# CLIMATE VARIATIONS, SOIL CONSERVATION, AND RESERVOIR SEDIMENTATION

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**Abstract:** The integrated effects of soil conservation and a wetter climate on reservoir sedimentation were investigated for the Fort Cobb Reservoir watershed in west-central Oklahoma. A 12% wetter climate since the mid-1980s led to an increase in soil erosion and downstream sediment yield that offset the reduction in sediment yield achieved by extensive soil conservation practices. Additional conservation efforts that reduce sediment yield by another 30%, as well as a drier climate, would be needed to slow the reservoir sedimentation rate enough to where the storage capacity allocated for sediment retention is not filled prematurely. Findings indicated that conservation benefits and impacts of climate variations had similar magnitude and offset one another. Both should be taken into consideration when projecting the potential impacts of conservation programs on downstream reservoir sedimentation.

## INTRODUCTION

Soil conservation practices are effective at reducing overland soil erosion and sediment delivery to channels (Berg et al., 1988; McGregor et al., 1990). However, for a variety of reasons, upstream soil conservation does not always translate into an immediate and proportional reduction in sediment yield at a downstream location, such as a reservoir (Trimble, 1999; Santhi et al., 2005; Shields, 2008; Garbrecht and Starks, 2009). This study focused on assessing the integrated effects of land use conversion, upstream soil conservation practices, and an increase in annual precipitation on the sedimentation of Fort Cobb Reservoir in west central Oklahoma. Available climatic, watershed runoff, and sediment yield data reached back to the 1940s and provided a unique opportunity to conduct a "before-and-after" analysis and establish the impacts on reservoir sedimentation rates and filling of the allocated sediment storage capacity.

## AVAILABLE DATA

**Watershed Sediment Yield and Discharge Data:** The Fort Cobb Reservoir in Central Oklahoma was constructed in 1958-59 by the US Bureau of Reclamation. It is a multipurpose reservoir for flood control, municipal and industrial water supply, and recreation. The reservoir receives inflow from a 787 [$km^2$] agricultural watershed. In 1943-1950, the US Geological Survey (USGS) made daily flow measurements and 1249 instantaneous suspended-sediment measurements at the Cobb Creek gauging station just below the location of today's Fort Cobb dam. In 2004-2008, 150 sediment and discharge measurements were taken by the USGS at three gauging stations on tributaries flowing into Fort Cobb reservoir. A record of estimated monthly discharge into the reservoir since 1959 was also available.

**Land Use and Conservation Practices in the 1940s and 1950s:** Storm et al. (2007) estimated that in years 1940-1957, 72% of the watershed area was in cropland, about 25% in grassland (range and pasture land), and the remaining 3% in forest, roads, and urban areas. Historical accounts suggest that early conservation work in Oklahoma during the 1930s and 1940s consisted primarily of widely scattered demonstration projects (Phillips and Harrison, 2004). Thus, the extent of conservation practices in the Fort Cobb Reservoir watershed before the 1950s was rather limited and, for the purpose of this study, assumed to be essentially non-existent.

**Land Use and Conservation Practices in 2004-2008:** At the beginning of the 21$^{st}$ century, three separate land use studies using remote sensing suggested that land use remained rather stable from 2001 through 2005 with 52% in cropland, 36% in grass, and 12% in other land uses (urban, forest, roads, water etc.). Conservation efforts were extensive and targeted mostly cropland. Eighty to 90% of cropland was terraced, about 50% of the cropland was switched to conservation tillage, gullies were shaped on 6.6 [ha], and 39 grade stabilization structures were installed. Few conservation efforts targeted the stabilization of the channel system. Nine miles of selected channel bank sections were protected from cattle impacts, and 30 creek jacks were installed to shore up failing channel banks. In the late 1950s the Soil Conservation Service (now NRCS) constructed 8 flood retarding structures that controlled 14% of the watershed area. Despite these conservation efforts, several long unstable channel reaches were identified by a geomorphic assessment conducted in 2007 by the USDA-ARS National Sedimentations Laboratory of Oxford, Mississippi (Simon and Klimetz, 2008).

## SEDIMENT YIELD AND RESERVOIR SEDIMENTATION

**Suspended Sediment-Discharge Rating Curves:** Sediment yield was estimated from suspended sediment-discharge (SS-Q) rating curves and discharge records. In this study, a rating curve was defined by a polynomial function fitted to measured sediment versus discharge data. One rating curve was developed with the 1940-1950 sediment and discharge data at the USGS Cobb Creek gauging station, 3.5 [km] downstream of the Fort Cobb dam. This rating curve represented land use and management conditions that prevailed in the 1940s and early 1950s, before conservation practices were implemented (the pre-conservation period). Likewise, three additional SS-Q rating curves were developed with the 2004-2008 suspended-sediment and discharge data at each of the three USGS gauging stations located on major tributaries flowing into the reservoir. These three rating curves represented land use and conservation practices that prevailed since 2004 (the post-conservation period). With the SS-Q rating curves of the two periods the effect of extensive soil conservation practices on watershed sediment yield and reservoir sedimentation rate can be estimated.

**Watershed Sediment Yield and Reservoir Sedimentation Rate:** Mean annual watershed sediment yield at the Cobb Creek gauging station for pre-conservation conditions was estimated by evaluating the pre-conservation SS-Q rating curve with 1940-1964 discharge data at that gauge. Sediment yield into the reservoir was approximated by adjusting the sediment yield at the gauge to reflect differences in drainage area and delivery ratio between the gauge and reservoir inflow location. The mean annual sediment yield into the reservoir under pre-conservation conditions was 255'000 [Mg/yr]. Likewise, mean annual sediment yield at the three gauging stations on the tributaries upstream of the reservoir was estimated by evaluating each post-

conservation SS-Q rating curve with 1984-2008 discharge data at each respective gauge. Sediment yield into the reservoir was again approximated by making adjustments to account for changes in drainage area and delivery ratio between the gauge and reservoir inflow location. The mean annual sediment yield into the reservoir under post-conservation conditions was 248'000 [Mg/yr]. The difference in sediment yield between pre and post-conservation was surprisingly small (3%) given the extensive conservation practices over the last 50 years.

This apparent disconnect between watershed sediment yield and upstream conservation practices can be explained by a shift in mean annual precipitation around 1985 (Figure 1). Mean annual precipitation for 1940-1964 was 728 [mm/yr], whereas for 1984-2008 it was 820 [mm/yr], a 12% average increase sustained over a 25 year period. Heavy storms (>100 [mm/day]) were more frequent during 1940-1964 (7 heavy storms) than during 1984-2008 (4 heavy storms). This shift in precipitation produced a corresponding increase in mean annual reservoir inflow from 1.43 [$m^3$/s] to 2.60 [$m^3$/s], an average increase of about of 80% (Figure2), which in turn led to an increase in soil erosion and watershed sediment yield. Specifically, in the case of the Fort Cobb reservoir watershed, the nearly constant mean annual sediment yield for pre- and post-conservation conditions suggested that the reduction in sediment yield due to conservation practices was offset by an equal increase in sediment yield due to the increase in runoff.

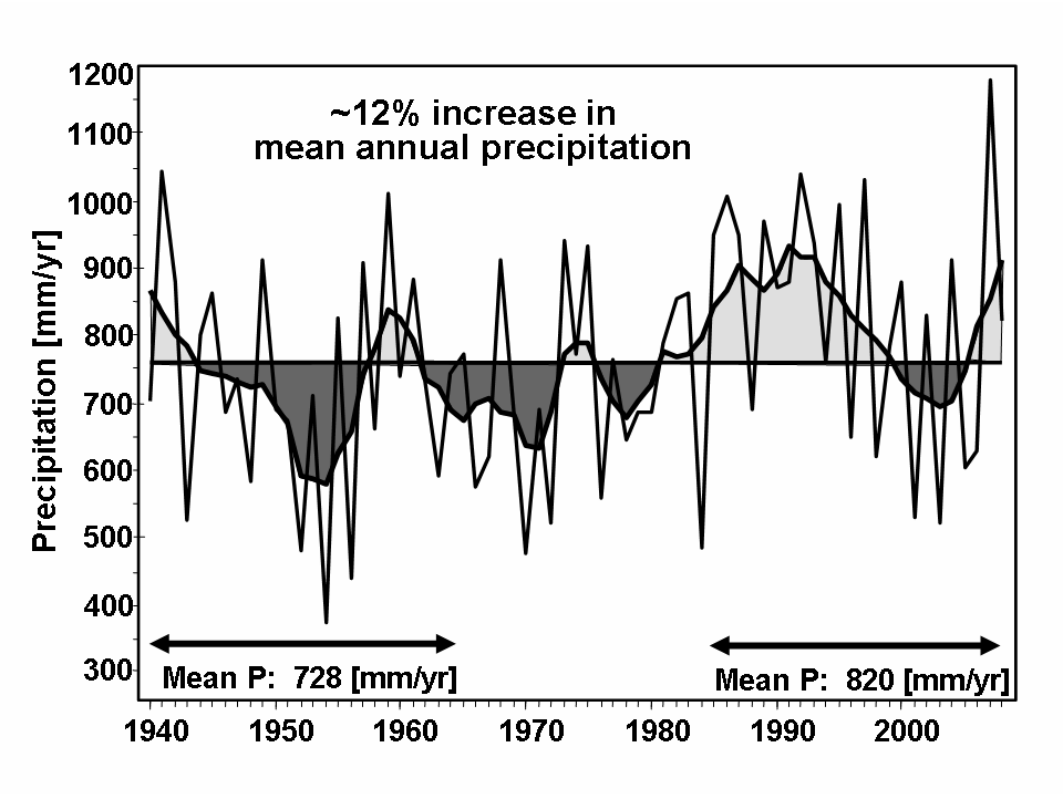


Figure 1 Annual precipitation and persistent precipitation variations for the Fort Cobb Reservoir watershed. The pre- and post-conservation periods are identified by the arrows at the bottom of the figure.

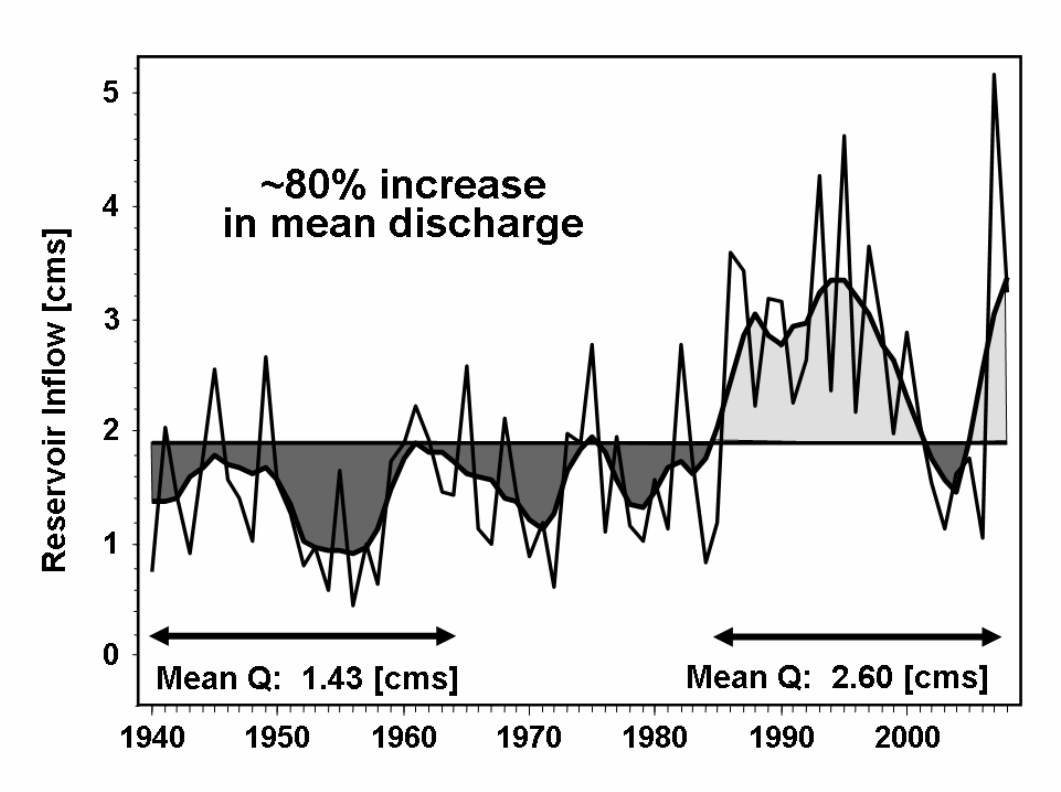


Figure 2 Annual reservoir inflow and persistent variations for the Fort Cobb Reservoir. The pre- and post-conservation periods are identified by the arrows at the bottom of the figure.

The size of the sediment reduction due to conservation practices was approximated by evaluating the pre-and post conservation SS-Q rating curve with the same 1984-2008 discharge. This approximation resulted in a sediment yield of 586'000 [Mg/yr] and 248'000 [Mg/yr] for pre- and post-conservation conditions, respectively. Thus, conservation practices reduced watershed sediment yield by a factor of about 2.4. Since the combined effect of conservation and wetter climate produced no reduction in sediment yield between the pre- and post-conservation periods, one can infer that the increase in precipitation and runoff must have increased sediment yield by an amount equal to the sediment yield reduction due to conservation practices.

**Reservoir Sedimentation:** The estimation of the time to fill the storage capacity allocated for sediment deposition and at which reservoir sedimentation begins to encroach upon reservoir storage capacities provided for other purposes is a critical issue in reservoir design. The design storage capacity for sediment retention was 18.5 [$10^6$ $m^3$] (US, 1953), and it was initially estimated to take 50 years to fill. Upon additional sediment sampling, and anticipation of future conservation efforts, it was determined that the allocated storage for sediment retention would be sufficient for at least 100 years, or until about 2060 (US, 1953). The potential of future climatic variations was most likely not a consideration for reservoir sedimentation issues in the 1950s.

Cumulative reservoir sedimentation is shown in Figure 3. The upper-most curve represents the cumulative sedimentation under the assumption that pre-conservation conditions persisted through 2008, i.e. without implementation of any conservation practices. The lower-most curve

represents the cumulative sedimentation under the assumption that post- conservation conditions were in effect back to the 1960s. The true cumulative reservoir sedimentation lies somewhere in between. If one were to estimate reservoir sedimentation with the previously calculated SS-Q rating curves (assuming the switch from pre- to post-conservation occurred half-way between 1959 and 2008), then one would obtain the middle curve. The validity of the estimated sedimentation based on these assumptions and SS-Q rating curves is supported by two reservoir sedimentation surveys that were conducted in 1993 and 2005 (indicated by a dot in Figure 3).

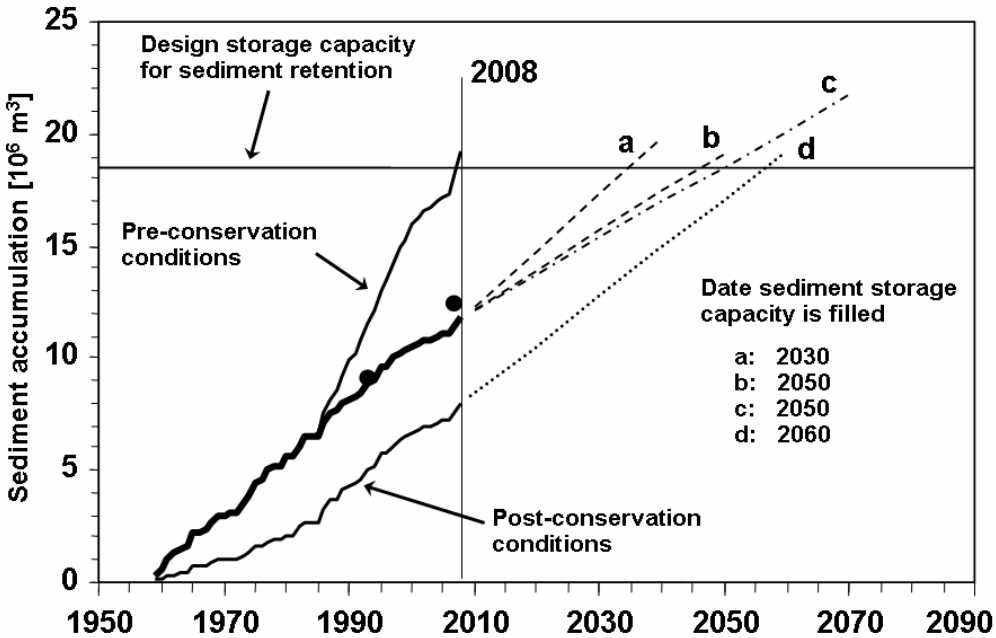


Figure 3 Cumulative Fort Cobb Reservoir sedimentation and estimation of time when allocated storage for sediment retention is filled (dashed lines). Line a: current (1984-2008) climatic and current (2004-2008) conservation conditions persist. Line b: current (1984-2008) climatic conditions persist and additional conservation measures are taken that reduce sediment yield by another 30%. Line c: 1959-2008 climatic conditions and current (2004-2008) conservation persist. Line d: current (1984-2008) climate conditions and current (2004-2008) conservation practiced in effect since 1959.

If 1940-1960 pre-conservation land use and management conditions had persisted the entire time (through 2008), then the storage allocated for sediment deposition would have been filled in 50 years or by 2008, which was in line with initial design estimates (US, 1953). On the other hand, if all conservation practices during the 2005-2008 post-conservation period had been in place the entire time (back to 1959) and today's climate persisted, then the storage allocated for sediment deposition would have been filled in about 110 years or by 2060 (line d in Figure 3), which was in line with the revised and final design estimates (US, 1953). The actual reservoir sedimentation

in 2008 was about 11.8 [$10^6$ $m^3$], or 60% of allocated storage. If today's post-conservation conditions and climate persist, then the allocated storage for sediment retention would be filled by 2035 (line a in Figure 3). If additional conservation practices were installed and sediment yield were reduced by 30%, then the date at which the storage would be filled is pushed back to 2050 (line b in Figure 3). Alternatively, if the present (1984-2008) climate reverted to the 1959-2008 average climate, then the date of filling would also be 2050 (line c in Figure 3). The close correspondence of curves b and c demonstrated that changing the identification of present climate from 1984-2008 conditions to 1959-2008 conditions has about the same impact on reservoir sedimentation as a 30% reduction in sediment yield. Based on the given estimates, both additional conservation practices and a drier climate may be needed to slow the reservoir sedimentation rate to where the design storage capacity for sediment retention is filled by the design date of 2060.

## CONCLUSIONS

For the Fort Cobb Reservoir watershed, the reduction in watershed sediment yield and reservoir sedimentation rate achieved by extensive conservation practices implemented over a 50-year period (1960-2008) was offset by a shift in the mid-1980s to a 12% wetter climate. In 2008, the design storage capacity allocated for sediment retention was 60% full. It was inferred that an additional reduction in sediment yield/sedimentation rate of about 30% and a drier climate would be necessary to meet the design date of 2060 before filling the design sediment storage capacity. These results show that conservation benefits and the impacts of observed climate variations can be of similar magnitude, and both should be taken into consideration when projecting the potential impacts of conservation programs.

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