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Quantifying suspended sediment loads delivered to Cheney Reservoir, Kansas: Temporal patterns and management implications

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Abstract: Cheney Reservoir, constructed during 1962 to 1965, is the primary water supply for the city of Wichita, the largest city in Kansas. Sediment is an important concern for the reservoir as it degrades water quality and progressively decreases water storage capacity. Long-term data collection provided a unique opportunity to estimate the annual suspended sediment loads for the entire history of the reservoir. To quantify and characterize sediment loading to Cheney Reservoir, discrete suspended sediment samples and continuously measured streamflow data were collected from the North Fork Ninnescah River, the primary inflow to Cheney Reservoir, over a 48-year period. Continuous turbidity data also were collected over a 15-year period. These data were used together to develop simple linear regression models to compute continuous suspended sediment concentrations and loads from 1966 to 2013. The inclusion of turbidity as an additional explanatory variable with streamflow improved regression model diagnostics and increased the amount of variability in suspended sediment concentration explained by 14%. Using suspended sediment concentration from the streamflow-only model, the average annual suspended sediment load was 102,517 t (113,006 tn) and ranged from 4,826 t (5,320 tn) in 1966 to 967,569 t (1,066,562 tn) in 1979. The sediment load in 1979 accounted for about 20% of the total load over the 48-year history of the reservoir and 92% of the 1979 sediment load occurred in one 24-hour period during a 1% annual exceedance probability flow event (104-year flood). Nearly 60% of the reservoir sediment load during the 48-year study period occurred in 5 years with extreme flow events (9% to 1% annual exceedance probability, or 11- to 104-year flood events). A substantial portion (41%) of sediment was transported to the reservoir during five storm events spanning only eight 24-hour periods during 1966 to 2013. Annual suspended sediment load estimates based on streamflow were, on average, within ±20% of estimates based on streamflow and turbidity combined. Results demonstrate that large suspended sediment loads are delivered to Cheney Reservoir in very short time periods, indicating that sediment management plans eventually must address large, infrequent inflow events to be effective.

Key words: Cheney Reservoir—continuous data—Kansas—regression—reservoir management—sediment load

Sediment is a primary aquatic impairment in the United States (US EPA 2009), including Kansas (Kansas Department of Health and Environment 2012). Reservoir sedimentation decreases storage capacity for flood control, water supply, recreation, and habitat for fish and wildlife. Frequently, if not typically, the majority of the deposited sediment in large reservoirs is silt and clay (Morris and Fan 1998). Such fine-grained sediment is an environmental concern because it degrades habitat and water quality (Owens et al. 2005), contributes to declines in aquatic organism populations (Waters 1995; Henley et al. 2000), and creates lower light conditions in the water column, which can inhibit the growth of some phytoplankton and aquatic macrophytes (Wetzel 2001; Donohue and Molinos 2009) while possibly favoring cyanobacterial growth (Chorus and Bartram 1999). Fine-grained sediment also provides attachment sites and a transport medium for nutrients, metals, and several other contaminants (Owens et al. 2005; Luoma and Rainbow 2008). Management to ensure the long-term viability of a reservoir requires that the sedimentation issue be addressed. Requisite for the development of an effective sediment management plan is an understanding of sediment delivery to the reservoir.

Cheney Reservoir, located on the North Fork Ninnescah River in south-central Kansas (figure 1), was constructed between 1962 and 1965 by the Bureau of Reclamation to provide a municipal water supply for the city of Wichita, as well as flood control, wildlife habitat, and recreation. The reservoir has been identified as impaired under Section 303(d) of the Federal Clean Water Act for eutrophication and siltation (Kansas Department of Health and Environment 2012). Sedimentation is progressively reducing the storage capacity of the reservoir. As of 2012, the reservoir may have lost about 6% of its original multipurpose pool capacity because of sedimentation according to Christian Gnau (Kansas Water Office, personal communication, August 6, 2012). Given the unknown accuracy of the original capacity, combined with the limited coverage of the bathymetric survey used to estimate the volume of sedimentation (Mau 2001), the accuracy of the 6% storage loss estimate is uncertain.

The objectives of this paper are to describe a study to quantify and characterize suspended sediment loads (SSLs) delivered to Cheney Reservoir and discuss the management implications. Understanding sediment transport is important for the development of effective sediment management strategies to help ensure the long-term viability of the reservoir. A unique outcome of this study was the estimation of annual suspended sediment loads delivered over the entire 48-year history of the reservoir.

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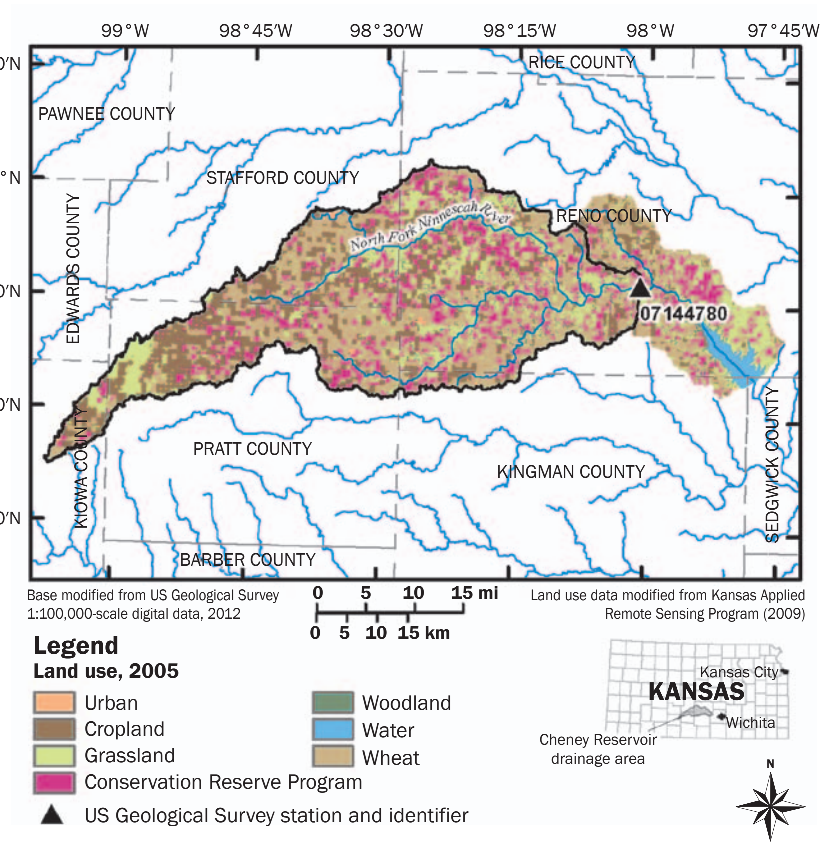
Figure 1

Location of continuous real-time water quality monitoring site and land use in the Cheney Reservoir basin.



Materials and Methods

Study Site. Cheney Reservoir (figure 1) has a drainage area of about 2,420 km^2 (934 mi^2). The reservoir has a multipurpose pool storage capacity of about 206,000,000 m^3 (7,275,000,000 ft^3), a surface area of about 38 km^2 (15 mi^2), and a mean depth of about 5 m (16 ft). The North Fork Ninnescah River contributes about 70% of the inflow to Cheney Reservoir (Christensen et al. 2006) (figure 1). The reservoir basin is underlain by consolidated rocks of Permian age that are covered by unconsolidated fluvial and eolian deposits of Pleistocene age (Zeller 1968). Topographically, the basin is typified by a land surface that is flat to gently sloping. Soils in the basin are mostly sandy loam and loamy sand (SCS 1966, 1968, 1978). The basin is predominately rural, and cropland accounts for approximately 51% of the land use (figure 1). About 26% of the basin is grassland, and about 18% is Conservation Reserve Program (CRP) land (Peterson et al. 2008). Mean annual precipitation in the basin was about 75 cm (30 in) during 1966 through 2013 (High Plains Regional Climate Center 2014).

Continuous Data. Continuous daily (1966 to 2013) and hourly (1999 to 2013) streamflow data (USGS 2013) were collected at the North Fork Ninnescah River above Cheney Reservoir streamgage (US Geological Survey [USGS] gaging station 07144780; figure 1) (hereinafter referred to as the inflow site) using standard USGS methods (Sauer and Turnipseed 2010; Turnipseed and Sauer 2010). The log Pearson Type III distribution (Brooks et al. 2012), following Flynn et al. (2006) with a computed generalized skew coefficient of 0.4, was used for the analytical development of peak discharge frequency curves for the characterization of substantial streamflow peaks during the study period.

Continuous turbidity data were collected hourly using a YSI 6600 Extended Deployment System water quality monitor equipped with YSI model 6026 or 6136 optical turbidity sensors from December of 1998 to December of 2013. For parity, all turbidity data collected using the 6026 sensor were converted to 6136 turbidity data as described in Stone et al. (2013a). Turbidity data obtained using the two sensors were strongly correlated (r^2 = 0.96). The monitor was installed near the centroid of streamflow to best represent conditions across the river width and was maintained in accordance with standard USGS procedures (Wilde and Radke 1998; Wagner et al. 2006).

Discrete Data. Discrete water samples were collected over a range of streamflow conditions from 1970 to 2012 (figure 2) using depth- and width-integrating sample collection techniques (Guy and Norman 1970; Wilde and Radke 1998; Edwards and Glysson 1999; US Geological Survey 2006). The samples were analyzed for suspended sediment concentration (SSC) at the USGS Iowa Sediment Laboratory in Iowa City, Iowa, according to methods described in Guy (1969).

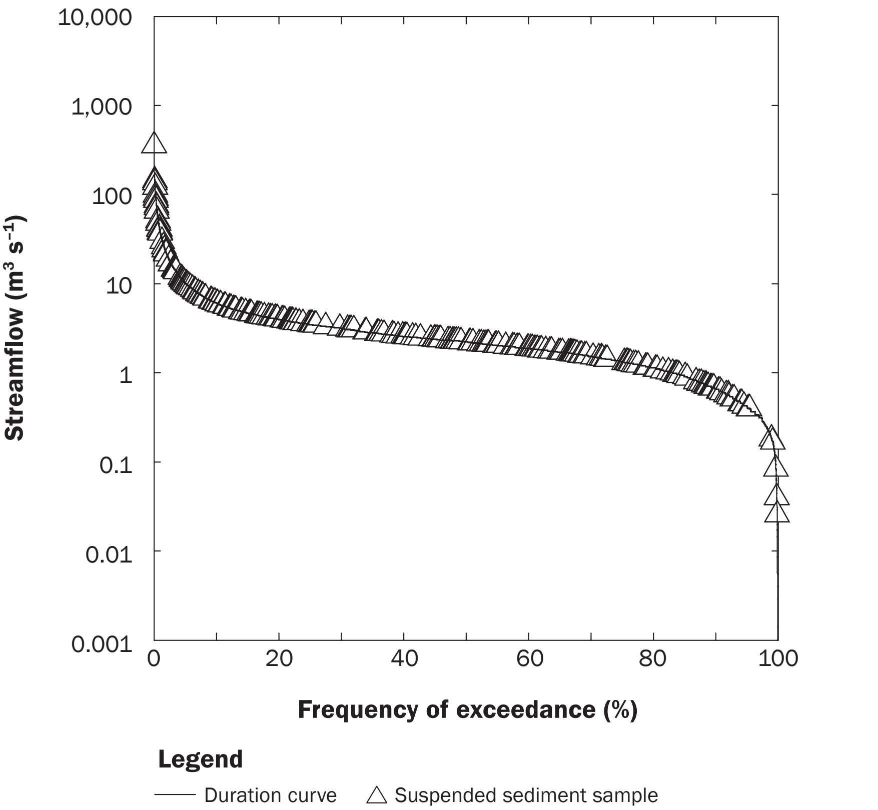
Model Development. Models were developed using simple linear regression analyses to relate discrete SSC samples to continuously measured streamflow and (or) turbidity (Helsel and Hirsch 2002; Rasmussen et al. 2009). Four SSC models were developed for this study that used the following sets of available continuous data as explanatory variables: daily mean streamflow data from 1970 to 2012, daily mean streamflow data from 1999 to 2012, hourly turbidity data from 1999 to 2012, and hourly streamflow and hourly turbidity data from 1999 to 2012. All data were log-transformed to normalize variability in regression residuals.

Methods used for model development, quantifying uncertainty, and computation of loads and yields are described in detail in Rasmussen et al. (2009) and Stone et al. (2013a, 2013b). Data were analyzed using TIBCO Spotfire S+ 8.1 for Windows statistical software (TIBCO Software, Inc. 2008). Outliers were identified and removed from model datasets using leverage (Hoaglin and Welsch 1978), Cook's distance (Cook 1979), and difference in fits (DFITS) (Welsch and Kuh 1977) values.

Mean square error and root mean square error were calculated for each model to assess the variance between computed and measured values (Helsel and Hirsch 2002). Model standard percentage error also was calculated and is the root mean square error expressed as a percentage (Rasmussen et al. 2009). A bias correction factor was calculated

Figure 2

Duration curve for daily streamflow at the North Fork Ninnescah River upstream from Cheney Reservoir (US Geological Survey gaging station 07144780), south-central Kansas, during 1965 through 2013.



for each model for transformation of estimates back into original units (Duan 1983).

Concentration and Load Computations. Continuous daily and hourly SSCs were calculated using the developed regression models and continuous water quality data. Two methods were used to compute SSCs for infrequent brief periods of missing continuous data. Continuous measurements were linearly interpolated when two or fewer values were missing using the least squares method (Sokal and Rohlf 2012). The streamflow-only regression model was used for SSC computation when more than two values of continuous turbidity data were missing because streamflow data were available for almost all (99.9%) of the period. Computed SSC data varied because of differences in continuously monitored turbidity-based and streamflow-based regression models. The streamflow-based SSCs were shifted to the next available continuous datum based on methods described in Porterfield (1972) to smooth the steps in computed SSC data from the different models. When no flow or turbidity data were available, SSCs were not computed. Uncertainty associated with regression-computed SSCs was quantified using 90% prediction intervals (Helsel and Hirsch 2002). Duration curves were constructed to evaluate frequency and magnitude characteristics using the Weibull formula (Helsel and Hirsch 2002) for calculating plotting position.

Suspended sediment loads were calculated for the period of record (1966 to 2013) using SSCs from the daily streamflow-only model developed from 1970 to 2012 data and from 1999 to 2013 using SSCs from the hourly streamflow and hourly turbidity-based model. The other two models were used for comparative purposes only. Daily and hourly SSLs were calculated by multiplying the calculated SSCs in milligrams per liter by daily or hourly streamflow in cubic meters per second, then multiplying by 8.64×10^{-5} for daily loads or 3.6×10^{-6} for hourly loads to obtain load in tons. Annual SSLs, calculated by summing the daily or hourly SSLs, were adjusted using a multiplier to convert gage-specific SSLs to reservoir basin-equivalent SSLs.

Results and Discussion

Streamflow and Turbidity. Mean daily streamflow at the inflow site from 1966 to 2013 was about 4 m^3 s^{-1} (141 ft^3 s^{-1}) with a range in daily values of <0.001 to 1,124 m^3 s^{-1} (<0.035 to 39,694 ft^3 s^{-1}; table 1). Daily streamflows that were <0.001 m^3 s^{-1} (<0.035 ft^3 s^{-1}) occurred in July of 1966 and 2012 and August of 2012. The largest daily streamflow from 1966 to 2013 was recorded on October 30, 1979. Annual mean streamflow ranged from about 1.2 m^3 s^{-1} (42 ft^3 s^{-1}) in 2012 to about 9.7 m^3 s^{-1} (343 ft^3 s^{-1}) in 1973. Hourly streamflow from 1999 to 2013 ranged from <0.001 m^3 s^{-1} (<0.035 ft^3 s^{-1}) to about 240 m^3 s^{-1} (8,476 ft^3 s^{-1}) and averaged about 3.7 m^3 s^{-1} (131 ft^3 s^{-1}; table 1). The largest hourly streamflow from 1999 to 2013 was measured on July 6, 2010. Mean hourly turbidity from 1999 to 2013 was 30.0 formazin nephelometric units (FNU) and ranged from <1.0 FNU to 1,195 FNU (table 1). Turbidities that were <1.0 FNU occurred in October and November of 2012 and the highest turbidity occurred in September of 2001. Annual mean turbidity ranged from 12.8 FNU in 2012 to 55.8 FNU in 2002.

Regression Models. Streamflow is commonly used as a surrogate for SSC (Rasmussen et al. 2009) and previously has been used for that purpose at the inflow site (Putnam and Pope 2003; Christensen et al. 2006; Stone et al. 2013a, 2013b). Streamflow was positively correlated with SSC in both streamflow-only models (table 2). The regression model developed using SSC and daily streamflow data from 1970 through 2012 had a multiple r^2 value of 0.52 (n = 285; table 2), whereas the regression model developed using SSC and daily streamflow data from 1999 through 2012 had a multiple r^2 value of 0.79 (n = 62; table 2). The lower r^2 for the longer time period was explained by increased variability in the SSC-streamflow relation.

Turbidity also is commonly used as a surrogate for SSC (Rasmussen et al. 2009) and previously has been used for that purpose at the inflow site (Putnam and Pope 2003; Christensen et al. 2006; Stone et al. 2013a, 2013b). Turbidity was positively correlated with SSC. The regression model using hourly turbidity data from 1999 through 2012 as an explanatory variable for SSC had a multiple

Table 1

Summary statistics for variables measured continuously at the North Fork Ninnescah River upstream from Cheney Reservoir (US Geological Survey gaging station 07144780), south-central Kansas, for the period of record (daily) and 1999 through 2013 (hourly).

Continuous variable	*n*	Minimum	Maximum	Mean	Median	Missing data (%)
Daily streamflow ($m^3\ s^{-1}$), for period of record*	17,532	<0.001	1,124	4.0	2.2	<1
Hourly streamflow ($m^3\ s^{-1}$)†	132,851	<0.001	240	3.7	2.4	<1
Hourly turbidity (FNU)†	121,566	<1.0	1,195	30.0	18.0	9

Notes: Continuous real-time water quality data are available on the US Geological Survey National Real-Time Water-Quality Website (http://nrtwq.usgs.gov/ks). FNU = formazin nephelometric units.

*January 1966 through December 2013.

†January 1999 through December 2013.

Table 2

Suspended sediment concentration regression models and summary statistics for the North Fork Ninnescah River upstream from Cheney Reservoir (US Geological Survey gaging station 07144780), south-central Kansas, 1970 through 2012.

									Discrete data				
Model	Multiple r^2	r^2 Adjusted	MSE	RMSE	MSPE (upper)	MSPE (lower)	Bias correction factor (Duan 1983)	90% prediction interval (± %)	*n*	Range of values in variable measurements	Mean	Median	Standard deviation
logSSC = 0.7077log(Q) + 1.5979*	0.52	0.52	0.0912	0.3020	0.21	−0.21	1.2636	179	285	SSC: 8-1,340	143	77	205
										Q: 0.17-48	4.8	2.5	6.6
logSSC = 0.9021log(Q) – 1.5400†	0.79	0.78	0.0543	0.2330	0.09	−0.09	1.1554	117	62	SSC: 15-1,240	253	162	296
										Q: 0.39-48	8.3	4.4	9.8
logSSC = 1.0040log(TBY) + 0.4317‡	0.74	0.73	0.0671	0.2590	0.10	−0.10	1.2047	139	62	SSC: 15-1,240	253	162	296
										TBY: 8.4-421	77	51	75
logSSC = 0.5794log(Q) + 0.5146log (TBY) + 0.8729§	0.88	0.88	0.0307	0.1753	0.07	−0.07	1.0828	77	62	SSC: 15-1,240	253	162	296
										Q: 0.42-59	8.6	4.4	11
										TBY: 8.4-421	77	51	75

Notes: r^2 = coefficient of determination. MSE = mean square error. RMSE = root mean square error. MSPE = model standard percentage error. SSC = suspended sediment concentration. Q = streamflow in cubic meters per second. log = $\log_{10}$. TBY = turbidity in formazin nephelometric units.

*Model uses suspended sediment and concomitant daily streamflow data from 1970 through 2012.

†Model uses suspended sediment and concomitant daily streamflow data from 1999 through 2012.

‡Model uses suspended sediment and concomitant hourly turbidity data from 1999 through 2012.

§Model uses suspended sediment and concomitant hourly streamflow and hourly turbidity data from 1999 through 2012.

r^2 value of 0.74 (n = 62; table 2). The use of both hourly streamflow and turbidity in a regression model improved model diagnostics, which included a decrease in uncertainty and a 14% increase in the amount of variability in SSC explained (adjusted r^2 = 0.88 and n = 62; table 2). Stone et al. (2013a, 2013b), using hourly data for the inflow site from 1999 to 2009, determined that the turbidity plus streamflow regression model explained 8% more variance in SSC than the streamflow-only model.

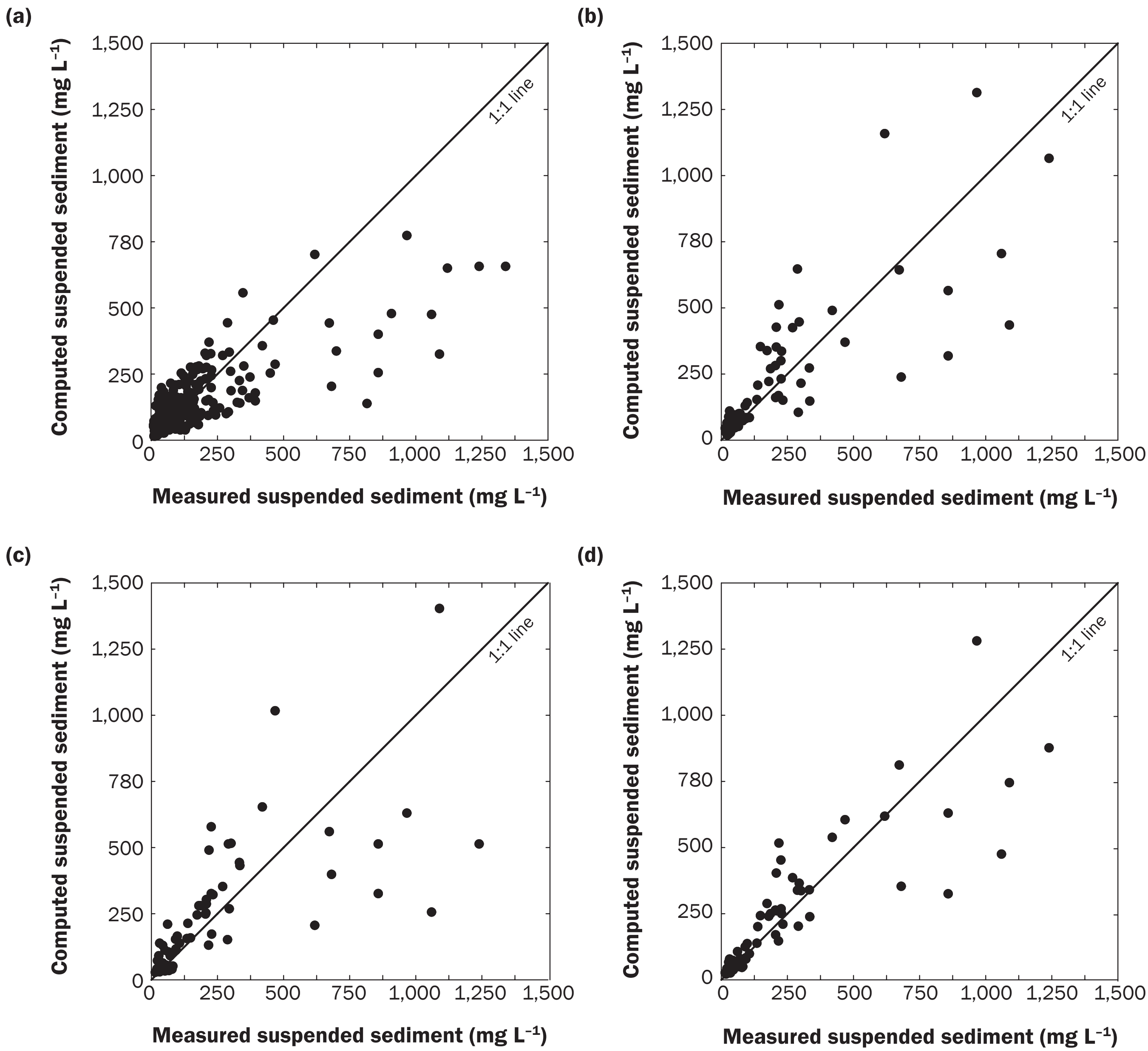
Regression-computed vs. measured SSC bivariate plots (figure 3) provide an indication of regression model accuracy in addition to the model statistics presented in table 2. The model predictions are more accurate when the points plot closely to the 1:1 line. Using this criterion, it is likely that the streamflow-only model using data from 1970 to 2012 underestimates the upper range of SSCs (figure 3a) as compared to the streamflow-only model that was developed using data from 1999 through 2012 (figure 3b). The combined use of streamflow and turbidity increased model accuracy (figure 3d).

Suspended Sediment Concentrations and Loads. Using the daily streamflow-only model developed from 1970 to 2012 data, daily computed SSC for the inflow site ranged from <0.01 to 7,222 mg L^{-1} (ppm) and averaged 113 mg L^{-1} (ppm) from 1966 to 2013. During that period, daily SSCs <0.01 mg L^{-1} (ppm) occurred in July of 1966 and 2012 and in August of 2012, corresponding with the periods of lowest streamflow. The maximum daily computed SSC occurred on October 30, 1979, which had the highest daily mean streamflow (1,124 $m^3\ s^{-1}$ [39,694 $ft^3\ s^{-1}$]) during the period of record (USGS 2013). Mean hourly computed SSC was 111 mg L^{-1} (ppm) and ranged from 0.15 to 2,418 mg L^{-1} (ppm) from 1999 to 2013. Mean annual computed SSC ranged from 52.1 mg L^{-1} (ppm) in 2012 to 201.7 mg L^{-1} (ppm) in 1987.

Using SSCs from the daily streamflow-only model developed from 1970 to 2012 data, daily computed SSLs for the inflow site ranged from <0.01 to 886,458 t (<0.01 to 977,153 tn) and averaged 281 t (310 tn) from 1966 to 2013. Daily SSLs that were <0.01 t (<0.01 tn) occurred during low flows in July of 1966 and July and August of 2012. The daily SSL maxima

Figure 3

Simple linear regression analysis graphs showing measured versus computed suspended sediment for (a) model using daily streamflow data from 1970 through 2012; (b) model using daily streamflow data from 1999 through 2012; (c) model using hourly turbidity data from 1999 through 2012; and (d) model using hourly streamflow and hourly turbidity data from 1999 through 2012 for the North Fork Ninnescah River upstream from Cheney Reservoir (US Geological Survey gaging station 07144780), south-central Kansas.



occurred on October 30, 1979. Mean annual SSL during the study period was 102,517 t (113,006 tn) and ranged from 4,826 t (5,320 tn) in 1966 to 967,569 t (1,066,562 tn) in 1979, corresponding to the smallest (0.04 km^3 [0.01 mi^3]) and fourth-largest (0.26 km^3 [0.06 mi^3]) annual streamflows (table 3 and figure 4).

Most sediment is transported during relatively brief high-flow periods and substantial temporal variability in sediment transport is a common attribute of rivers (Meade and Parker 1985; Morris and Fan 1998). For Cheney Reservoir, the total delivered SSL during 1966 through 2013 was estimated to be 4,920,825 t (5,424,281 tn; table 3). It is stated here for clarity that this load estimate does not include bedload or material delivered to the reservoir by shoreline erosion. Nearly 60% (2,806,159 t [3,093,261 tn]) of the total SSL during the study period occurred in five years with extreme flow events (11- to 104-year flood events, or 9% to 1% annual exceedance probabilities; table 3 and figure 4). The annual SSLs for these episodic five years substantially exceeded the

Table 3

Computed annual suspended sediment loads at the North Fork Ninnescah River upstream from Cheney Reservoir (US Geological Survey gaging station 07144780), south-central Kansas, during 1966 through 2013.

Year	Streamflow (km^3)	Suspended sediment load (t)	Annual suspended sediment load as percent of total load for 1966 to 2013
1966	0.04	4,826	0.1
1967	0.06	11,342	0.2
1968	0.07	34,743	0.7
1969	0.10	33,304	0.7
1970	0.09	38,245	0.8
1971	0.06	8,250	0.2
1972	0.05	5,885	0.1
1973	0.31	462,978	9.4
1974	0.19	339,932	6.9
1975	0.11	46,884	1.0
1976	0.10	85,870	1.7
1977	0.21	217,851	4.4
1978	0.12	46,821	1.0
1979	0.26	967,569	19.7
1980	0.13	47,626	1.0
1981	0.08	18,165	0.4
1982	0.11	35,993	0.7
1983	0.12	41,807	0.8
1984	0.12	44,682	0.9
1985	0.14	61,270	1.2
1986	0.18	86,325	1.8
1987	0.30	370,758	7.5
1988	0.09	19,508	0.4
1989	0.13	57,789	1.2
1990	0.11	31,297	0.6
1991	0.09	58,548	1.2
1992	0.11	29,437	0.6
1993	0.28	236,244	4.8
1994	0.06	8,718	0.2
1995	0.25	664,921	13.5
1996	0.08	16,380	0.3
1997	0.10	18,102	0.4
1998	0.13	39,150	0.8
1999	0.11	28,271	0.6
2000	0.11	49,779	1.0
2001	0.12	38,002	0.8
2002	0.07	12,882	0.3
2003	0.10	44,852	0.9
2004	0.12	36,268	0.7
2005	0.14	51,956	1.1
2006	0.05	5,859	0.1
2007	0.15	84,904	1.7
2008	0.14	45,017	0.9
2009	0.18	76,377	1.6
2010	0.19	150,823	3.1
2011	0.05	6,017	0.1
2012	0.04	4,983	0.1
2013	0.13	93,613	1.9
Total load 1966 to 2013	6.10	4,920,825	—
Minimum	0.04	4,826	—
Maximum	0.31	967,569	—
Mean	0.13	102,517	—
Median	0.11	43,245	—

Notes: All loads are estimated using suspended sediment concentrations from the daily streamflow-only model developed from 1970 to 2012 data.

mean annual SSL of 102,517 t (113,006 tn), as well as an estimated mean annual load of 205,477 t (226,500 tn) that was based on a bathymetric survey of sediment deposition in the reservoir during 1965 through 1998 (Mau 2001) (figure 4). As shown in figure 4, the long-term mean annual loads typically are a poor indicator of the actual load delivered to the reservoir for any given year.

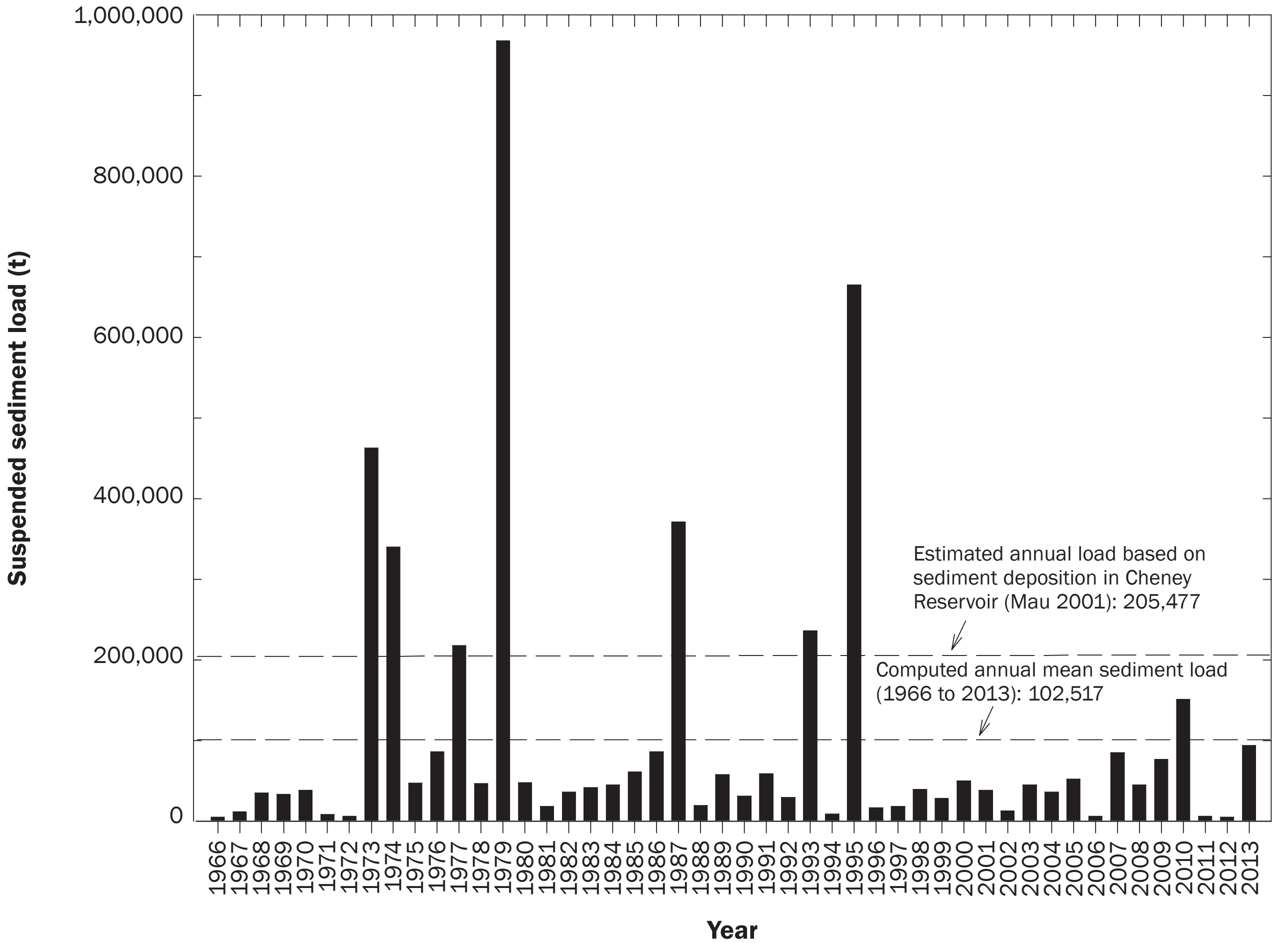
The substantial difference between the two mean annual load estimates likely is a result of several factors. First, whereas the SSL estimate only addressed suspended sediment, the bathymetrically derived estimate also addressed contributions from bedload and reservoir shoreline erosion. Second, the bathymetrically derived estimate was based on a bathymetric survey that was limited in coverage (Mau 2001) and, therefore, may have introduced substantial error into the sediment volume estimate. Third, the sediment bulk density data used in the volume-to-mass conversion were derived from a limited number of sediment cores (Mau 2001) and may not have been representative for at least parts of the reservoir.

A substantial portion (41%) of sediment was transported to the reservoir during five storm events spanning only eight 24-hour periods during 1966 through 2013; restated, about 40% of the total sediment load was conveyed during <0.05% of the study period. The 1979 sediment load accounted for about 20% of the total load over the 48-year history of the reservoir (table 3 and figure 4) and 92% of the 1979 sediment load (18% of the study period load) occurred in a 24-hour period during a 1% annual exceedance probability flow event (104-year flood event) during October 30 through November 2. The remaining seven 24-hour periods, which accounted for approximately 23% of the sediment load (1,115,625 t [1,229,766 tn]) for the study period, occurred during the years 1973, 1974, 1987, and 1995 (table 3 and figure 4). Within these four years, 53% to 75% of the annual sediment load (5% to 9% of the 1966 to 2013 sediment load) was transported during each of the seven 24-hour storm periods (October 11 and 13, 1973; April 20, 1974; July 4 to 6, 1987; and May 27, 1995).

Addition of turbidity to streamflow-based regression models has been shown to decrease uncertainty and increase the amount of variance explained by suspended sediment concentration regression models for the inflow to Cheney Reservoir (Stone

Figure 4

Computed annual suspended sediment loads using suspended sediment concentrations computed using the daily streamflow-only model (based on 1970 to 2012 data) at the North Fork Ninnescah River upstream from Cheney Reservoir (US Geological Survey gaging station 07144780), south-central Kansas, during 1966 through 2013.



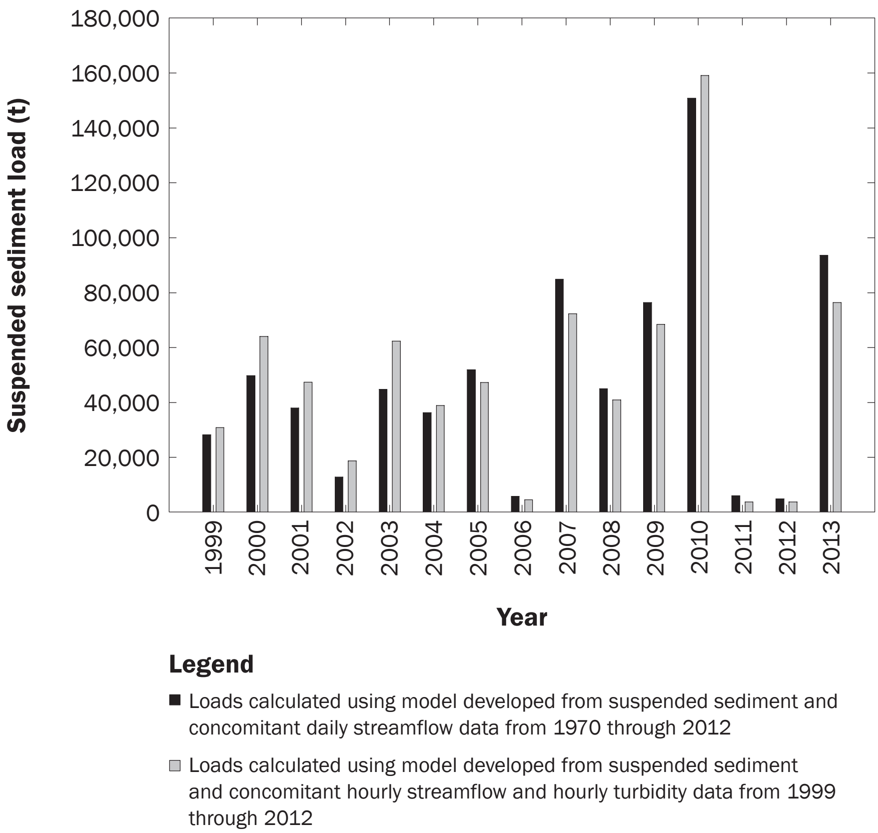
et al. 2013a, 2013b). Annual SSL estimates for 1999 through 2013 based on daily mean streamflow were, on average, within ±20% of estimates based on the combination of hourly streamflow and hourly turbidity (figure 5). Annual SSL estimates from both models indicate similar trends among years (figure 5).

Management Implications. Chronologically, Cheney Reservoir is middle aged if not old. However, in terms of physical age, determined on the basis of total storage capacity lost to sedimentation (about 6% as of 2012) and mean annual sedimentation rate (about 0.1%), Cheney Reservoir is a young reservoir with a slow aging rate according to a classification developed by Juracek (2014). Given that the number of days of heavy precipitation is not expected to change substantially in response to climate change during the next several decades in the central Great Plains (including the Cheney Reservoir basin) (Shafer et al. 2014) and that a recent modeling study predicted that sediment loads would not differ over the twenty-first century in a primarily agricultural Midwest basin (Ahmadi et al. 2014), it is reasonable to project that the current sedimentation rate will continue into the future. Assuming the same mean annual sedimentation rate, the reservoir would lose 50% of its original capacity in about 500 years, or about the year 2465. Although, given the increasing importance of the reservoir as the primary water supply for the city of Wichita, the loss of capacity likely will become a critical issue long before the 50% milestone is reached.

Effective sediment management may require a combination of solutions. For the near term (perhaps one or more decades), given the low sedimentation rate at Cheney Reservoir, voluntary conservation practices in the basin may constitute an acceptable sediment management strategy. Use of conservation practices to minimize sediment runoff has been shown to decrease sediment delivery to streams and reservoirs (McIntyre 1993; Renwick et al. 2005; Renwick et al. 2008; Richards et al. 2008) and prioritized implementation of such practices may further enhance the improvements realized (Legge et al. 2013). Between 1994 and 2011, nontargeted best management practices were implemented at more than 1,000 sites in the Cheney Reservoir basin (Cheney Lake Watershed Incorporated, written communication, 2011). However, a discernable reduction in SSCs has not been observed (Stone et al. 2013a). Prioritized implementation would be appropriate in the agricultural Cheney Reservoir basin where it was estimated that approximately 76% of the sediment load delivered to the reservoir came from 10% of the basin (USDA 2006).

Figure 5

Comparison of computed annual suspended sediment loads using different models at the North Fork Ninnescah River upstream from Cheney Reservoir (US Geological Survey gaging station 07144780), south-central Kansas, during 1999 through 2013.



To have the best chance for success, sediment reduction strategies need to correctly identify the primary sources of sediment in a basin and then implement the appropriate practice(s) in the priority locations.

However, at some point in the future, voluntary conservation practices alone will be inadequate. In particular, such practices may be overwhelmed during the infrequent large storm runoff events that deliver large sediment loads to Cheney Reservoir. In this study it was determined that about 40% of the total 48-year sediment load was delivered to the reservoir in only eight days. To address these events, a more aggressive sediment management strategy eventually will be required. Such a strategy may involve one or more sediment reduction techniques. One possibility is modification of reservoir operational practices to pass sediment-laden inflows through the reservoir more quickly thereby reducing sedimentation (Lee and Foster 2013). Other possibilities include sediment bypass and dredging. A description of various sediment reduction techniques is provided elsewhere (Morris and Fan 1998; Annandale 2013).

Long-term monitoring is imperative for understanding environmental change and providing key resource management insights (Lindenmayer et al. 2012; Gao et al. 2013). For reservoir management, continuous monitoring of inflow (volume, turbidity) is advantageous for the purpose of estimating SSLs, which can be used to project future reservoir sedimentation and water-storage capacity loss. Such information is relevant for various management issues including, but not limited to, sediment removal and disposal, sedimentation reduction strategies, water-supply allocation, development of alternate water supplies, and use of water-conservation practices. Moreover, continuous monitoring of reservoir inflow also can provide decision support for water withdrawals and recreational use, enable assessments of the efficacy of sediment reduction practices implemented in the basin, and provide guidance for the scheduling of bathymetric surveys using sediment accumulation thresholds. For Cheney Reservoir, the availability of continuous long-term inflow data (volume, turbidity) made it possible to estimate suspended sediment concentrations and loads over time scales (decades) and with a level of accuracy that would not otherwise have been attainable.

Summary and Conclusions

Cheney Reservoir, located in south-central Kansas, is the primary water supply for the city of Wichita. In response to concerns about sedimentation in the reservoir and sediment associated water quality issues, long-term data collection was used to quantify and characterize suspended sediment loads delivered to Cheney Reservoir from 1966 to 2013.

Simple linear regression models were used to relate discretely collected suspended sediment concentrations to continuously measured streamflow and turbidity data. These models were used to estimate continuous suspended sediment concentrations and loads during the 48-year study period. Suspended sediment concentration was positively correlated with both streamflow and turbidity. The inclusion of turbidity as an additional explanatory variable with streamflow improved regression model diagnostics and increased the amount of variance explained in suspended sediment concentration. Annual suspended sediment load estimates based on streamflow were, on average, within ±20% of estimates based on streamflow and turbidity combined. The majority (nearly 60%) of the reservoir sediment load over the study period was delivered in five years with extreme flow events (9% to 1% annual exceedance probability, or 11- to 104-year flood events). A substantial portion (41%) of sediment was transported to the reservoir during five storm events spanning only eight 24-hour periods. The sediment load in 1979 accounted for about 20% of the total load over the 48-year history of the reservoir and 92% of the 1979 sediment load occurred in one 24-hour period during a 1% annual exceedance probability flow event (104-year flood).

Suspended sediment concentrations and loads were characterized by pronounced variability during the 48-year study period that likely was caused, in large part, by hydrologic variability in the study area.

Nationally, many studies have shown that large flow events are the main carriers for sediment, and Kansas is no exception. This study demonstrated that large suspended sediment loads are delivered to Cheney Reservoir in very short time periods. In the future, effective sediment management eventually will require the implementation of additional sediment reduction techniques to account for the occasional large storm runoff events that deliver large sediment loads to the reservoir.

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