand upon, the implementation of existing conservation programs and develop conservation strategies that are tailored to mitigate effects of anticipated climatic conditions. Agronomic management practices that provide protective ground cover, slow surface runoff, promote infiltration, and hold the soil in place should be encouraged. Coverage of proven conservation measures such as conservation tillage, strip cropping, and no-till operations should be expanded. These steps would continue improving the quality of agricultural environments and would mitigate detrimental effects of future potential climate intensification on soil erosion.

A persistent pluvial time period in an Oklahoma watershed in the 1980s and 1990s was shown to lead to runoff and soil erosion rates that were large enough to offset the reduction in soil loss achieved by existing conservation practices or conservation measures designed on past rainfall-runoff characteristics. These findings are a

Figure 7

Curve number (CN) vs precipitation (P) for entire period of record using WS130 and RG103 North Appalachian Experimental Watershed data ($CN_{\infty} = 76$).

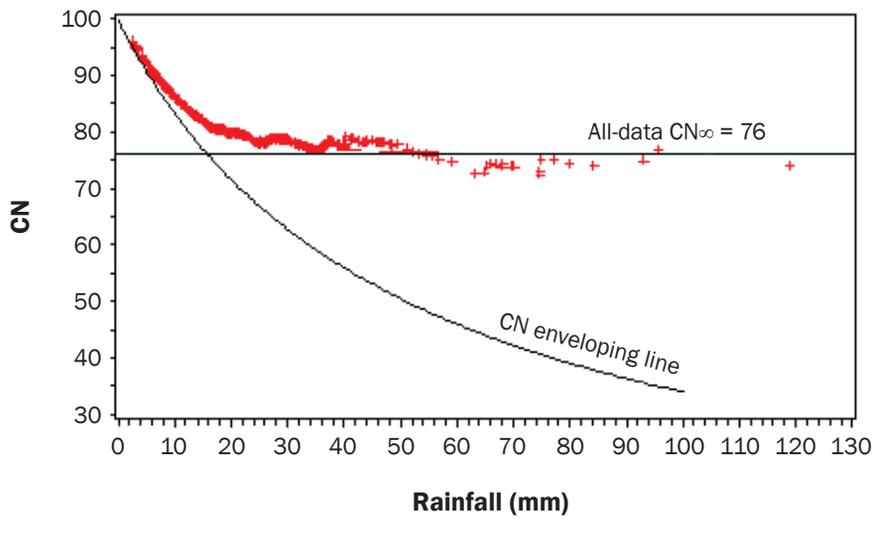
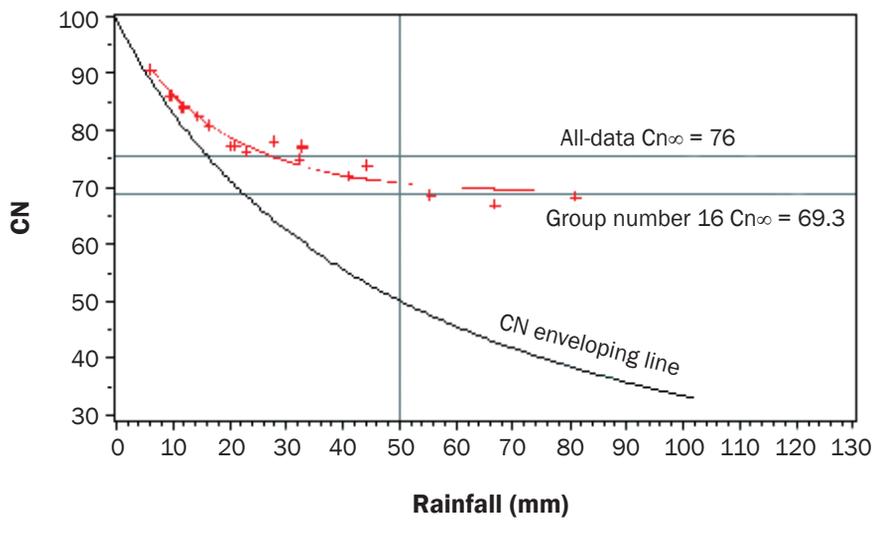


Figure 8

Curve number (CN) vs precipitation (P) for group 16, 1998 to 2001, for WS130 at the North Appalachian Experimental Watershed ($CN_{\infty} = 69.3$).

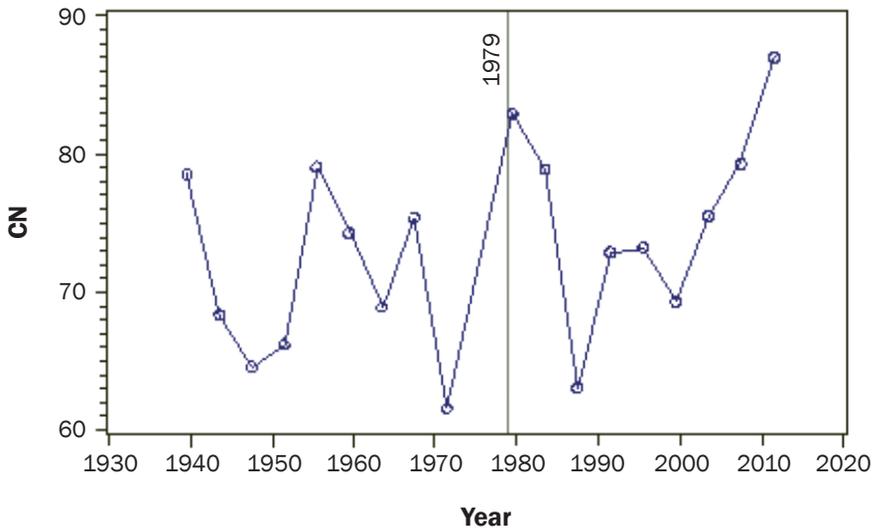


reminder that soil erosion and watershed sediment yield reflect the integrated effects of climate variations, diversity of sediment sources, cumulative and integrative effects of watershed drainage processes, anthropogenic activities, and legacy impacts of past watershed management. This makes it inherently difficult to identify, extract, and attribute trends in observed soil erosion and runoff to climate change. Absence of a correlation between conservation efforts and observed reduction in downstream sediment

yield does not necessarily imply that such a relationship does not exist. It merely implies that the signal may be obscured by sediment yield variations due to other causes. Thus, watershed sediment yield is often an inadequate measure of the effectiveness of in-field conservation measures to reducing downstream watershed sediment yield, and should be used with caution when assessing conservation needs or rating the performance of conservation programs.

Figure 9

Variation of curve number (CN) with time for watershed WS130 at the North Appalachian Experimental Watershed.



In alluvial-floodplain environments, watershed sediment yield is, to a large degree, controlled by channel discharge and energy slope at the watershed outlet, neither of which is directly influenced by traditional hillside conservation practices or channel bank stabilization structures. In such transport-limited systems, sediment yield reflects changes in channel discharge and sediment transport capacity brought about by climate change. Furthermore, the sediment storage capacity of the floodplain system acts as sediment source/sink, and changes in edge-of-field conservation outcomes as a result of climate change will be dampened as the conservation signal travels downstream towards the watershed outlet. Control of sediment yield will gradually shift in the downstream direction from sediment supply to sediment transport capacity and further veil the direct effects of climate change on conservation outcomes at a watershed outlet. The effectiveness and benefits of soil conservation practices, the effects of climate change, and conservation outcomes are best measured at the edge of the field. This is where in-field soil conservation practices that slow runoff, enhance infiltration, and increase in-field water storage capacity are likely to help reduce watershed sediment yield under climate change. In addition, edge-of-field and riparian practices such as channel re-meandering, floodplain restoration, wetlands and retention basins, and similar practices will reduce sediment transport capacity and yield, even during extreme events.

Channel bank stability observations on the South Fork Iowa River suggested that existing channel bank protection measures that have proven effective under extreme rainfall-runoff events of the present climate are likely to also be effective under future climate conditions. Bank protection may include buffer strips, riparian vegetation, trees and willows, stone rip-rap, and cattle exclusion zones. Such bank protection helps control the migration of head cuts into the channel bank and neighboring fields and should be considered whether climate change occurs or not. A no-regret decision to expand channel bed and bank erosion controls to withstand today's storms will contribute to making the channel system more resilient under changed climatic conditions.

Annual flow, peak flow, and number out-of-bank flow events in a Missouri watershed increased over a period of 40 years without a corresponding increase in the observed precipitation record. A land use analysis revealed that the observed trend in flow was the result of land use changes and urban development over time. This illustrates that a trend in flow may be due to a number of conceivable reasons unrelated to soil conservation or climate change. In most real world applications, the conservationist assessing the effectiveness of conservation practices at reducing watershed sediment yield under various climate change scenarios is confronted with the confounding effects of many integrated controls of sediment yield. If a climate change were present, it would be difficult to untangle the contribution of climate change and conser-

vation measures from that of other natural or anthropogenic causes. Computer simulations of soil erosion and sediment yield are more successful at quantifying the impact of climate change on conservation effects than analysis of observational records, because, in simulation studies, physiographic variables can be held constant and natural background noise suppressed while evaluating the impacts of climate change scenarios on conservation outcomes. Most importantly, computer simulations are ideal for simulating impacts of alternative conservation measures under identical climate forcing and determining conservation outcomes under climate change scenarios. Computer simulations are particularly well suited for planning, comparing, and assessing watershed-scale effects of conservation targeting and coverage in large heterogeneous watersheds with or without climate change.

The above considerations leave little doubt that soil erosion and watershed sediment yield will increase in the future if the climate gradually shifts to a wetter state, and that additional conservation measures may be required to control increasing soil erosion rates. Anticipating the actual extent of climate change is the greatest source of uncertainty. Global Circulation Models are the primary source of climate projections through the end of the twenty-first century. While there is general agreement that air temperature has increased in recent decades and will continue to do so in the near future, there is still great uncertainty and conflicting GCM simulation results with regard to precipitation projections for many regions in the contiguous United States. In addition to annual climate trends, seasonal trends are an important consideration in agriculture. Studies that have examined multiple projections from groups of models (i.e., ensembles) suggest that seasonal shifts in precipitation frequency and intensity are likely. Drier summers and wetter springs in much of the Midwest are being projected, and these projected trends are supported by observations, especially since the 1970s. Because agricultural soils are most vulnerable to intense rainfall in spring when tillage and planting operations take place, greater conservation efforts and mitigating agronomic management practices (such as strip-cropping and no-till) may be required in the future to maintain the soil resource. Furthermore, consistent and concurring long term annual and seasonal precipitation pro-

jections are a prerequisite for development, funding, and implementation of new conservation programs that specifically address soil erosion under climate change scenarios.

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