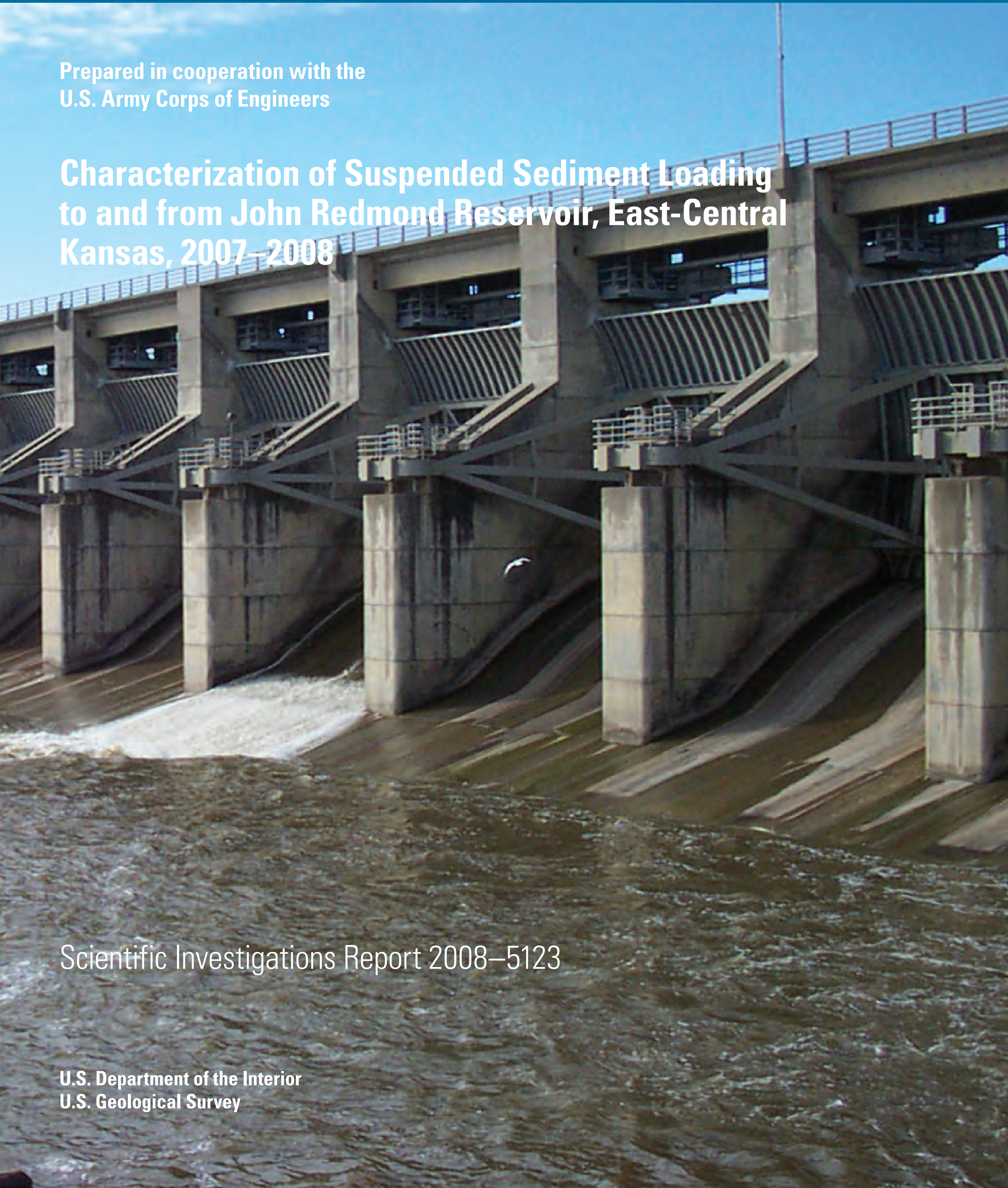

Prepared in cooperation with the
U.S. Army Corps of Engineers

Characterization of Suspended Sediment Loading to and from John Redmond Reservoir, East-Central Kansas, 2007–2008

Scientific Investigations Report 2008–5123

U.S. Department of the Interior
U.S. Geological Survey

Cover. Outflow from John Redmond Reservoir, east-central Kansas (photograph taken by Ashli Maddox, U.S. Geological Survey).

Characterization of Suspended-Sediment Loading to and from John Redmond Reservoir, East-Central Kansas, 2007–2008

By Casey J. Lee, Patrick P. Rasmussen, and Andrew C. Ziegler

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
foot per mile	0.1894	meter per kilometer
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
acre-foot	1,233	cubic meter (m^3)
acre-feet per square mile	476	cubic meters per square kilometer
	Weight	
ton	2,000	pound
ton per square mile	0.3503	metric ton per square kilometer
ton per square mile per year	0.003503	metric ton per hectare per year
pound per cubic foot	16.02	kilogram per cubic meter
	Rate	
tons per day	0.0231	pounds per second
pounds per second	0.453592	kilograms per second
pounds per day	0.4536	kilograms per day
tons per year	0.9072	metric tons per year

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Characterization of Suspended-Sediment Loading to and from John Redmond Reservoir, East-Central Kansas, 2007–2008

By Casey J. Lee, Patrick P. Rasmussen and Andrew C. Ziegler

Abstract

Storage capacity in John Redmond Reservoir is being lost to sedimentation more rapidly than in other federal impoundments in Kansas. The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, initiated a study to characterize suspended-sediment loading to and from John Redmond Reservoir from February 21, 2007, through February 21, 2008. Turbidity sensors were installed at two U.S. Geological Survey stream gages upstream (Neosho River near Americus and the Cottonwood River near Plymouth) and one stream gage downstream (Neosho River at Burlington) from the reservoir to compute continuous, real-time (15-minute) measurements of suspended-sediment concentration and loading.

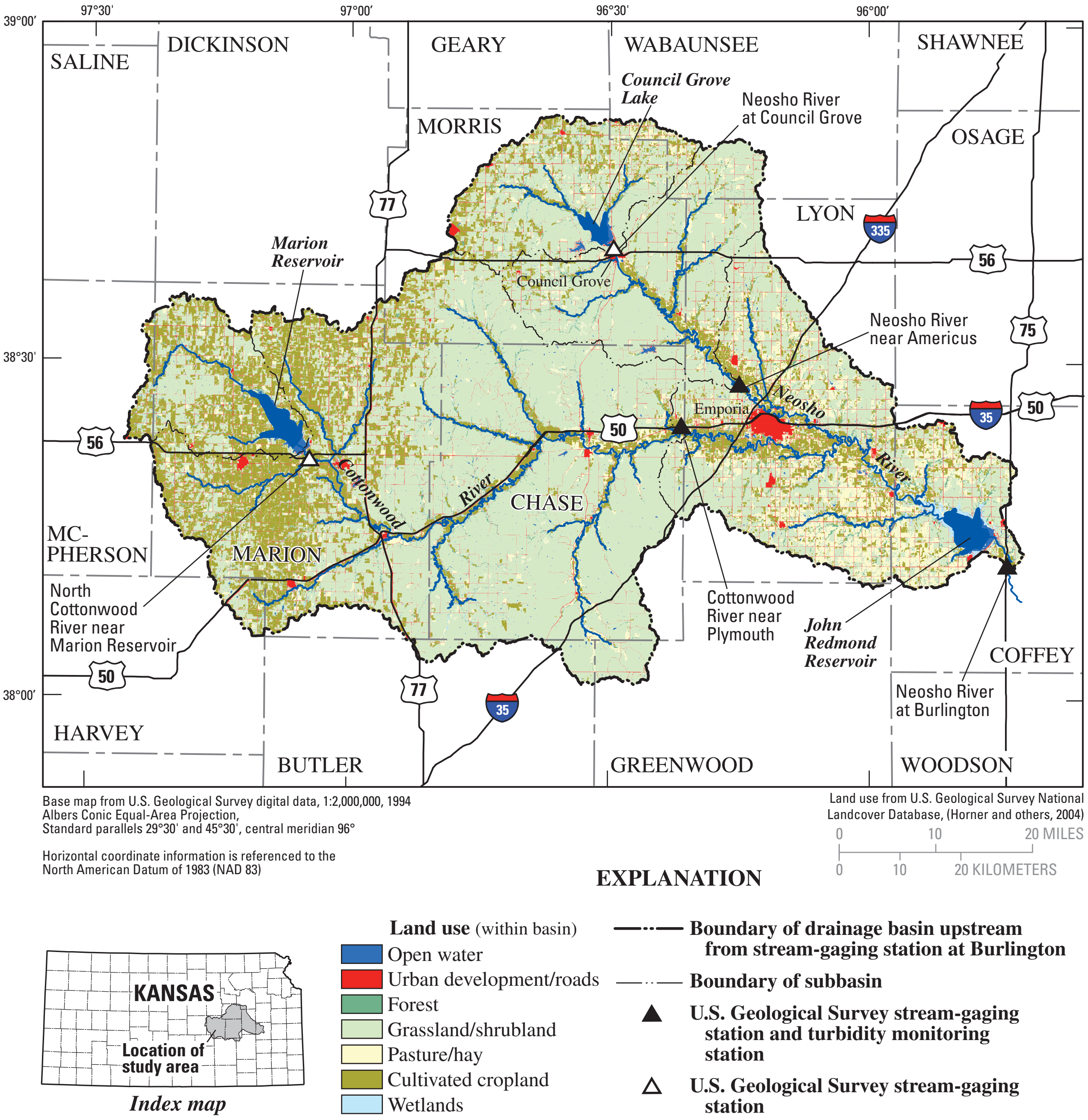
About 1,120,000 tons of suspended-sediment were transported to, and 100,700 tons were transported from John Redmond Reservoir during the study period. Dependent on the bulk density of sediment stored in the reservoir, 5.0 to 1.4 percent of the storage in the John Redmond conservation pool was lost during the study period, with an average deposition of 3.4 to 1.0 inches. Nearly all (98–99 percent) of the incoming sediment load was transported during 9 storms which occurred 25 to 27 percent of the time. The largest storm during the study period (peak-flow recurrence interval of about 4.6–4.9 years) transported about 37 percent of the sediment load to the reservoir. Suspended-sediment yield from the unregulated drainage area upstream from the Neosho River near Americus was 530 tons per square mile, compared to 400 tons per square mile upstream from the Cottonwood River near Plymouth.

Comparison of historical (1964–78) to current (2007) sediment loading estimates indicate statistically insignificant (<90 percent confidence) differences at the Neosho River near Americus and the Cottonwood River near Plymouth, but a significant (>99 percent) decrease in sediment loading at the Neosho River at Burlington. Ninety-percent confidence intervals of streamflow-derived estimates of total sediment load were 7 to 21 times larger than turbidity-derived estimates. Results from this study can be used by natural resource managers to calibrate sediment models and estimate the ability of John Redmond Reservoir to support designated uses into the future.

Introduction

John Redmond Reservoir was constructed from 1959 through 1964 for purposes of flood control, water supply, and recreation (U.S. Corps of Engineers, 2002). The reservoir is on the Neosho River and drains 3,015 square miles of mostly grassland and cropland (fig. 1). Seventy-one percent of water rights downstream from John Redmond are allocated for purposes of cooling the Wolf Creek Nuclear Power Plant (U.S. Army Corps of Engineers, 2002). Fourteen percent of the water rights are allocated to municipalities, 10 percent to irrigation and recreational uses, and 5 percent for industrial uses. Sediment deposition threatens the ability of John Redmond Reservoir to support designated uses. Approximate sedimentation rates to John Redmond Reservoir from 1964–2006 (874 acre-feet per year) are more than double the designed sedimentation rate (404 acre-ft/year; Kansas Water Office, 2008b). Since the closing of the dam in 1964, John Redmond has lost 46 percent of storage in the multipurpose pool; the largest percentage of federally owned reservoirs in the State of Kansas (Kansas Water Office, 2008b). The Kansas Department of Health and Environment has identified impairments to ecosystem quality in the Neosho and Cottonwood River upstream from John Redmond Reservoir because of excessive siltation and nutrient loading (Kansas Department of Health and Environment, 2003).

The Kansas Water Office and the U.S. Army Corps of Engineers initiated a watershed feasibility study to identify strategies to ensure the long-range availability of habitat, water storage capacity, and ecosystem function within John Redmond Reservoir and the surrounding watershed. The U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers, characterized suspended-sediment loading to and from John Redmond Reservoir for part of this overall study. Results from this study can be used by resource managers to assess the ability of the reservoir to support designated uses now and in the future.



Base map from U.S. Geological Survey digital data, 1:2,000,000, 1994
Albers Conic Equal-Area Projection,
Standard parallels 29°30′ and 45°30′, central meridian 96°

Horizontal coordinate information is referenced to the
North American Datum of 1983 (NAD 83)

Land use from U.S. Geological Survey National
Landcover Database, (Horner and others, 2004)

Figure 1. Location of watershed boundaries, land use, and sampling sites upstream and downstream from John Redmond Reservoir, east-central Kansas, February 2007–2008.

Purpose and Scope

The purpose of this report is to estimate suspended-sediment loading to and from John Redmond Reservoir from February 21, 2007, to February 21, 2008. Sediment loads are computed at three sites near inflow/outflow locations of the reservoir through collection of continuous turbidity and streamflow data. Data from this report can be used to estimate the useful lifetime of the reservoir and calibrate models to predict future sediment loading. The approach developed in this study can be used at additional impoundments in the State of Kansas to estimate sediment loading, trapping efficiency, and the length of time reservoirs will continue to support designated uses.

Description of Study Area

The study area is in the Osage Plains section of the Central Lowland Province (Schoewe, 1949). Study area streams typically have deep, narrow valleys with outcropping rock ledges (Carswell and Hart, 1985). The Neosho River (excluding the Cottonwood River tributary) drains about 1,110 square miles (mi^2) upstream from John Redmond Reservoir and has a slope ranging from 3 feet per mile (ft/mile) near Council Grove to 1.5 ft/mile near Emporia (Carswell and Hart, 1985). The largest tributary to the Neosho River is the Cottonwood River, which runs a length of about 127 river miles and drains about 1,900 square miles. River slope ranges from 3.5 ft/mile in the headwaters to 1.5 ft/mile near Emporia (Jordan and Hart, 1985). Silty-clay loam (material with 27 to 40 percent clay and less than 20 percent sand) is the dominant soil type along riparian areas and farther downstream in the watershed. Silty clay (material with 40 percent or more clay and 40 percent or more silt) is the dominant soil type in the upstream part of the basin (U.S. Department of Agriculture, 1994). Erodibility of these soil classes generally are similar (Brady and Weil, 1999).

USGS stream gages on the Neosho River near Americus and the Cottonwood River near Plymouth are the farthest downstream gages prior to stream entry to John Redmond Reservoir (table 1). These gages are downstream from 2,362 mi^2 of the approximate 3,015 mi^2 that drains to the reservoir (U.S. Army Corps of Engineers, 2002). Two federally-owned impoundments regulate streamflow in the watershed draining to John Redmond. Council Grove Lake has a drainage area of 246 mi^2 on the upper Neosho River, and Marion Reservoir has a drainage area of 200 mi^2 on the upper Cottonwood River. Council Grove Lake impounds 40 percent of the watershed upstream from the stream gage at Americus; Marion Reservoir impounds 11 percent of the watershed upstream from the stream gage at Plymouth.

Land use in the John Redmond basin is mostly grassland, with substantial areas of cultivated crops and land devoted to pasture/hay (fig. 1). Cultivation of surface soils have been observed to increase sediment yield compared to undisturbed and (or) grassland conditions (Wolman, 1967). Unprotected cropland has been cited as the primary source of sediment to Kansas streams (Devlin and McVay, 2001). Areas of cultivation are concentrated in the headwater parts of the watershed (primarily of the Cottonwood River) and along the riparian corridor of larger streams (fig. 1). Riparian vegetation has been shown to decrease sediment flux to streams (Lee and others 2003; McKergow and others, 2003) whereas disturbance in riparian areas result in easily transportable sediment. To estimate the extent and location of cropland in riparian areas, land-use was defined for buffers of 160 and 1,000 feet along streams with approximate mean annual flows of 0.1, 1, and 10 cubic feet per second (table 2). The riparian areas of larger streams had the most cropland because of fertile, alluvial soils. Grassland was the dominant land use in the riparian areas of smaller streams.

Previous Sediment Transport Investigations

Few studies have been performed on sediment transport in the upper Neosho or Cottonwood Rivers. Collins (1965) characterized average sediment yields as ranging from 750 to 2,000 tons per square mile per year (tons/mi^2/yr) in the study

Table 1. Location and contributing drainage area of sampling sites upstream and downstream from John Redmond Reservoir east-central Kansas, February 2007–May 2008.

[mi^2, square mile]

U.S. Geological Survey identification number	Site name (fig. 1)	Total drainage area (mi^2)	Unregulated drainage area (mi^2)	Nearest upstream reservoir and corresponding regulated drainage area (mi^2)	Latitude, in degrees, minutes, and seconds	Longitude, in degrees, minutes, and seconds
07179730	Neosho River near Americus	622	376	Council Grove Lake (246)	38°28'01"	96°15'01"
07182250	Cottonwood River near Plymouth	1,740	1,540	Marion Lake (200)	38°23'51"	96°21'21"
07182510	Neosho River at Burlington	3,042	27	John Redmond Reservoir (3,015)	38°11'40"	95°44'40"

Table 2. Approximate land use in riparian areas of various sized streams in the Neosho River basin, east-central Kansas, 2004.

[Data from the U.S. Geological Survey National Landcover Database, Homer and others, 2004; mi^2, square mile; ft^3/s, cubic feet per second]

Stream size designation	Area (mi^2)	Percentage land use						
		Open water	Urban development/ roads	Forest	Grass-land	Pasture/ hay	Cultivated crops	Wetlands/ streams
160-foot buffer riparian area								
Stream with mean annual flow less than or equal to 0.1 ft^3/s	247	1.7	3.0	19.1	47.7	8.3	12.8	7.4
Stream with mean annual flow less than or equal to 1 ft^3/s	99	1.9	3.0	32.2	23.9	8.8	15.0	15.2
Stream with mean annual flow less than or equal to 10 ft^3/s	31.4	4.5	2.6	33.7	6.2	6.4	17.7	29.0
1,000-foot buffer riparian area								
Stream with mean annual flow less than or equal to 0.1 ft^3/s	706	.9	3.6	10.3	53.6	8.8	19.1	3.7
Stream with mean annual flow less than or equal to 1 ft^3/s	277	1.1	3.8	18.8	33.2	10.5	24.3	8.3
Stream with mean annual flow less than or equal to 10 ft^3/s	87.2	2.3	3.6	22.0	12.4	9.9	33.4	16.4

area, and characterized erosion hazards as primarily relating to sheet and gully erosion on sloping croplands and on overgrazed pastures. Yu and others (1993) analyzed trends in water-quality data collected in the Neosho River upstream and downstream from John Redmond Reservoir from 1973–1988. The study found no detectable trend in streamflow or suspended-solids concentration upstream from John Redmond Reservoir and a statistically significant downward trend in suspended-solids concentration downstream from the reservoir. The Kansas Department of Health and Environment (KDHE) collected water-quality data in study area streams and reservoirs to establish total maximum daily loads (TMDLs) to determine impairments. KDHE has established TMDLs for siltation of John Redmond Reservoir and Council Grove Lake, and eutrophication TMDLs for John Redmond Reservoir, Council Grove Lake, and Marion Reservoir (Kansas Department of Health and Environment, 2002, 2003a, 2003b, 2005).

Many studies have been performed that provide precedent for approaches used in this study. Christensen and others, (2000), Putnam and Pope (2003), and Rasmussen and others (2005) have shown that continuous turbidity and streamflow provide accurate computations of suspended-sediment concentrations, loads, and yields in selected Kansas streams.

Methods

Continuous Water-Quality and Streamflow Monitoring

USGS streamflow-gaging stations on the Neosho River near Americus (hereafter Americus), the Cottonwood River near Plymouth (Plymouth), and the Neosho River at Burlington (Burlington) (table 1, fig. 1) were equipped with YSI 6600 continuous water-quality monitors that measured specific conductance, water temperature, and turbidity (model 6136). Sensors collected values in stream, and were housed in polyvinyl chloride pipes drilled with holes to allow stream water to flow through the installation. Sensors at Americus and Plymouth were installed along the bank nearest the stream gage, and sensors at Burlington were suspended from a bridge by chain near the center of the stream. Measurements were logged every 15 minutes, and data are available in real time on the USGS Web pages *http://ks.water.usgs.gov/Kansas/rtqw/*. Historic and current analyses of water-quality samples at monitoring sites are available on the USGS web page *http://waterdata.usgs.gov/ks/nwis/qw*.

Monitor maintenance and data reporting commonly followed procedures described in Wagner and others (2006), with the exception of increased length between calibration checks (~2 months). Fewer calibration visits were necessary because dissolved oxygen and pH data were not collected at monitoring sites. Sensors were cleaned and calibrated approximately bimonthly; additional cleaning visits were made when real-time data indicated error because of environmental fouling. Quality-assurance checks were made before and after sensor cleaning and calibration with an independently calibrated sensor. Fouling or calibration errors found during these visits were used to compute data corrections and estimate error in the continuous-data record.

Because in-stream turbidity conditions occasionally exceeded the upper measurement limit of nephelometric YSI 6136 turbidity sensors, optical-backscatter Hach SOLITAX SC turbidity sensors (SOLITAX) were installed at Americus and Plymouth adjacent to YSI sensors. The SOLITAX sensor uses an internal algorithm to convert backscatter signal strength to an estimate of suspended-solids concentration. SOLITAX sensors have an approximate range from 0 to 50,000 milligrams per liter (mg/L) of suspended solids (Hach Company, 2005) and were installed to estimate suspended-sediment concentration (SSC) when YSI turbidity values were missing or more than the published range (1,000 formazin nephelometric units (FNUs); YSI, 2007). YSI 6136 turbidity and SOLITAX suspended-solids data have shown linearity throughout observed values (Lee and others, 2006). Because there are no independent calibration methods recommended for the SOLITAX by the manufacturer, and because experimental calibration methods did not yield consistent results, independent regression models were developed to estimate error in SOLITAX estimates of suspended-sediment concentration.

Time-series turbidity measurements were occasionally missing or deleted from the continuous record because of equipment malfunctions and (or) environmental fouling. Values for these periods were estimated to allow for an unbiased comparison of suspended-sediment loading among sampling sites. Values were interpolated among measured data points for missing record during stable streamflow (Rasmussen and Ziegler, 2003; Rasmussen and others, 2005). SSC values were computed using data from SOLITAX sensors (rather than the YSI) as the explanatory variable for missing YSI turbidity values during changing streamflow. SOLITAX sensor values were used to compute SSC when YSI turbidity values were greater than 1,000 FNU. SOLITAX sensors were removed during freezing conditions, and not reinstalled during a storm event beginning February 18, 2008, in which turbidity sensors reached maximum values at Americus (for 9 hours) and Plymouth (for 5 hours). Although sediment loading is underestimated during this portion of the continuous record, the relatively short duration of the maximization is not expected to substantially bias total sediment-load computations.

Computing a streamflow time series involved collection of continuous stage records along with periodic streamflow measurements. Observations also were made of factors affecting the stage-streamflow relation. Stage records were obtained from a water-stage recorder. Streamflow measurements were made with a current meter or acoustic Doppler current profiler, using the general methods adopted by the USGS. These methods are described in Rantz and others (1982) and Oberg and others (2005). A more in-depth description of streamflow time-series computation is beyond the scope of this report. These data are available in real time on USGS Web pages (*http://waterdata.usgs.gov/ks/nwis* and *http://ks.water.usgs.gov/Kansas/rtqw/*).

Suspended-Sediment Sample Collection and Analysis

Suspended-sediment samples were collected using equal-width increment methods according to methods described in Gray and others (2008) and Nolan and others (2005). Samples were analyzed for SSC; selected samples were analyzed for grain-size distribution (percent of sediment less than 2, 4, 8, 16, 31, and 62 micrometers in diameter). Samples were analyzed at the USGS Sediment Laboratory in Iowa City, Iowa, using methods described by Guy (1969).

Quality Assurance

Turbidity values were measured across the width of the stream during the collection of suspended-sediment samples. Median values of cross-sectional measurements are compared with in-stream sensors to assess the ability of the in-stream sensor to determine turbidity across the width of the stream. Comparisons were accurate (R^2 = between 0.91–1.0) and near 1:1 relation in slope (0.93 to 1.01; fig. 2). Measurements that plotted outside of a 1:1 fit likely were caused by localized differences in turbidity and (or) instrument error. Because consistent bias was not observed in the relation at any monitoring location, values from continuous-water-quality monitors are representative of stream-water quality across the width of the stream cross section. Turbidity records were generally rated good (error of 5–10 percent) and occasionally fair (10–15 percent) based on guidelines developed by Wagner (2006).

Regression Models

Ordinary-least-square regression analysis was used to develop statistical relations among SSC, in-stream turbidity, and SOLITAX values. Because of data spiking and occasional uneven distribution of turbidity near channel banks (fig. 2), cross-sectional turbidity measurements were used in place of in-stream turbidity measurements for 6 of the 13 samples at Plymouth. All values were log-transformed in order to better approximate normality and to even the variability in regression residuals. After development of the regression model, SSC values were retransformed back to linear space. Because this retransformation can cause bias when adding instantaneous

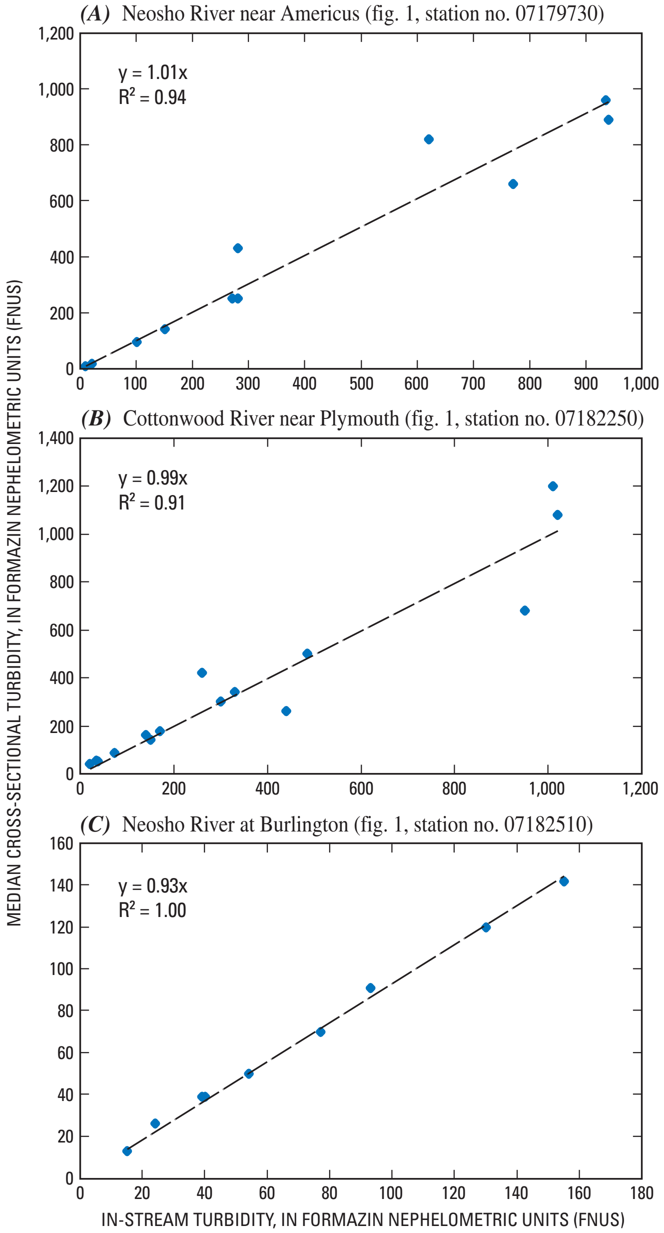


Figure 2. Relation between cross-sectional median and in-stream turbidity readings at John Redmond sites, February 2007–08.

values of load estimates over time, a log-transformation bias correction factor (Duan's smearing estimator; Duan, 1983) was multiplied to correct for potential bias (Cohn and Gilroy, 1991; Helsel and Hirsch, 1992). Uncertainty of regression estimates were determined by 90-percent prediction intervals (Helsel and Hirsch, 1992). Regression methods used in this study are described in greater detail in Cohn and others (1989), Helsel and Hirsch (1992), and Rasmussen and Ziegler (2003). The continuous concentration estimates, uncertainty, and duration curves for the three monitoring sites are available on the World Wide Web at URL *http://ks.water.usgs.gov/Kansas/rtqw*.

Computation of Sediment Concentrations, Loads, and Yields

Instantaneous-suspended-sediment loads were computed from time-series turbidity, SOLITAX reported suspended-solids, and streamflow data as follows: (1) Instantaneous loads were computed by first using regression formulas to compute suspended-sediment concentration from turbidity data every 15 minutes. YSI Turbidity regressions were used when values were less than 1,000 FNUs (the specified sensor limitation of YSI instruments) and if SOLITAX sensors malfunctioned while turbidity values were larger than 1,000 FNUs. (2) Regressions between SOLITAX and SSC values were used whenever YSI turbidity values exceeded 1,000 FNUs, or when YSI turbidity data were not recorded because of sensor malfunction.

SSC values computed from regression estimates were multiplied by the log-transformation bias correction, and then by corresponding streamflow values and a unit conversion to compute 15-minute estimates of suspended sediment load in pounds per second. These instantaneous computations of sediment load are summed and multiplied by a unit conversion to compute sediment loading in tons. The sediment load contributed from a given drainage is divided by upstream drainage area to estimate sediment yield. Sediment yields are calculated to compare sediment loading among drainages of different size, and are not meant to imply equal sourcing of sediment throughout the drainage.

Loads and yields of suspended sediment were estimated for the ungaged drainage area upstream from John Redmond and downstream from the Americus and Plymouth gages (table 1) using data from existing monitoring sites. Because Council Grove Lake and Marion Reservoir trap sediment upstream from monitoring sites, estimates of sediment loading and yield from unregulated parts of monitored drainages are required to accurately estimate sediment contributed from ungaged parts of the study area. Two assumptions were necessary to distinguish sediment loading between regulated and unregulated drainages. First, mean sediment yield upstream from Council Grove Lake and John Redmond and Marion Reservoirs (prior to trapping by impoundments) were estimated based on results of bathymetric surveys (Kansas Water Office, 2008a, 2008b, 2008c). Mean sediment yield upstream from Council Grove Lake and Marion Reservoir is estimated to be 2.52 times and 1.80 times respectively, that of John Redmond (Kansas Water Office, 2008a, 2008b, 2008c). The relative differences in sediment yield among reservoirs can be used to reflect differences in sediment loading during the study period. Second, sediment trapping efficiency at Council Grove Lake and Marion Reservoir is approximated using theoretical relations with hydraulic residence time developed by Brune (1953). Sediment trapping efficiency was estimated as 95 percent in Council Grove Lake and 97 percent in Marion Reservoir during the period of study.

The following equations can be used to estimate sediment loading from regulated and unregulated drainage areas, and from ungaged parts of the study area upstream from John

Redmond Reservoir. Sediment loading computed at streamgage sites is presumed to equal the sum of sediment from the unregulated drainage, and the regulated drainage area multiplied by one minus the trapping efficiency of the reservoir.

$$L_g = L_i + (1- (T_e/100))\ L_r \qquad (1)$$

where L_g is sediment load at the stream gage (in tons), L_i is sediment load of the unregulated drainage area, T_e is the trapping efficiency of the upstream reservoir (in percent), and L_r is sediment loading to the upstream reservoir. Because sediment yield is equivalent to the sediment load divided by upstream drainage area, mean sediment yield to Council Grove Lake and Marion Reservoir (Kansas Water Office, 2008a, 2008b, 2008c) were related to the sediment yield of John Redmond to estimate loading to upstream reservoirs:

$$L_C/D_C = 2.52L_{JR}/D_{JR} \qquad (2)$$

$$L_M/D_M = 1.80L_{JR}/D_{JR} \qquad (3)$$

where D is the drainage area upstream from a specified reservoir (in square miles), and L is the sediment load upstream from a specified reservoir (in tons). Subscript “C” indicates Council Grove Lake, “M” indicates Marion Reservoir, and “JR” indicates John Redmond Reservoir. Given drainage areas from table 1:

$$L_C = .206L_{JR} \qquad (4)$$

$$L_M = .119L_{JR} \qquad (5)$$

Thus sediment loading from the unregulated drainage area upstream from the Americus gage is calculated as (from equation 1):

$$L_{ia} = L_{ga} – (1 - .95)\ .206L_{JR} \qquad (6)$$

Sediment loading from the unregulated drainage upstream from the Plymouth gage is calculated as (from equation 1):

$$L_{ip} = L_{gp} – (1 - .97)\ .119L_{JR} \qquad (7)$$

where subscript “a” indicates Americus and “p” indicates Plymouth. Sediment loading to John Redmond is estimated by multiplying sediment yield (load divided by drainage area) from the unregulated drainages by the ungaged drainage area:

$$L_{JR} = L_{ga} + L_{gp} + (D_{da}L_{ia}/D_{ia}) + (D_{dp}L_{ip}/D_{ip}) + (D_{dc}(L_{ia}+L_{ip})/$$
$$(D_{ia} + D_{ip}) \qquad (8)$$

where D_{da} is the ungaged part of the Neosho River downstream from the Americus gage (184 mi^2), D_{dp} is the ungaged part of the Cottonwood River downstream from the Plymouth gage (162 mi^2), D_{dc} is the ungaged part of the Neosho River downstream from the confluence with the Cottonwood River (307 mi^2). After drainage areas are inserted:

$$L_{JR} = L_{ga} + L_{gp} + .489L_{ia} + .105L_{ip} +$$
$$.161(L_{ia} + L_{ip}) \qquad (9)$$

Given equations 6 and 7 calculating sediment loading from the unregulated drainages upstream from Americus and Plymouth:

$$L_{JR} = L_{ga} + L_{gp} + .489(L_{ga} - .0103\ L_{JR}) +$$
$$.105(L_{gp} - .0036\ L_{JR}) + .161((L_{ga} - .0103L_{JR}) +$$
$$(L_{gp} - .0036\ L_{JR})) \qquad (10)$$

Multiplying it out:

$$L_{JR} = 1.64\ L_{ga} + 1.26\ L_{gp} \qquad (11)$$

Using equation 6 for sediment loading from the unregulated drainage area upstream from the Americus gage:

$$L_{ia} = L_{ga} – (1 - .95).206(1.64\ L_{ga} + 1.26\ L_{gp}) \qquad (12)$$

$$L_{ia} = .983L_{ga} - .013L_{gp} \qquad (13)$$

Using equation 7 for sediment loading from the unregulated drainage area upstream from the Americus gage:

$$L_{ip} = L_{gp} – (1 - .97).119(1.64\ L_{ga} + 1.26\ L_{gp}) \qquad (14)$$

$$L_{ip} = .996L_{gp} - .00059L_{ga} \qquad (15)$$

Although estimating sediment loading to, and trapping efficiency of Council Grove Lake and Marion Reservoir contain undefined error, the estimated sediment load and trapping efficiency are likely more accurate than either assuming constant sediment yield for the entire drainage upstream from gage sites, identical sediment trapping efficiency among reservoirs of different size, or neglecting to account for sediment trapping from upstream reservoirs.

Characterization of Sediment Loading to and from John Redmond Reservoir

Hydrologic Conditions

Total streamflow observed at gage sites in 2007 was similar to median historical streamflow (fig. 3). Median annual streamflow (calculated by summing mean daily values) from the Americus, Plymouth, and Burlington gages from

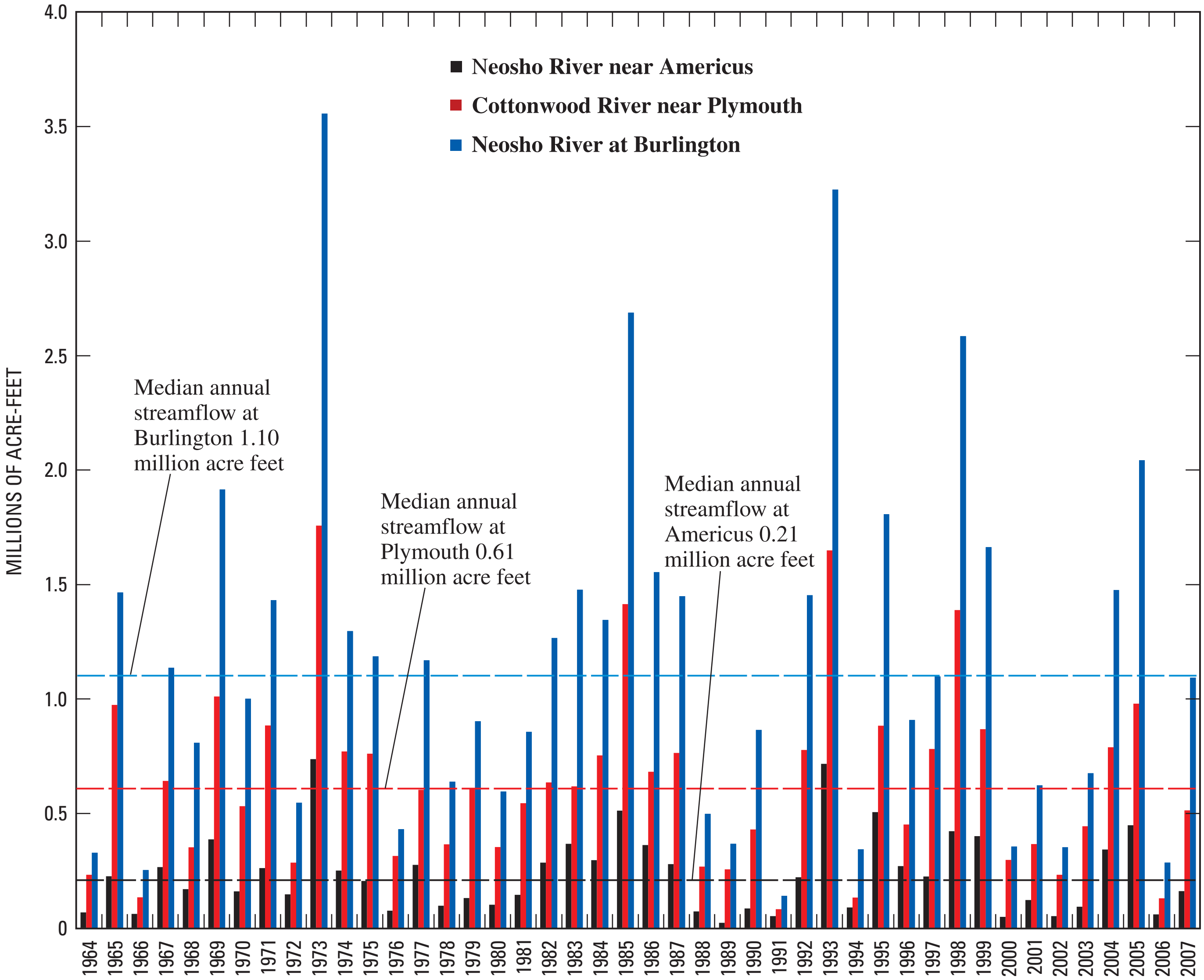


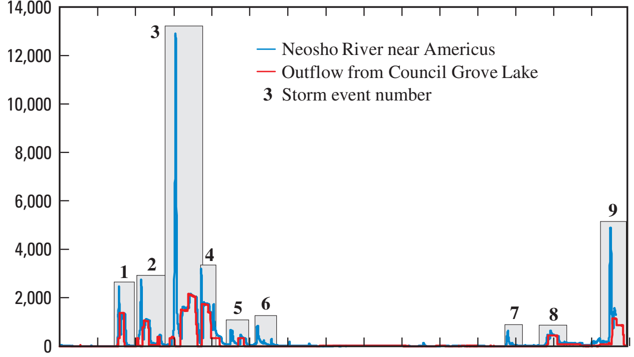
Figure 3. Annual flow at John Redmond sites, 1964–2007.

1964–2007 was 0.21, 0.61, and 1.10 million acre-feet respectively. Annual flow from 2007 streamflow record was 0.16, 0.51, and 1.09 million acre-feet respectively.

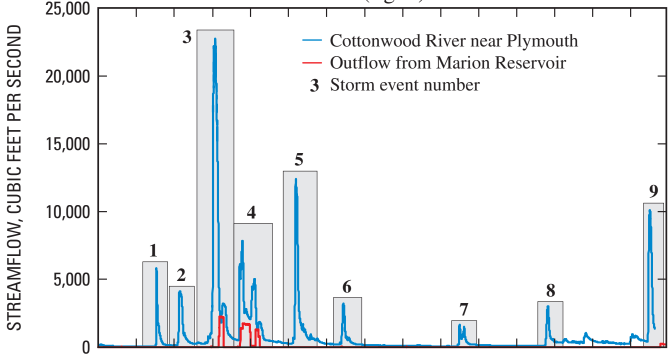
Stormflow events during the study period are defined by peak-streamflow-recurrence interval (Rasmussen and Perry, 2000; Perry and others, 2004). Polynomial relations among 2-, 5-, 10-, 25-, 50-, and 100-year streamflow recurrence interval and peak streamflow were calculated to estimate peak-streamflow recurrence for individual storm events observed during the study period. Although the accuracy of extrapolating these relations is undefined between estimated points, relations are established as a general reference to compare storm size in and among monitoring sites. Storms were not defined by peak streamflow recurrence interval at the Burlington site because of streamflow regulation by John Redmond Reservoir.

Nine storms were observed from February 21, 2007 through February 21, 2008 (fig. 4). Stormflow periods were approximated from the first rise in streamflow (after a period of precipitation) until streamflow approximated base-flow conditions prior to the storm. Stormflow at the Americus and Plymouth gages included releases from Council Grove Lake (based on 15-minute USGS stream-gage data at the Neosho River near Council Grove, KS; figs. 1, 4) and Marion Reservoir (based on 15-minute USGS stream-gage data at the North Cottonwood River near Marion Reservoir, KS; fig. 1). Delineated stormflows contributed 86 (Americus) and 81 (Plymouth) percent of total streamflow, and occurred during 25 (Americus) and 27 (Plymouth) percent of the study period. The largest storm at Americus and Plymouth occurred from May 2 to 23, 2007, had a peak-streamflow recurrence of about once every 4.6–4.9 years (or an estimated annual peak-streamflow probability of about 20 percent), and contributed 36 (Americus) and 31 percent (Plymouth) of the total streamflow (fig. 4).

(A) Neosho River near Americus and outflow from Council Grove Reservoir (fig. 1)



(B) Cottonwood River near Plymouth and outflow from Marion Reservoir (fig. 1)



(C) Neosho River at Burlington (fig. 1)

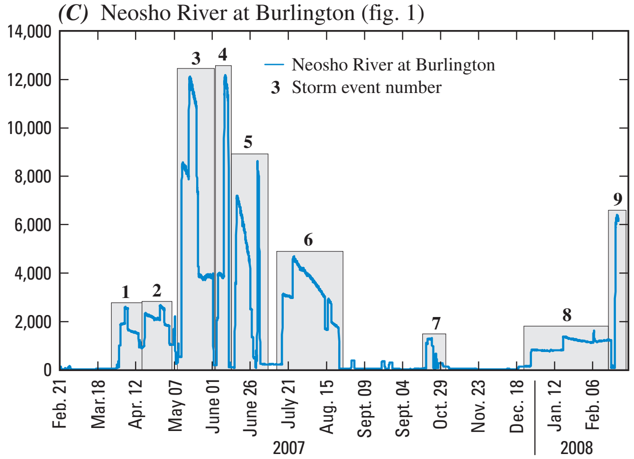


Figure 4. Time-series streamflow values and storms delineated by number, John Redmond sites, February 2007–2008.

The magnitude and duration of streamflow at Burlington is controlled by the outflow from John Redmond Reservoir. Nine separate outflow events were delineated (fig. 4) that contributed 97 percent of the total streamflow volume observed at the site. The largest outflow event (in terms of volume) occurred from May 11 to June 2, 2007, and contributed 26 percent of total streamflow observed during the period of study.

Total flow computed from February 21, 2007–2008, (based on 15-minute streamflow data) was 0.20 million acre-feet (Americus), 0.60 million acre-feet (Plymouth), and 1.09 million acre-feet (Burlington). Total streamflow from Council Grove Lake was 0.11 million acre-feet, 55 percent of the total streamflow at Americus. Total streamflow from Marion Reservoir was 0.04 million acre-feet, 7 percent of total streamflow at Plymouth. Streamflow yield (flow volume/drainage area) was calculated for the regulated drainage area upstream from Council Grove Lake and Marion Reservoir (U.S Army Corps of Engineers, 2008) and for the unregulated drainage area by subtracting reservoir outflows from total streamflow at gaged sites during the period of record. Streamflow yield upstream from Council Grove Lake was 530 acre-ft/mi^2 and was 440 acre-ft/mi^2 upstream from Marion Reservoir. After subtracting outflow from reservoirs, streamflow yield from the unregulated watershed upstream from Americus was 250 acre-feet/mi^2, and 370 acre-feet/mi^2 from the unregulated drainage area upstream from Plymouth. Including discharge from John Redmond Reservoir, streamflow yield was 360 acre-feet/ mi^2 at Burlington.

Duration curves are shown to compare the distribution of streamflow values at each site (fig. 5). Streamflow control and release from John Redmond decreased peak flow values (0–5 percent exceedence) and increased the duration of high flow (10–40 percent exceedence) at Burlington relative to upstream sites. A larger percentage of watershed regulation upstream from Americus (by Council Grove Lake) decreased peak streamflow (0.5–4 percent exceedence) at Americus relative to Plymouth.

Regression Models

Turbidity-sensor response has been shown to increase as particle-size composition of suspended-sediment decreases (Downing, 2006). Turbidity has been used to compute suspended-sediment concentration in Kansas streams in which silt and clay compose the majority of suspended-sediment (Christensen and others, 2000; Rasmussen and others, 2005). The diameter of suspended sediment (by weight) less than 100, 63, 31, 16, 8, 4, and 2 micrometers (µm) was analyzed in selected samples collected during high flow (table 3). Silt and clay (<63 µm) composed greater than 89 percent of sediment concentration (by weight) for all study-area samples (table 3). Clay-sized particles (<4 µm, Guy, 1969) comprised 44 to 68 percent of selected sediment-samples by weight; whereas silt-sized particles (4–63 µm, Guy, 1969) composed 30 to 52 percent of selected sediment samples. The preponderance of clay and silt-sized particles during high flow (when large-sized grain sizes are most readily transported) indicate that optical sensors are appropriate to compute suspended-sediment concentration.

Regression models were developed to estimate continuous (15-minute) SSC using turbidity measurements (table 4, fig. 6). Models developed to compute suspended-sediment concentration for these sites are based on one year of data, and can continue to be refined as additional samples are collected through September 2009. After log-transformation,

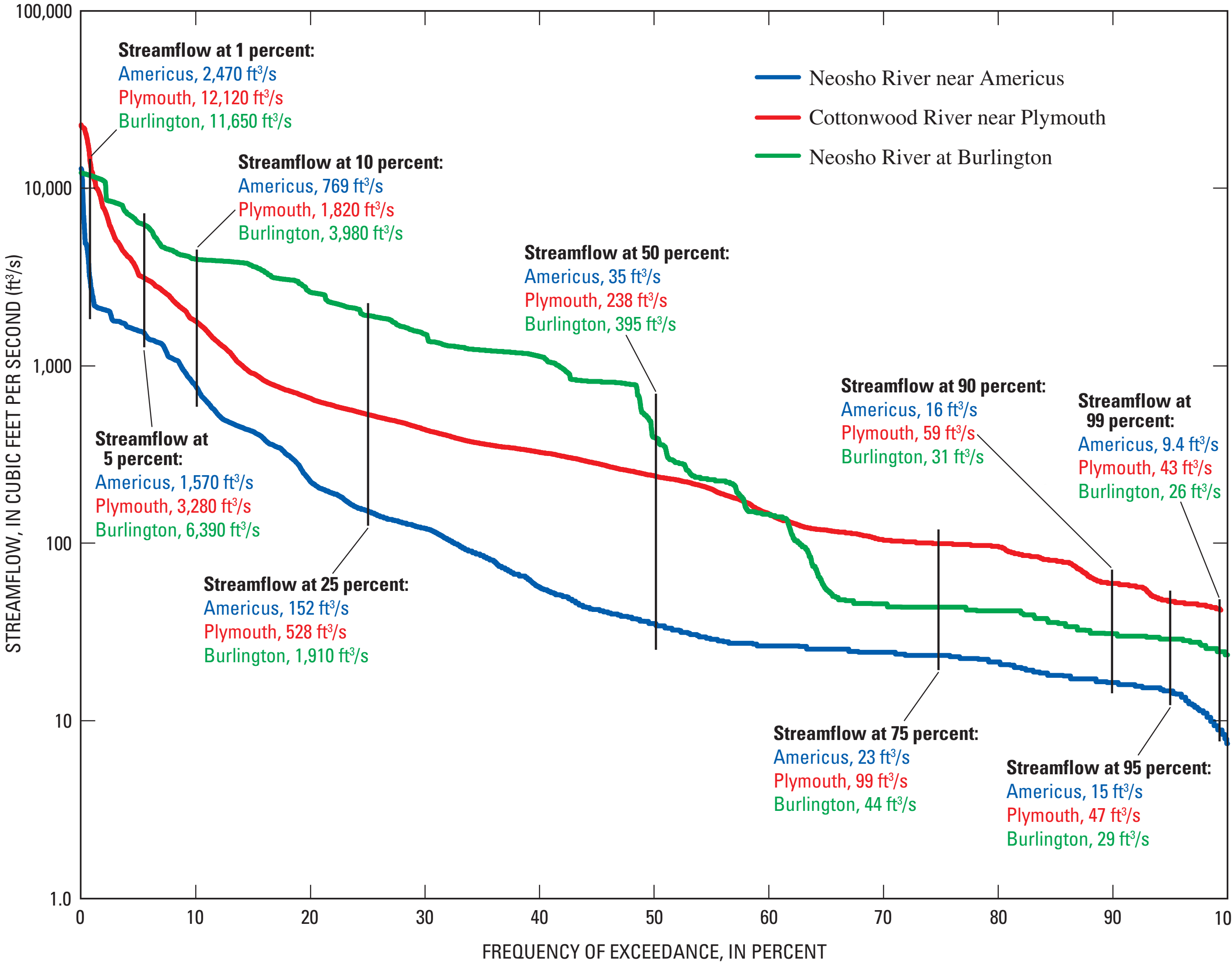


Figure 5. Streamflow duration curves at John Redmond sites, February 2007–2008.

regression residuals approximated normality and did not indicate consistent bias around the regression fit (fig. 6). One outlier was omitted from SOLITAX/SSC models at Americus because the value had a small SSC value, and biased the slope of regression models at high SSC values (when the SOLITAX is primarily used to estimate SSC). Turbidity explained 94 to 98 percent of the variability in SSC from in-stream samples (based on the coefficient of determination, R^2; table 4). YSI/SSC models at Americus and Plymouth had similar slopes (1.004 and 1.005 respectively) and y-intercept values (0.38 and 0.35 respectively) indicating that suspended-sediment size and color (the primary factors affecting these models) were similar among sampling sites. Burlington has the fewest samples (9) but also had less than 10 percent of the range in sediment concentration compared to inflow sites (table 4).

Stormflow Effects on Sediment Loading

Nine storms observed during the study period contributed nearly the entire suspended-sediment load to John Redmond Reservoir (table 5). At Americus, 86 percent of total streamflow and 99 percent of sediment load was contributed by 9 storms (which occurred 25 percent of the time). At Plymouth, 81 percent of total streamflow and 98 percent of the sediment load were contributed by storms (which occurred 27 percent of the time). Releases from John Redmond in excess of base flow occurred 50 percent of the time and contributed 97 percent of the streamflow and sediment load observed at Burlington. The largest stormflow [May 2–23, 2007; estimated peak-streamflow recurrence interval of 4.6–4.9 years (or an annual peak-streamflow probability of about 20 percent; table 5)] contributed the most suspended sediment past

Table 3. Suspended-sediment concentration, percent silt/clay (<63 µm diameter), and grain-size distribution from discrete samples collected from John Redmond sites, February 2007–2008.

[<, less than, µm, micrometers; mg/L, milligrams per liter; FNU, formazin nephelometric units; ft^3/s, cubic feet per second; --, not applicable; Max, sensor truncated]

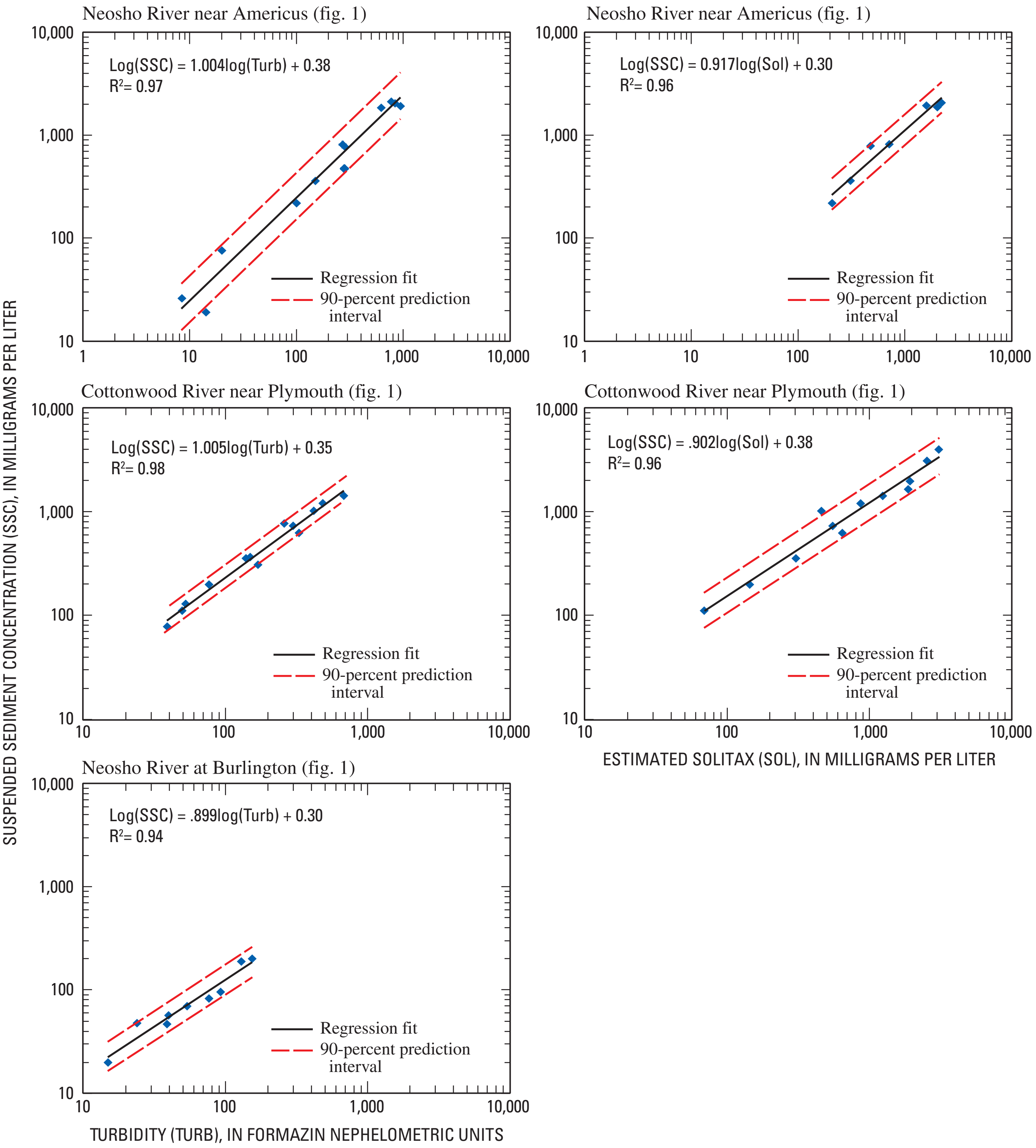
Sample date	Suspended sediment concentration (mg/L)	Insitu turbidity (FNU)	Insitu SOLITAX (estimated mg/L)	Streamflow (ft^3/s)	Percent of sediment (by weight) less than specified diameter						
					< 100 µm	< 63 µm	< 31 µm	< 16 µm	< 8 µm	< 4 µm	< 2 µm
				Neosho River near Americus							
03/26/07	26	8	--	20		92					
03/30/07	76	20	8	110		93					
03/31/07	1,880	620	1,280	1,210		100					
03/31/07	1,940	940	2,160	1,710		99					
04/02/07	790	280	680	1,340		99					
04/15/07	2,150	770	1,520	2,760	100	96	86	58	45	44	40
04/16/07	820	270	640	430		97					
04/17/07	360	150	320	810		99					
04/20/07	220	100	160	1,070		99					
05/07/07	2,070	940	1,920	6,090	100	94	87	67	61	56	51
05/08/07	480	280	360	6,600		98					
07/17/07	19	36	40	36		97					
				Cottonwood River near Plymouth							
03/26/07	78	20	--	48		95					
03/30/07	110	38	40	61		90					
03/30/07	1,010	260	480	190		99					
03/31/07	1,640	Max	1,520	4,510		99					
03/31/07	1,420	950	1,480	4,180		99					
04/02/07	350	140	280	840		98					
04/15/07	730	300	560	4,110		95					
04/16/07	1,200	490	840	3,700		98					
04/17/07	620	330	600	1,780		98					
04/20/07	200	73	160	510		89					
05/07/07	1,960	Max	1,760	17,800	100	98	94	79	71	68	63
05/08/07	770	440	--	22,400		96					
05/24/07	3,960	Max	2,280	5,200	99	99	85	67	59	53	50
05/24/07	3,080	Max	2,040	5,490	100	99	90	73	58	56	50
07/02/07	360	150	--	4,030		99					
07/18/07	130	34	80	260		95					
10/18/07	310	170	--	810		99					
				Neosho River at Burlington							
03/26/07	20	15		45		98					
03/30/07	83	77		220		97					
03/31/07	96	93		180		98					
04/12/07	190	130		1,790		92					
04/20/07	70	54		2,840		90					
06/22/07	47	39		6,570		98					
07/19/07	48	24		4,230		96					
09/21/07	57	40		390		94					

Table 4. Regression models and statistics for estimating suspended-sediment concentration (SSC) from turbidity values at study area sites, February 2007–2008.

[SSC, suspended-sediment concentration; R^2, coefficient of determination; MSE, mean-squared error; YSI, Yellow Springs Instruments; mg/L, milligrams per liter; Turb, turbidity in formazin nephelometric units; Sol, SOLITAX in estimated milligrams per liter]

Site name (fig. 1)	Regression relation	Duan bias correction[1]	R^2	MSE	Discrete sample results					
					Number of samples	Range in response variable	Range in SSC (mg/L)	Mean	Median	Standard deviation
Suspended-sediment concentration and YSI model 6136 turbidity sensor										
Neosho River near Americus	Log(SSC) = 1.004log(YSI)+.38	1.04	0.97	0.02	12	8.5–940	19–2,150	900	630	860
Cottonwood River near Plymouth	Log(SSC) = 1.005log(YSI)+.35	1.01	0.98	0.004	13	20–680	78–1,420	560	360	440
Neosho River at Burlington	Log(SSC) = 0.899log(YSI)+.30	1.01	0.94	0.007	9	15–160	20–200	90	70	63
Suspended-sediment concentration and SOLITAX turbidity sensor										
Neosho River near Americus	Log(SSC) = 0.917log(Sol)+.30	1.01	0.96	0.01	7	8–2,190	19–2,150	900	630	860
Cottonwood River near Plymouth	Log(SSC) = 0.902log(Sol)+.38	1.02	0.96	0.01	12	69–3,060	78–1,960	660	493	560

[1](Duan, 1983).


Neosho River near Americus (fig. 1)

Neosho River near Americus (fig. 1)

Cottonwood River near Plymouth (fig. 1)

Cottonwood River near Plymouth (fig. 1)

Neosho River at Burlington (fig. 1)

Figure 6. Regression models between optical sensors and suspended-sediment concentration at study area sites, February 2007–2008.

Table 5. Dates, streamflow, and suspended sediment loading of stormflow for study period at John Redmond sites, February 2007–2008.

[tons/mi^2, tons per aquare mile; --, no data]

Storm designation	Start date	End date	Peak streamflow recurrence interval (years)	Total streamflow (acre-feet)	Percent of total streamflow	Turbidity-computed suspended-sediment load (tons)	Percent of total suspended-sediment load	Suspended-sediment yield of total drainage area (tons/mi^2)
Neosho River near Americus								
1	03/30/07	04/07/07	0.4	13,200	6.7	18,800	9.1	30
2	04/13/07	04/22/07	.5	15,900	8.1	12,900	6.2	21
3	05/06/07	05/23/07	4.6	70,500	36	85,600	41	140
4	05/24/07	06/09/07	.6	32,700	17	48,400	23	78
5	06/12/07	06/24/07	.1	5,890	3.0	1,820	.9	2.9
6	06/28/07	07/04/07	.1	3,330	1.7	1,010	.5	1.6
7	12/11/07	12/16/07	.1	2,110	1.1	660	.3	1.1
8	01/05/08	01/16/08	.1	7,910	4.0	1,120	.5	1.8
[1]9	02/16/08	02/21/08	1.1	18,600	9.4	34,800	16.8	56
Entire period of record	02/21/07	02/21/08	--	197,100	100	207,500	100	330
Cottonwood River near Plymouth								
1	03/30/07	04/07/07	.3	14,500	2.4	30,400	4.9	18
2	04/13/07	04/25/07	.2	27,900	4.7	31,500	5.1	18
3	05/02/07	05/21/07	4.9	182,900	31	219,900	36	130
4	05/24/07	06/09/07	.6	102,700	17	120,200	19	69
5	06/28/07	07/09/07	1.5	63,800	11	69,500	11	40
6	07/29/07	08/08/07	.1	17,300	2.9	20,700	3.3	12
7	10/14/07	10/23/07	.03	10,800	1.8	8,940	1.4	5.1
8	12/10/07	12/17/07	.1	14,700	2.5	11,900	1.9	6.8
[1]9	02/16/08	02/21/08	1.0	50,100	8.4	96,400	16	55
Entire period of record	02/21/07	02/21/08	--	598,800	100	620,100	100	360
Neosho River at Burlington								
1	03/29/07	04/15/07	--	49,900	4.6	8,580	8.5	2.8
2	04/16/07	05/05/07	--	76,200	7.0	11,100	11.0	3.6
3	05/11/07	06/02/07	--	288,000	26	32,400	32	11
4	06/03/07	06/12/07	--	102,700	9.4	8,300	8.2	2.7
5	06/15/07	07/03/07	--	149,600	14	12,700	13	4.2
6	07/16/07	08/23/07	--	240,800	22	12,100	12	4.0
7	10/18/07	10/23/07	--	11,200	1.0	2,200	2.2	.7
8	12/26/07	02/17/08	--	110,200	10	6,250	6.2	2.1
[1]9	02/19/08	02/21/08	--	26,600	2.4	3,750	3.7	1.2
Entire period of record	02/21/07	02/21/08	--	1,091,000	100	100,700	100	33.1

[1] Storm ongoing at the end of study period.

monitoring sites (41 percent at Americus, 36 percent at Plymouth). Sediment yields were larger at Plymouth (360 tons/mi^2), in part because of increased total and unregulated drainage area compared with Americus (330 tons/mi^2). Suspended-sediment load (100,700 tons) and yield (33 tons/mi^2) at the Neosho River at Burlington is substantially smaller than upstream sites because of the settling of sediment in (or upstream from) John Redmond Reservoir (table 5).

Total suspended-sediment load and streamflow volume are compared for the nine storms/flood control releases observed at monitoring sites (fig. 7), to determine sediment loading among different-sized storms. Best fit lines are shown to provide a frame of reference for comparison of sediment/streamflow relations; additional events need to be measured to verify potential relations. Sediment load generally increased in a linear fashion with increases in streamflow volume at all three monitoring sites. Flood-control releases at Burlington had much smaller sediment loading per streamflow volume because of sediment trapping in John Redmond Reservoir. The largest stormflow (storm 3; fig. 7, table 5) at Americus and Plymouth did not indicate decreased sediment supply relative to other storms despite the large volume of streamflow. Larger sediment loading per streamflow volume during storm 9 at upstream sites was partially because values had not returned to base flow by the end of the study period.

Duration curves were calculated for 30-minute computations of suspended-sediment load (SSL) at study area sites. Sediment trapped in John Redmond substantially decreased maximum (0–5 percent exceedence) sediment loads at Burlington relative to upstream sites (fig. 8). Whereas, the most (>50 percent) sediment was transported during 0.9 percent of the study period (~3.1 days) at Americus, and 1.5 percent of the time (~5.7 days) at Plymouth, the most of sediment was transported in 8.5 percent of the time (~31 days) at Burlington. Council Grove Lake trapped a larger percentage of sediment upstream from the Americus gage than did Marion Reservoir, causing smaller duration of high sediment loading conditions (>100 pounds per second) relative to Plymouth. Prolonged, large releases from John Redmond resulted in longer duration of sediment loading more than 1 pound per second at Burlington.

Effects of Upstream Reservoirs on Sediment Loading

The vast majority of water released from Council Grove Lake and Marion Reservoir was contributed by a few large releases. These releases transported additional sediment past downstream monitoring sites, increasing observed sediment loads. In order to compare sediment loading among sites, and to estimate sediment loading from ungaged parts of the John Redmond watershed, sediment loads were distinguished between regulated and unregulated parts of upstream watersheds. Sediment originating from impoundment outflows and from unregulated watersheds is distinguished using methods described in “Computation of sediment concentrations, loads, and yields.”

About 6 percent (11,700 tons) of the 207,500 tons of sediment transported past Americus, originate in outflows from Council Grove Lake (table 6). About 0.6 percent (4,000 tons) of the 620,100 tons of sediment transported past Plymouth originate in outflows from Marion Reservoir. After subtraction of sediment loading from upstream reservoirs, sediment yield estimates for the unregulated watershed upstream from monitoring sites are 530 tons/mi^2 at Americus and 400 tons/mi^2 at Plymouth.

Reservoir releases transport sediment from both the reservoir and the downstream channel. Because flood-control releases from Council Grove Lake and Marion Reservoir commonly occurred after large storms or during base flow, resultant increases in sediment loading could be estimated at downstream monitoring sites (fig. 9). Continuous streamflow and sediment loading values before and after reservoir releases were used to create an exponential fit to estimate hypothetical streamflow and sediment loading without upstream reservoir releases. These estimates were subtracted from observed values to estimate total streamflow and sediment load contributed by upstream impoundments to downstream monitoring sites (fig. 9, table 6). One outflow at Plymouth was estimated by using only streamflow and sediment loading values observed prior to a release from Marion Reservoir, because a storm increased streamflow and sediment loading before the Cottonwood River returned to base flow.

Streamflow measured from upstream reservoir releases are compared with values estimated at downstream sites to evaluate the accuracy of methods used to estimate total sediment loading from large reservoir releases. Streamflow from the seven flood-control releases from Council Grove Lake (92,900 acre-feet) were larger than those estimated at Americus (75,400 acre-ft), partially because the release from February 19, 2008, had not yet reached Americus by the end of the study period. Outflows from the remaining six releases (87,500 acre-ft) were slightly larger than those estimated at Americus (74,200 acre-ft). Outflows from the three large releases from Marion Reservoir (over two storms) were 40,100 acre-ft, compared to an estimate of 25,700 acre-ft at Plymouth. Smaller estimates of streamflow volume at downstream monitoring sites are likely because of dispersion of the release and (or) loss of flow to ground water in the intermediate stream channel.

Reservoir releases from Council Grove Lake are estimated to transport 51,000 tons of sediment past the monitoring site near Americus. Subtraction of the estimated 11,700 tons of sediment transported directly from the Council Grove outflow results in 39,300 tons of sediment estimated to have been transported from the stream channel of the Neosho River by reservoir releases (table 6). Outflows from Marion Reservoir are estimated to have transported 18,200 tons of sediment past Plymouth. After subtraction of the estimated 4,000 tons that originated from the outflow, 14,200 tons of sediment are estimated to have been transported from the

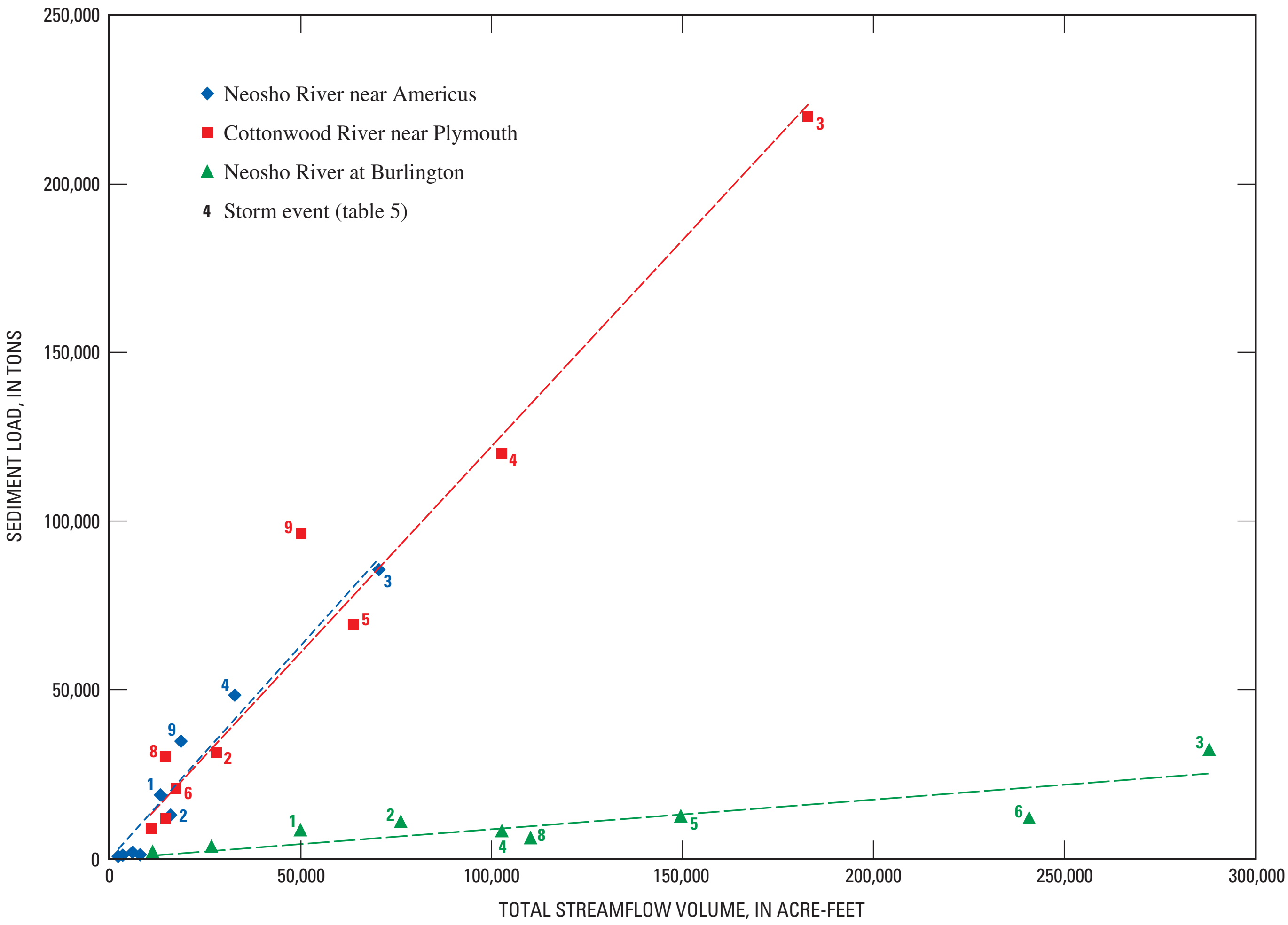


Figure 7. Relation between sediment loading and streamflow volume during stormflow events at John Redmond sites, February 2007–2008.

Cottonwood River channel by reservoir releases. Evidence that channel sediments are transported by reservoir releases was obtained by collection of turbidity readings at the Council Grove Lake outflow on February 20, 2008. Turbidity readings from the outflow were 17 formazin nephelometric units (FNU) at 1,150 cubic feet per second of streamflow. Sixteen hours later (approximate travel time of the release) readings at Americus were about 110 FNU at 1,420 cubic feet per second. The large increase in turbidity and relatively small increase in flow between the two sites indicate that substantial sediment had been transported from the Neosho River channel by the reservoir release.

Tributaries contribute streamflow and sediment to the mainstem of the Cottonwood and Neosho Rivers during storms. Immediately downstream from impoundments, tributary flows are relatively small compared to the historic, unregulated floods that formed the main channel (Morris and Fan, 1997). The velocity of small tributary flows decrease as it enters the regulated, low streamflow of the main channel, allowing time for sediments to fall to the streambed. Higher-energy streamflows released from upstream reservoirs likely transport these sediments downstream. Thus, sediment transported by reservoir flood-control releases may have been transported by runoff events without the presence of the dam. Because of this, sediment transported from stream channels downstream from dams are considered to have originated from the unregulated drainage area.

Trapping Efficiency and Storage Loss

Sediment yields from the unregulated drainages upstream from Americus and Plymouth were used to estimate sediment loading from the ungaged drainage upstream from John Redmond Reservoir according to methods described in “Computation of sediment concentrations, loads, and yields.” About 1,120,000 tons of sediment entered John Redmond from February 21, 2007, through February 21, 2008. Compared with 100,700 tons of sediment transported past Burlington, a trapping efficiency of 91.0 percent was calculated for John Redmond during the study period (fig. 10).

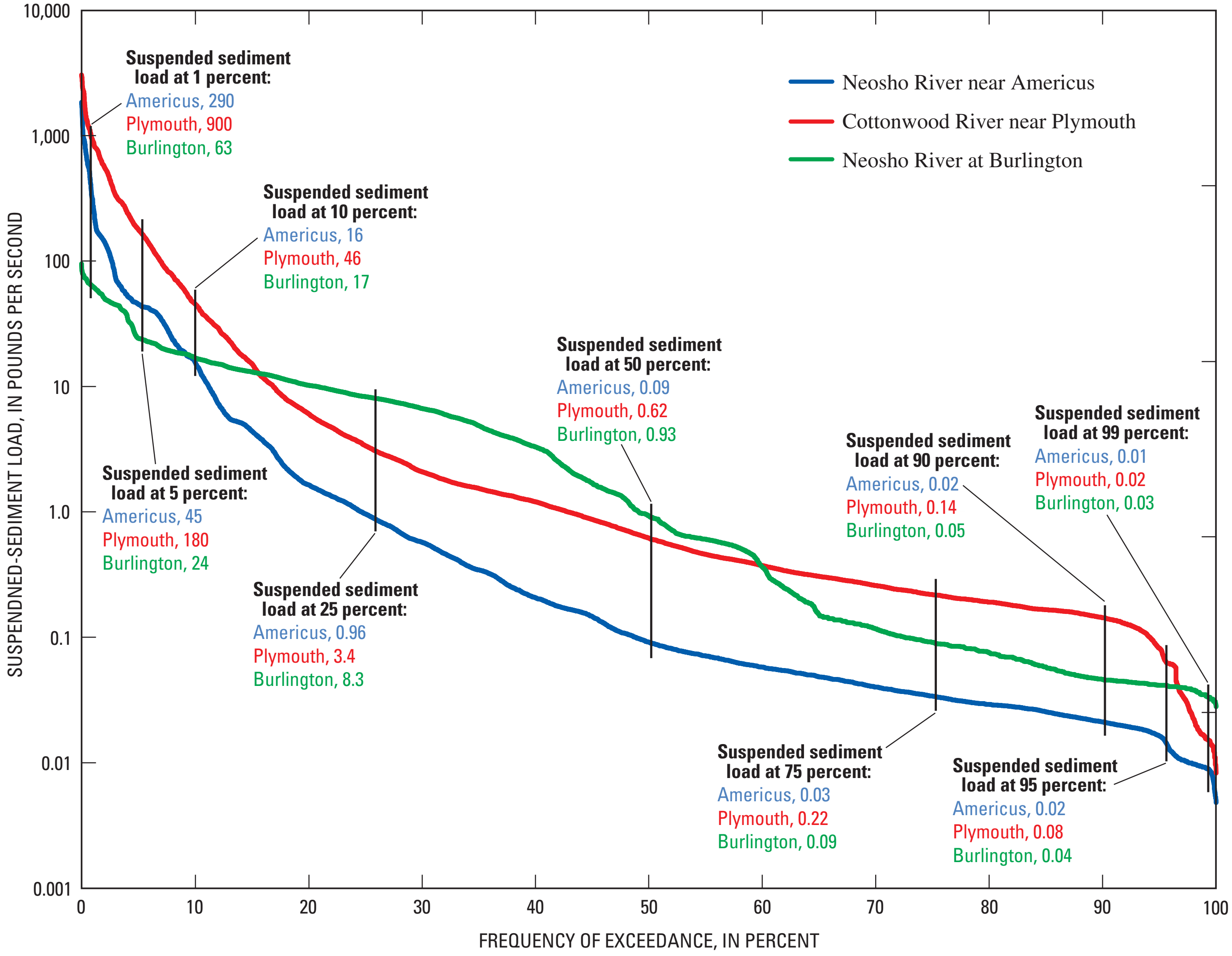


Figure 8. Suspended-sediment load duration curves at John Redmond sites, February 2007–2008.

Potential sources of error in this estimate include the settling of suspended sediment prior to entry to the John Redmond Reservoir, error in estimation methods, and transport of sediment from the stream channel between the John Redmond outflow and the Burlington site. The large logjam present upstream may promote settling of sediment prior to entry to the reservoir (U.S. Army Corps of Engineers, 2005). Error is present in estimates of sediment yield upstream from, and sediment trapping efficiency of Council Grove Lake and Marion Reservoir, as well as in estimates of sediment loading from ungaged parts of the drainage. However, because Council Grove Lake and Marion Reservoir trap most of the incoming sediment from upstream drainages, changes in estimates of sediment yield and trapping efficiency do not substantially change estimates of loading to John Redmond. Additionally, because 78 percent of the drainage upstream from John Redmond is gaged, variation in sediment yields used to estimate the ungaged portion of the drainage do not cause substantial differences in loading to the reservoir. Whereas sediment may be transported from the channel between John Redmond and Burlington, instantaneous comparisons of turbidity between the John Redmond outflow and Burlington were similar (within 20 percent) during observations on February 8 and 28, 2008.

Estimates of the bulk density in small Kansas impoundments have ranged from about 20 to 70 lbs/ft^3 (Juracek, 2004); mean bulk density in Cheney Reservoir was 62 lbs/ft^3 (Mau, 2001). Sediment loading into John Redmond was divided by bulk densities ranging from 20 to 70 lbs/ft^3 to estimate sedimentation rates to John Redmond Reservoir during the study period (table 7). Sediment volume accumulated from February 21, 2007, through February 21, 2008, ranged from 2,340 acre-ft (20 lbs/ft^3) to 670 acre-ft (70 lbs/ft^3). Calculated sedimentation rates were larger than the designed sedimentation rate (404 acre-ft/year; Kansas Water Office, 2008b) during a study period with about median historical streamflow. Estimates of lake surface area and volume were obtained from a 2007 bathymetric survey (Kansas Biological Survey, 2007)

Table 6. Streamflow, sediment load, and sediment yield from regulated and unregulated drainage areas at monitoring sites upstream from John Redmond Reservoir, February 2007–08.

[tons/mi^2, tons per aquare mile]

Site name (fig. 1)	Streamflow			Sediment load			Sediment yield	
	Total stream-flow volume (acre-feet)	Total streamflow from reservoir releases (acre-feet)	Total streamflow from large, flood control releases (acre-feet)	Total suspended-sediment load (tons)	Suspended-sediment load originating from reservoir release (tons)	Suspended-sediment load transported from down-stream channel by res-ervoir releases (tons)	Sediment yield from total upstream watershed (tons/mi^2)	Sediment yield from unregulat-ed watershed (tons/mi^2)
Neosho River near Americus	197,100	105,400	92,900	207,500	11,700	39,300	330	530
Cottonwood River near Plymouth	598,800	44,100	40,100	620,100	4,000	14,200	360	400

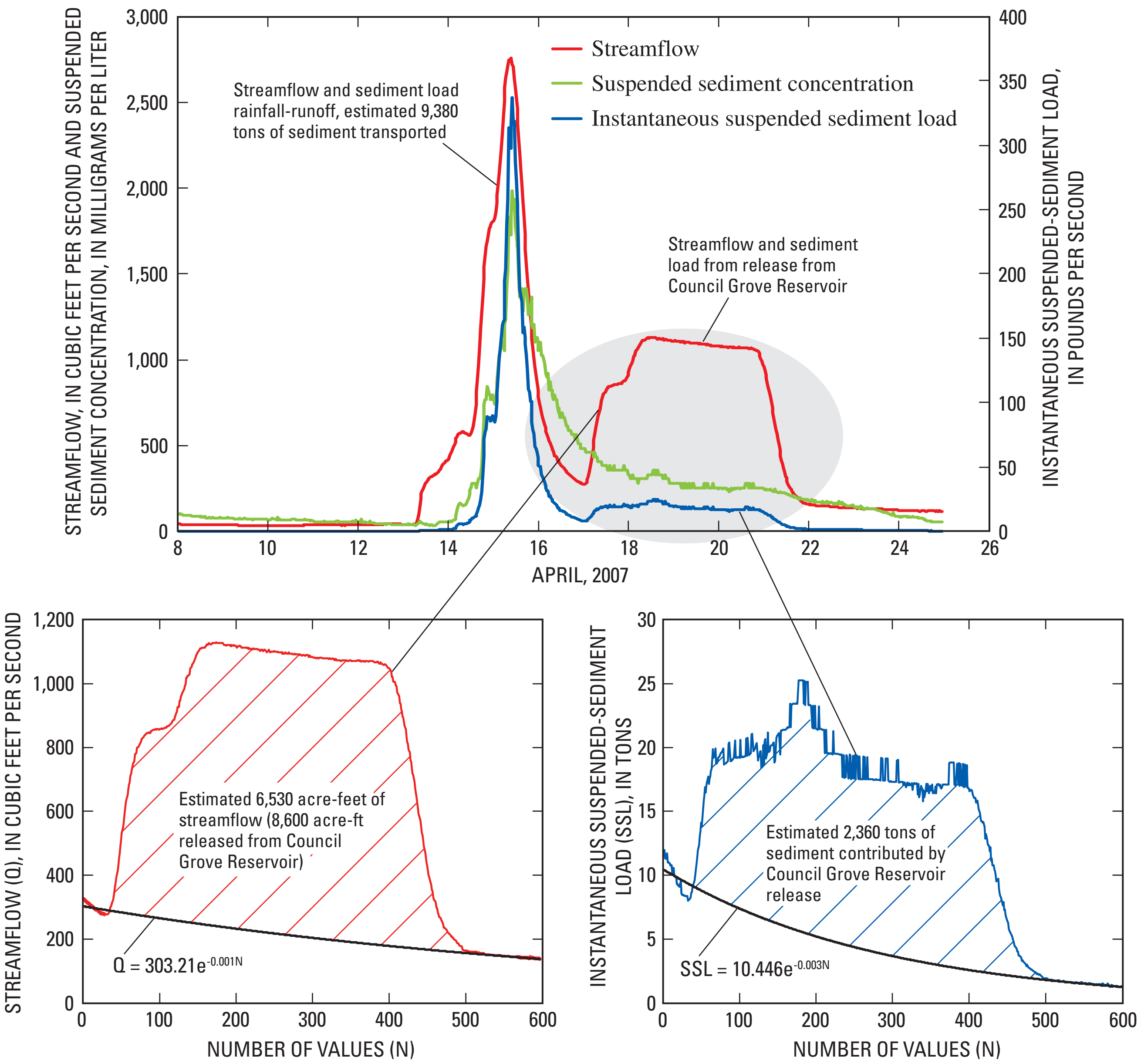


Figure 9. Estimation of streamflow and sediment loading originating from Council Grove Reservoir at the Neosho River near Americus, April 8–26, 2007.

to estimate storage lost and depth of sediment accumulation during the period of study. Approximate lake volume at the elevation (1,038.5 ft) nearest the top of the multipurpose pool (1,039 ft) was 47,284 acre-feet, with a surface area of 8,368 acres (Kansas Biological Survey, 2007). A range of bulk density values from 20 to 70 lbs/ft^3, was used to estimate storage lost that ranged from 5.0 to 1.4 percent, with an average sediment deposition of 3.4 to 1.0 inches (table 7).

Comparison to Historical Data

Historically, 497 SSC samples were collected by the USGS from the three sampling sites from 1944 to 1992. Regression models were developed between streamflow and suspended-sediment load for historic samples, and applied to continuous (15-minute) streamflow values recorded from February 21, 2007, through February 21, 2008. Historic SSC samples were only considered after gates had closed at upstream impoundments (October 1964 at Americus, February 1968 at Plymouth, and September 1964 at Burlington) and only if data were collected at least annually (table 8). Total sediment loads are calculated by using historic streamflow/sediment loading relations to estimate the magnitude of historic sediment loading expected given the flow regime observed during the current study period. Percentage root mean square error, 90-, and 99-percent confidence intervals of total load estimates are defined for historic streamflow/

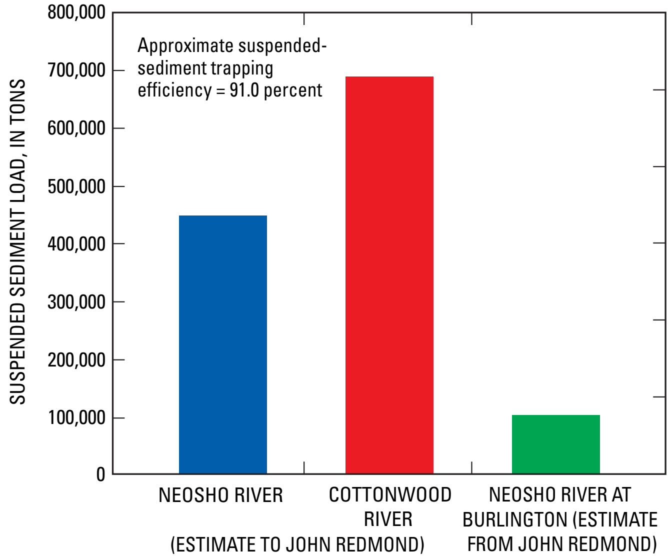


Figure 10. Approximate suspended-sediment load to and from John Redmond Reservoir, February 2007–2008.

sediment loading estimates and turbidity/SSC relations using error approximation methodology described in Gilroy and others (1990). If differences in total sediment loads calculated between historic and current relations exceed 90-percent confidence intervals, then the presumption (with 90-percent confidence) is that differences in sediment loads in observed streamflow from February 2007–2008 are due to factors other than error in estimation techniques.

Streamflow/sediment load relations at Americus were underrepresented by a single log-linear fit at large streamflow values. Two log-linear relations were developed, one representing low flow (<279 cubic feet per second) and one representing high flow (>279 cubic feet per second) using methods described in Glysson (1987). Relations at Plymouth and Burlington did not have identifiable bias around a single log-linear fit, and thus were represented by a single relation. Streamflow explained 81 to 88 percent of the variability in historic SSC samples (based on R^2, fig. 11).

Table 7. Estimate of storage lost in John Redmond Reservoir under varying estimates of bulk density, February 2007–08.

[Estimates from 1,020,000 tons of sediment retained, and storage volume and surface area at a lake elevation of 1,038.5 feet[1]; lbs/ft^3, pounds per cubic foot]

Bulk density (lbs/ft^3)	Volume of deposition (acre-feet)	Percentage of storage lost	Mean depth of sediment accumulation (inches)
20	2,340	5.0	3.4
30	1,560	3.3	2.2
40	1,170	2.5	1.7
50	940	2.0	1.3
60	780	1.7	1.1
70	670	1.4	1.0

[1] Kansas Biological Survey, 2007.

Historic and current estimates of sediment loading at Americus and Plymouth were within the 90-percent confidence intervals of total load estimates, indicating no significant difference between historic and current study periods. Differences in sediment loading estimates at Burlington were outside of 99-percent confidence intervals indicating that changes in sediment loading have occurred between 1964–1978 and 2007–2008. Ninety-percent confidence intervals of total sediment loads calculated by using historic streamflow/sediment load relations was 7 to 21 times larger than turbidity estimated sediment loading at all sites (table 9).

Channel beds and banks have been documented to scour after upstream impoundments are constructed (Morris and Fan, 1997). Sediments in the streambed and channel banks directly downstream from John Redmond may have been transported during high-flow releases immediately after gates were closed, and are no longer available for transport because the downstream channel has adjusted to accommodate the stream-power of large releases. An alternative explanation is that the logjam upstream from John Redmond is trapping more sediment than during historic conditions, allowing less sediment to move through the outflow. Additional sediment sampling and continuous sediment monitoring of storms can be used to refine techniques to assess potential changes in sediment transport at monitoring sites.

Summary and Conclusions

Continuous turbidity sensors were used to characterize suspended sediment-loading to and from John Redmond Reservoir from February 21, 2007, to February 21, 2008. Sensors were installed at U.S. Geological Survey stream gage sites on the Neosho River near Americus and the Cottonwood River near Plymouth that monitor 78 percent of the watershed upstream from John Redmond Reservoir. Suspended-sediment concentrations and loads were monitored from the John Redmond outflow by sensor installation at a stream gage at the Neosho River at Burlington. Ordinary-least-squares regression equations were used to develop statistical relations between turbidity sensor measurements and in-stream samples of suspended-sediment concentration. Turbidity sensors explained 94 to 98 percent of the variability in suspended-sediment concentration from in-stream samples. Regression relations between turbidity sensors and suspended-sediment concentration were applied to continuous (15-minute) values of turbidity and streamflow to estimate sediment loading to and from John Redmond Reservoir.

Stormflow contributed nearly all the suspended-sediment load observed at each site. Ninety-nine percent of the suspended-sediment load at the Neosho River near

Table 8. Regression models and statistics for estimating suspended-sediment load (SSL) using historic (1964–1978) sediment and streamflow at study area sites, February 2007–2008.

[SSL, suspended-sediment load; mg/L, milligrams per liter; R^2, coefficient of determination; MSE, mean-square error; Q, streamflow, in cubic feet per second; SSC, suspended-sediment concentration; Q, streamflow in cubic feet per second]

Site name (fig. 1)	Period of record	Regression relation	Duan bias correction[1]	R^2	MSE	Number of samples	Range in Q	Suspended-sediment concentration (mg/L)			
								Range in SSC	Mean	Me-dian	Standard deviation
Neosho River near Americus	1966–77	$Q < 279$: $\mathrm{Log}(SSL) = 1.1885\log(Q) - 2.61$	1.28	0.82	0.084	83	3–270	10–300	98	90	60
		$Q > 279$: $\mathrm{Log}(SSL) = 1.9132\log(Q) - 4.40$	1.31	.78	.11	36	290–4,030	30–4,920	540	270	870
Cottonwood River near Plymouth	1968–77	$\mathrm{Log}(SSL) = 1.465\log(Q)-3.10$	1.34	.87	.096	105	38–15,800	10–2,640	330	190	430
Neosho River at Burlington	1964–78	$\mathrm{Log}(SSL) = 1.282\log(Q)-3.10$	1.46	.88	.13	151	7–15,100	3–730	110	80	110

[1] (Duan, 1983).

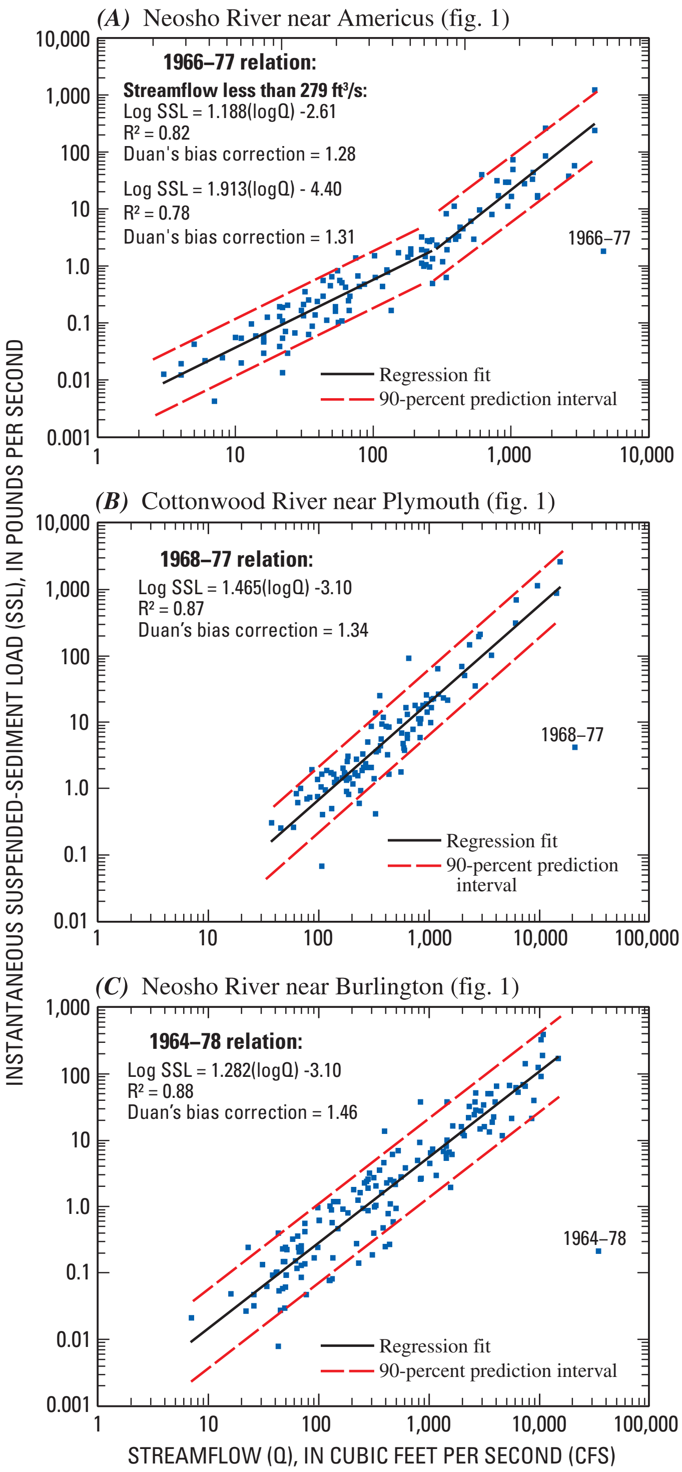


Figure 11. Relations between streamflow and suspended-sediment load (SSL) for historic sediment samples at study area sites.

Americus, and 98 percent of the suspended-sediment load at the Cottonwood River near Plymouth was transported by the nine storms observed during the study period (which occurred 25–27 percent of the time). The largest storm (4.6–4.9 year peak-streamflow recurrence interval) occurred from May 2 to May 23, and accounted for 41 percent of the total sediment load at the Americus site and 36 percent of the total sediment load at the Plymouth site. Sediment loading at Burlington was primarily controlled by streamflow releases from John Redmond Reservoir. Ninety-seven percent of the sediment load at the Burlington site was contributed by the nine outflow releases (which occurred 50 percent of the time).

Federal impoundments upstream from monitoring sites caused observable changes to streamflow and sediment loading at monitoring sites. The Cottonwood River near Plymouth had a larger suspended-sediment yield (360 tons/mi^2) than at the Neosho River near Americus (330 tons/mi^2) if sediment-trapping effects from upstream impoundments are not considered. When estimates of sediment trapped by the upstream reservoirs was subtracted from loads computed at monitoring sites, the unregulated watershed upstream from the Neosho River near Americus had a larger suspended-sediment yield (530 tons/mi^2) than upstream from the Cottonwood River near Plymouth (400 tons/mi^2). Reservoir releases transport sediment from the main channel downstream from the outflow in addition to sediment transported directly from Council Grove Lake and Marion Reservoir. Larger, more frequent releases from Council Grove Lake transported about 39,300 tons of sediment from the main stem channel of the Neosho River, compared to 14,200 tons of sediment transported from the Cottonwood River by releases from Marion Reservoir.

About 1,120,000 tons of suspended-sediment were transported to, and 100,700 tons were transported from John Redmond Reservoir, resulting in 91 percent trapping efficiency during the study period from February 21, 2007 to February 21, 2008. Based on estimates of bulk density ranging from 20 to 70 lbs/ft^3, 5.0 to 1.4 percent of the storage in the John Redmond conservation pool was lost during the study period, with an average deposition of 3.4 to 1.0 inches.

Regression models were developed between streamflow and sediment loading data collected from 1964–1978 at the three monitoring sites. Models were applied to streamflow observed during the current study period, and summed to obtain an estimate of total sediment load. Error in computed total load was estimated to determine if differences in historic and current sediment loading computation methods were because of uncertainty or changes in sediment loading conditions at monitoring sites. Sediment loads computed at Americus and Plymouth were statistically indistinguishable; whereas loads between historic and current load estimates at Burlington

Table 9. Comparison of total sediment loads estimated from turbidity (2007–2008) and historic (1964–1978) streamflow measurements, February 2007–2008.

[+/-, plus or minus]

Site name (fig. 1)	Turbidity derived estimates				Historic streamflow-derived estimates			
	Estimated sediment load (tons)	Percentage root mean squared error	90-percent confidence interval	99-percent confidence interval	Estimated sediment load (tons)	Percentage root mean squared error	90-percent confidence interval	99-percent confidence interval
Neosho River near Americus	207,500	3.2	± 14,430	± 22,920	257,100	13.7 19.8	±102,400	± 151,030
Cottonwood River near Plymouth	620,100	1.1	± 14,900	± 23,420	706,200	15.7	± 208,900	± 302,110
Neosho River at Burlington	100,730	2.4	± 5,500	± 8,290	291,600	19.7	± 113,720	± 164,480

were larger than 99 percent confidence estimates. Significant differences in sediment loading at Burlington are either because of less sediment transported from the stream channel between the John Redmond outflow and the Burlington site, or improved trapping of sediment upstream from John Redmond Reservoir. Ninety-percent confidence intervals of streamflow-derived estimates of sediment loading were 7 to 21 times that of turbidity-derived estimates of sediment loading. Additional sediment data collected through September 2009 can be used to refine regression models and trend analyses described in this report.

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